MOLECULAR ABSORPTION IN CEN A ON VLBI SCALES

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Abstract. Centaurus A, the nearest AGN shows molecular absorption in the millimeter and radio regime. By observing the absorption with VLBI, we try to constrain the distribution of the gas, in particular whether it resides in the circumnuclear region. Analysis of VLBA observations in four OH and two H_2CO transitions is presented here, as well as molecular excitation models parameterized with distance from the AGN. We conclude that the gas is most likely associated with the tilted molecular ring structure observed before in molecular emission and IR continuum. The formaldehyde absorption shows small-scale absorption which requires a different distribution than the hydroxyl.

Keywords: Centaurus A, NGC 5128, molecular absorption, radio absorption lines, masers, circumnuclear gas

1. Introduction

Centaurus A, the radio source in the nearest AGN, displays remarkable absorption in both molecular and atomic gas. While in similar objects the absorption is often made up of a few broad components, in Cen A it can be resolved into many narrow components that together cover 80 km/s. Moreover, these features can be traced in very many chemical components, because Cen A has a bright nucleus from radio to sub-millimeter wavelengths.

A matter of debate has been whether these tracers are associated with the obscuring dust band in the outer regions of NGC 5128, or whether some of these originate in the circumnuclear region. The first case would allow us to study the physics and chemistry of the interstellar medium in a recent merger galaxy, undergoing a starburst. The second case would possibly be even more exciting, as these lines could then be used as tracers of the physical and chemical conditions in the vicinity of a black hole, where conditions are affected by intense radiation and the ultimate fate of the gas is to feed the monster.

There are at least two ways in which we can hope to determine the location of the absorbing gas on the line-of-sight. The first is through geometrical arguments; for example, if it can be shown that only a small fraction of the background source

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is obscured and a torus shape is assumed, it may be argued that the obscuring ring is close to the nucleus.

The second method is to investigate whether the molecular excitation requires or excludes the influence of the nuclear emission. A related argument may be the chemical composition of the material, which could show the signature particular to X-ray processing if the gas is of nuclear origin.

In this paper, we combine VLBA observations of OH and H_2CO with excitation modeling to argue that most of the molecular material seen against Cen A is at considerable distance from the nucleus (between 200 pc to 2 kpc).

2. VLBA Results

The VLBA OH 18 cm data was taken on 8 July 1995. A single track was observed with all 10 telescopes. The frequency setup covered four base-bands in two polarizations, covering a bandwidth of 2 MHz ($\approx$360 km/s). In order to obtain sufficient spectral resolution ($\approx$0.8 km/s), two correlator passes were done. The formaldehyde lines were initially observed on 12 December 1996, covering the 6 and 2 cm transitions on consecutive days. Analysis of these observations showed that the 6 cm data had some problems and those were re-observed on 20 November 1997.

It turned out to be quite complicated to image the data properly; the low elevations at which Cen A is observed from the VLBA sites imply that the mutual visibility is limited. The array of antennas that has data on Cen A and can be calibrated properly as it changes many times during the stretch of the observations. This makes self-calibration quite difficult, especially for the 18-cm data which is dominated by flux on short baselines.

As a result, the best spectra are obtained directly in the uv-domain and show the most signal to noise when limited to short baselines. These spectra are shown in Figure 1. They are compared with a SEST HCO^+ spectrum (Israel et al., 1991) and previous ATCA results (Langevelde et al., 1995). The resulting VLBA OH spectra match the previous ATCA results, if we take the higher signal to noise in the large beam into account. This indicates that the absorption is smooth between the ATCA and VLBA scales. Earlier results on H_2CO were obtained by Seaquist and Bell (1990), who detected both formaldehyde lines with the VLA. Again the VLBA formaldehyde results seem consistent with their work, given the lower signal to noise in the high-resolution data.

