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Letter to the Editor

Gas near active galactic nuclei: A search for the 4.7 μm CO band★

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Abstract. In order to constrain the properties of dense and warm gas around active galactic nuclei, we have searched Infrared Space Observatory spectra of local active galactic nuclei (AGN) for the signature of the 4.7 μm fundamental ro-vibrational band of carbon monoxide. Low resolution spectra of 31 AGN put upper limits on the presence of wide absorption bands corresponding to absorption by large columns of warm and dense gas against the nuclear dust continuum. High resolution ($R \sim 2500$) spectra of NGC 1068 detect no significant absorption or emission in individual lines, to a 3σ limit of 7% of the continuum. The limits set on CO absorption in local AGN are much lower than the recent Spitzer Space Telescope detection of strong CO absorption by dense and warm gas in the obscured ultraluminous infrared galaxy IRAS F00183-7111, despite evidence for dense material on parsec scales near an AGN in both types of objects. This suggests that such deep absorptions are not intimately related to the obscuring "torus" material invoked in local AGN, but rather are a signature of the peculiar conditions in the circumnuclear region of highly obscured infrared galaxies like IRAS F00183-7111. They may reflect fully covered rather than torus geometries.

Key words. galaxies: active – galaxies: Seyfert – infrared: galaxies

1. Introduction

The circumnuclear regions of active galaxies, exposed to the intense nuclear UV and X-ray radiation field, host dense material in the form of the clumpy "torus" posited by unified models and/or of more irregularly distributed clouds. Under these conditions, significant quantities of warm ($\approx$1000 K) and dense ($\approx 10^7$ cm^{-3}) molecular gas can be created (e.g. Krolik & Lepp 1989; Maloney et al. 1996). While such gas can emit significantly in familiar tracers of molecular material like the mm CO rotational lines or the near-infrared H_2 rovibrational lines, these lines are also emitted by molecular gas under less extreme conditions. Focussing on transitions that originate only in warm/dense gas can help breaking these degeneracies, in particular if found at wavelengths able to penetrate significant obscuring dust columns.

One of the possible tracers are highly excited CO transitions, either in far-infrared rotational lines as modelled by Krolik & Lepp (1989), or using high rotational quantum number J transitions of the 1–0 rovibrational band near 4.7 μm. The lowest few transitions of the P and R branch of this band, superposed on broad absorption features of CO and "XCN" ice, have been detected towards galactic nuclei obscured by large columns of cold molecular material, like our Galactic Center (Lutz et al. 1996; Moneti et al. 2001) or the circumnuclear starburst of NGC 4945 (Spoon et al. 2003). Rovibrational transitions from higher ($J \gtrsim 10$) levels are expected only from warm and dense regions, and have been observed in emission (e.g. Scoville et al. 1983; Rosenthal et al. 2000; Pontoppidan et al. 2002) or absorption (e.g. Mitchell et al. 1989) near young stellar objects in our galaxy. Similarly, detection of high J rovibrational CO transitions near AGN would be direct evidence for the presence of warm and dense gas, with the caveat that complex geometries and radiative transfer can lead to difficult interpretation due to a complex interplay of line emission, line absorption and continuous absorption. As expected from "torus" dust models and mm-wave CO observations and confirmed directly by Brα spectroscopy of Seyfert 2 galaxies (Lutz et al. 2002), the dust optical depth in the nuclear regions can still be considerable at 4–5 μm. Part of the warm dense gas can thus be hidden at those wavelengths. In addition, the observable signature in the CO lines will depend on the temperature of regions that are optically thin in the continuum compared to the temperature of the dust continuum "photosphere". This can cause shallow line absorptions/emissions even in case of large columns of warm molecular gas.

The topic has recently gained further interest due to the Spitzer Space Telescope detection (Spoon et al. 2004) of

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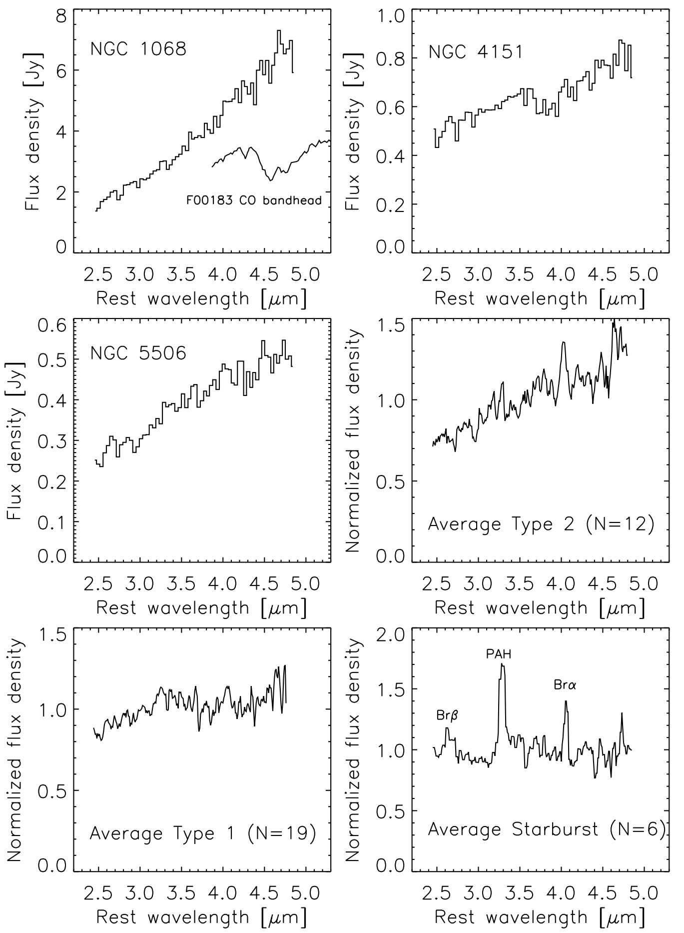

Fig. 1. ISOPHOT-S low resolution 2.5–5 μm spectra of AGN. We show three examples of good S/N spectra, plus averages for type 1 and type 2 Seyferts. These averages include fainter spectra, all normalized to median flux 1 in the observed range before averaging. They give equal weight to all objects irrespective of flux and S/N. A starburst spectrum is shown for comparison and to identify features also seen in some of the AGN spectra. In the top left panel, a scaled spectrum of IRAS F00183-7111 (Spoon et al. 2004) is included for comparison.

gaseous CO absorption indicating a large column of dense ($\sim 10^6$ cm^{-3}) and warm ($\sim$700 K) gas towards the nuclear region of the unusually obscured ultraluminous infrared galaxy (ULIRG) IRAS F00183-7111, most likely hosting an AGN. This detection has motivated us to use archival data from the Infrared Space Observatory ISO to detect or put limits on absorption or emission from the CO fundamental rovibrational band in bright local AGN. We analyse low resolution ISOPHOT-S spectra of 31 nearby AGN allowing us to put limits on the presence of strong and broad absorption bands of the type observed in IRAS F00183-7111. For the prototypical Seyfert 2 NGC 1068, a high resolution and high S/N SWS spectrum allows us to put limits on the presence of individual CO transitions. We discuss the implications of these nondetections for the conditions around nearby AGN, and for the interpretation of strongly different spectra like that of IRAS F00183-7111.

Table 1. Limits (3σ) on the depth of a 4.7 μm CO rovibrational band of the type observed in IRAS F00183-7111, for some bright nearby AGN. Depth is expressed in fraction of the continuum.

Object	Type	Depth
IRAS F00183-7111	Obscured AGN?	0.40
Ark 120	Type 1	<0.38
Cen A	Type 2	<0.10
Circinus	Type 2	<0.40
IC4329A	Type 1	<0.21
MCG8-11-11	Type 1	<0.25
Mrk 6	Type 1	<0.37
NGC 1068	Type 2	<0.12
NGC 1365	Type 2	<0.20
NGC 3516	Type 1	<0.33
NGC 3783	Type 1	<0.40
NGC 4151	Type 1	<0.12
NGC 5506	Type 2	<0.10
NGC 7213	Type 1	<0.16
NGC 7469	Type 1	<0.29
NGC 7582	Type 2	<0.37
Average spectrum	Type 1	<0.15
Average spectrum	Type 2	<0.09

2. Limits from low resolution ISOPHOT spectra

We have searched the ISOPHOT-S low resolution spectra of nearby ($cz < 10\,000$ km s^{-1}) AGN for the presence of broad absorptions similar to the ones observed in IRAS F00183-7111. These observations will not resolve individual transitions, but are sensitive to strong bands reaching up to high J values. At these modest redshifts, much of the CO band is still included in the short wavelength segment of ISOPHOT-S which extends to 4.9 μm observed wavelength. We use the database of extragalactic ISOPHOT-S spectra already exploited by Spoon et al. (2002) and Lutz et al. (2004). For signal-to-noise reasons, we have limited ourselves to 31 bright AGN having a 6 μm continuum (derived using the spectral decomposition of Lutz et al. 2004) in excess of 0.1 Jy. For objects with S/N good enough to individually exclude a feature of the type seen in IRAS F00183-7111, we quote in Table 1 3σ limits for the depth of a Gaussian of *FWHM* 0.4 μm, which is a reasonable approximation to the IRAS F00183-7111 feature over the rest wavelength range covered.

Figure 1 illustrates this by three examples of spectra with good S/N. In addition we show average spectra of all 19 type 1 and of all 12 type 2 spectra meeting our basic redshift and brightness criteria. The average spectra give equal weight to all objects irrespective of their brightness and S/N. This is appropriate since source-to-source variations in feature properties are conceivable, making weighting towards the few "best" spectra undesirable. Like the individual brightest sources, the average spectra clearly do not show strong band absorption of the type seen in IRAS F00183-7111. The peaks seen around 4.7 μm in the average spectra are not significant emissions, given that the noise at the long wavelength end of these ISOPHOT-S spectra is a factor $\sim$5 higher than near its minimum around 3 μm.

Brα 4.05 μm and tentative 3.2 μm PAH features are detected in the average spectra.