The next step is to image the hydroxyl absorption against the VLBI structure of Centaurus A. This is shown in Figure 2. At a distance of 3.4 Mpc 50 mas corresponds to 0.82 pc (Israel, 1998). It is clear that the systemic feature covers the entire source. Interestingly, at the red-shifted velocity it appears at first that the absorption only covers the brightest part of the source, but is not detected against the extended jet. However, careful analysis of the signal to noise in the source shows that the lack of absorption is not significant; the background is simply not bright enough to detect a

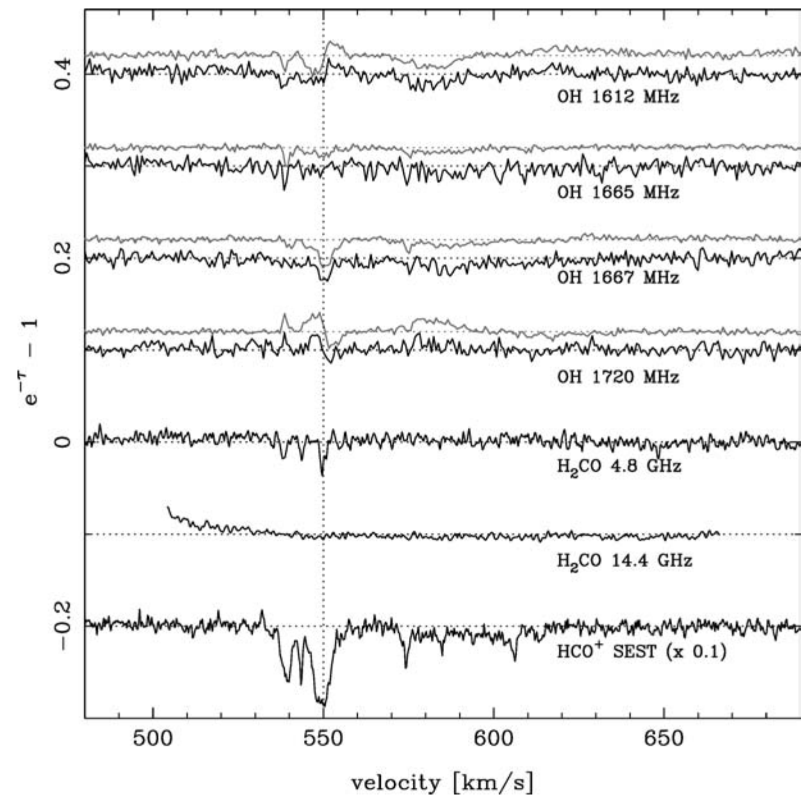

Figure 1. Spectra for OH and H_2CO from VLBA data, in a sub-arcsecond beam. For comparison of OH spectra obtained with the ATCA are shown as well in grey, slightly offset from the VLBA data (van Langevelde et al., 1995). The bottom spectrum is HCO^+ from the SEST (Israel et al., 1991).

homogeneous absorption screen at the jet position. We conclude that the OH result is consistent with both absorption components covering the entire VLBI source. But it is equally consistent with the systemic component covering the entire source and a red-shifted component in front of the brightest 18-cm component.

In Figure 3 the results from mapping the formaldehyde are shown. It should be kept in mind that at the 4.8 (and 15 GHz) we may be looking at different components in continuum emission. Following the analysis by Tingay and Murphy (2001) we interpret the brightest spot in the 1.6 and 4.8 GHz image as a knot in the jet. In the 18-cm image the core is absorbed, at 6 cm the core and jet components are approximately equally bright. We detect formaldehyde absorption at the systemic velocity against the core component. Surprisingly there is no absorption detected against the knot in the jet. As this component is equally bright as the core, *this* structure is significant. We conclude that the systemic formaldehyde absorption arises from a different place than the OH component, even though the velocity is identical.

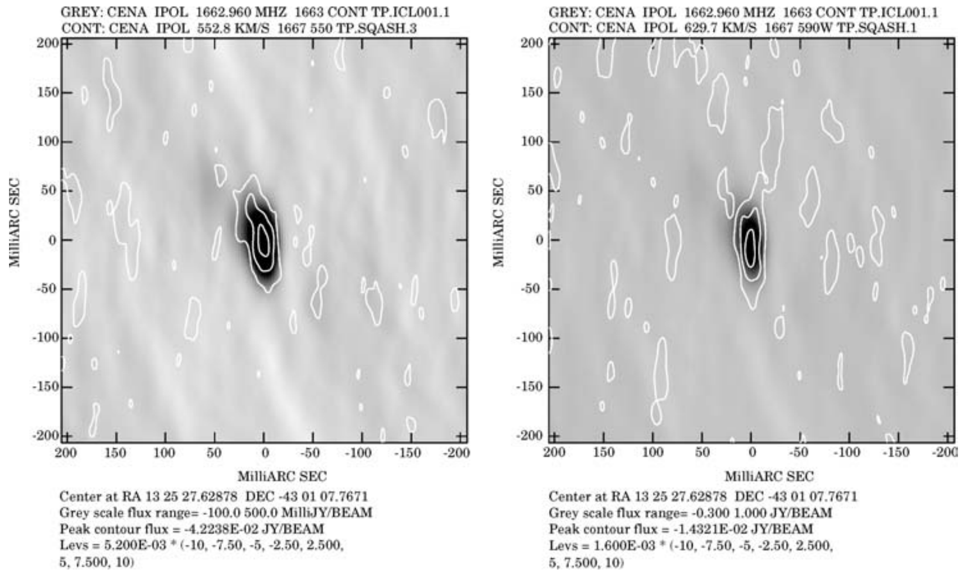

Figure 2. Contours show the OH 1667 MHz absorption feature at 550 km/s (left), overlayed on the continuum in grey scale, as well as the OH 1667 feature in the 590 km/s shallow component. The absorption seems to cover a large fraction of the source, at least at 550 km/s.

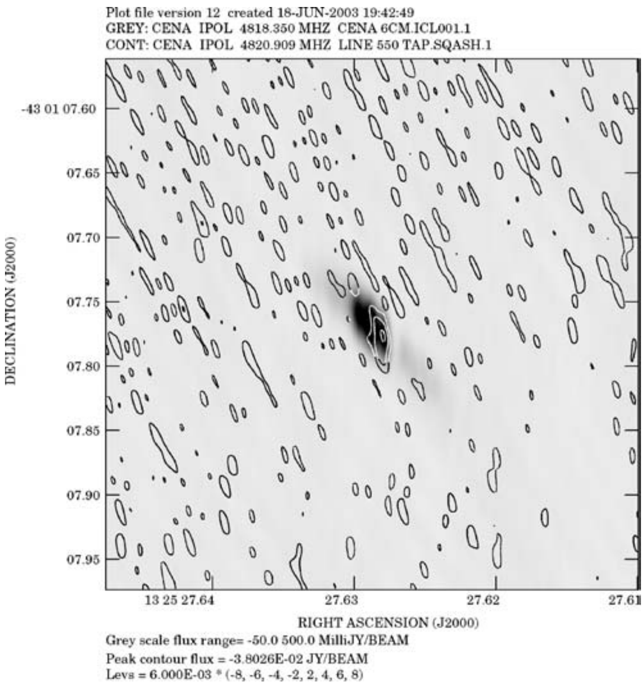

Figure 3. A map of the 4.8 GHz continuum of Cen A overlayed with the H_2CO absorption in the 550 km/s feature. Clearly the feature does not cover the entire structure equally.

3. Modeling

We have modeled the excitation of the OH and H_2CO following the analysis in van Langevelde et al. (1995). The gas in front of Cen A is treated with a simple escape probability code. In this analysis we have put emphasis on the excitation of the molecular gas by external radiation, expected to be an important factor in a galaxy that shows both signatures of starburst and an active nucleus. The excitation of both species is governed by the usual parameters of kinetic temperature, density of the ambient H_2 and OH/H_2CO column density, which transfers into a length scale and an abundance. In addition the excitation of OH by infrared radiation is taken into account. Following the previous analysis we consider two components: far-infrared radiation generated at the location of the OH gas, as well as intense mid-infrared radiation from the inner circumnuclear disk (<400 pc). For the excitation of formaldehyde radio emission is important and therefore a flat spectrum nuclear source is included too.

The total model has far too many parameters to explore all dependencies. Rather, we have fixed all our best guesses based on the available observations of Cen A and varied only one physical constraint, namely the distance of the absorbing gas from the nucleus of Cen A. Keeping the density and temperature of the gas constant, as well as the locally generated far infrared radiation, the molecular gas is subject to less mid-infrared and radio excitation as the solid angle that the nuclear source subtends decreases with increasing distance from the center (and for radii within the molecular ring the mid-infrared emission is assumed to be local). The relative strength of the 1.6 GHz OH components and the dominance of the 4.8 GHz formaldehyde over the 15 GHz line are taken to be the main quantities to be reproduced.

Within the context of this simple model, analysis shows that the gas cannot be much closer than 200 pc. Otherwise, we predict maser emission in the 6-cm formaldehyde line, as the radio emission starts to dominate the excitation. A similar effect appears in the OH models, where the infrared emission will dominate the excitation and main line masers will occur. It is more difficult to rule out very large distances from the nucleus, anything up to 2 kpc is possible, showing that this excitation is not exceptional compared to normal Galactic conditions. At very large distances the main lines are expected to be much stronger than the satellite lines. This does not appear in the main systemic component, but it seems this effect can be seen at some of the weaker systemic components that are slightly blue-shifted.

4. Discussion

From the excitation analysis it follows that the OH and formaldehyde gas seems to be constrained to radii of 200 pc–2 kpc. This seems to be a robust results based on interpretation of global properties of the spectra, although it should be realized that this follows from a rather crude model. Shielding of the molecular gas, e.g. in a very thin disk, could possibly allow a closer radius. On the other hand, a strong local interstellar radiation field, possible in starburst conditions, could support the specific excitation at larger radii.

On the relevant scales many authors have studied the structure and physics of the gas and dust in NGC 5128. Much of the discussion of on these components can be found in Israel (1998), but for our interpretation a model by Eckart et al. (1999) is most relevant. This model is based on CO, sub-mm and infrared imaging (e.g. Leeuw et al., 2002; Wild et al., 1997) which shows a warped structure on the scale of 0.5–1.5 kpc. Modeling this structure as a set of concentric disks, each with a slightly different axis orientation *and* assuming gas at considerable height above these is co-rotating, the millimeter absorption structure (like the HCO^+ spectrum in Figure 1) can be reproduced remarkably well.

There seems to be no problem to interpret the OH results in this context. According to this model neutral molecular gas components close to the systemic velocity arise at very different distances from the nucleus. At three different radii the tilted rings intersect the line-of-sight to the nucleus. This could thus be consistent with the different excitation of the systemic components. The red-shifted components arise at higher latitude above the tilted disk in this model. Like HCO^+ there must thus be considerable OH in the medium above the mid-plane. As this gas may be less embedded in the high density mid-plane of the disks one may expect more pronounced excitation effects. Indeed the satellite lines dominate in this component. Compared to the HCO^+, the OH seems to be more diffuse and shows fewer distinct components. The VLBI source extends for less than 1 pc. With a scale height of 300 pc it is therefore expected that OH absorption is homogeneous over the source, as observed.

The interpretation of the formaldehyde is less straightforward. From the spectrum it is noticeable that no formaldehyde is seen in the red-shifted component. Also the systemic components are much narrower. Moreover, the absorption occurs only against the core of the radio source, a line-of-sight not even sampled in OH.

If we interpret the H_2CO absorption structure across the source as a thin disk around the central engine, we derive a distance from the nucleus which is disturbingly small. At a distance of 3.4 Mpc the size of the absorption amounts to 0.4 pc. Even if this arises from a very thin disk, with a height/radius ratio of 100, this disk would be located within the 50 pc from the nucleus. Given the excitation modeling, as well as the narrow width of the absorption lines this seems unlikely.

An interpretation in which the formaldehyde absorption is located at larger distance runs into the uncomfortable situation that it requires a chance alignment of the absorbing cloud in front of the nucleus. Within the context of the model of Eckart et al. (1999), it is possible to explain the observations if the bulk of H_2CO is restricted to small clouds (<1 pc) in the mid-plane of the tilted rings. This fits in with the absence of red-shifted components in this tracer, the narrow line width and the small-scale structure in the absorption. However, on the relevant scale it is not clear why this absorption is seen against the core only. It is expected that the other velocity components could equally well appear in front of the jet. Unfortunately, we lack the signal-to-noise to test the appearance of the weaker components.

We conclude that the VLBI observations, as well as the excitation modeling is consistent with the absorption occurring on 200–2000 pc from the center of Centaurus A. The formaldehyde seems to have a distinctly different distribution, possibly restricted to small, high-density clouds in the circumnuclear disk.

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