The nondetection of strong CO absorption applies both to type 1 and to type 2 objects. We have tested this separately, since the latter are more likely to be absorbed from a point of view of AGN unification. The nondetection remains when taking the type 2 average only for 9 objects with X-ray absorbing column $N_{\rm H} > 10^{23}$ cm^{-2} – the resulting average type 2 spectrum is very similar to that shown. Since the CO absorptions searched for are sensitive only to absorbing material in a certain physical state and not directly proportional to total column, and since X-ray and infrared absorptions are towards different emitting regions of the AGN, the absence of strong CO absorptions towards Compton-thick AGN does not necessarily indicate a problem with the unified view.

3. Limits from resolution ~2500 SWS spectrum of NGC 1068

Since it is close, very bright in the mid-infrared continuum, and has a Compton-thick Seyfert 2 nucleus, NGC 1068 is well suited to probe for individual CO absorption lines. Lutz et al. (2000) have presented ISO-SWS spectroscopy of NGC 1068. The upper spectrum in Fig. 2 shows the region around the CO band from the SWS01 full spectrum presented in that paper, confirming and strengthening by an independent dataset the absence of a strong and wide CO absorption concluded in Sect. 2 from the ISOPHOT-S spectrum. We estimate an upper limit of ~10% for the depth of any possible broad feature.

A dedicated ISO-SWS observation (Observing mode SWS06, TDT number 79201901, see Leech et al. (2003) for details on SWS and its observing modes) has been set up to probe more deeply for individual CO absorptions, at better signal to noise and at the full resolution of the SWS (~2500 around 4.7 μm). Because of the way the SWS06 mode is defined, the 4.4–5.1 μm range was covered in repeated ~40 min long scans in between dark current measurements. These long scans are significantly affected by drifts and jumps of the individual detector signals, at a level that can cause broad structures at the few percent level in a standard processed average spectrum. The standard processed average spectrum indeed shows weak broad features at the ~5% level, at wavelengths not corresponding to the CO band or familiar solid state bands. We consider these structures not reliable and specially processed the data in a way dealing with the drift and jumps but maintaining information on possible individual absorption or emission lines. After standard dark current subtraction and relative response calibration, jumps were identified in the time sequences of the individual detectors and the pre- and post-jump signals smoothly connected by offsetting the post-jump data. We then subtracted from the flux history of each detector a median-smoothed flux history, with a smoothing width corresponding to ~0.03 μm, and continued data reduction from then normally. The lower spectrum of Fig. 2 shows the resulting spectrum, offset by an arbitrary amount. We significantly detect the [ArVI] 4.530 μm line at the redshift of NGC 1068, fainter non-significant emission lines may be present at the positions of Pfund β and of [NaVII] 4.685 μm.

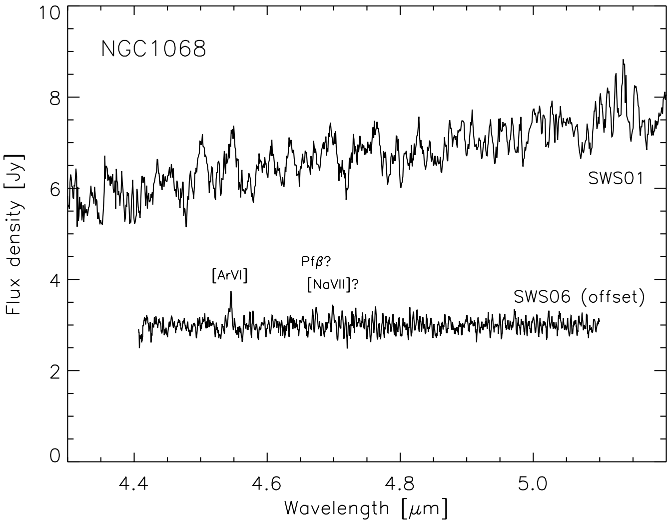

Fig. 2. The region of the CO fundamental rovibrational band in ISO-SWS spectra of NGC 1068. *Top*: part of the full SWS01 spectrum also presented by Lutz et al. (2000). *Bottom*: SWS06 spectrum specially processed as described in the text. This specturm has better signal-to-noise and resolution ~2500. Due to the special processing, information on continuum slope and broad features is lost, however, and the spectrum is shown at an arbitrary flux offset.

No significant individual absorption or emission lines from CO are detected, to a 3σ limit of 0.43 Jy (7% of the continuum) at the resolution 2500 of the SWS06 spectrum. We have probed for fainter band emissions or absorptions by crosscorrelating the NGC 1068 spectrum (with the three emission lines masked out) with template CO "spectra" containing Gaussians of appropriate width at the positions of CO band lines, up to a selectable maximum rotational level J. No clear positive or negative correlation peak near the systemic redshift was observed. This suggests that any clear band in emission or absorption must be noticeably fainter than the limit for individual lines quoted above, with exact limits a function of the adopted number of contributing rovibrational lines corresponding to the unknown physical conditions.

4. Implications

No clear signature of the CO 4.7 μm band has been detected in the spectra of bright local AGN. To our knowledge, no full treatment of these lines has yet been published for one of the currently available "torus" models. However, given the considerable uncertainties about the detailed structure of this region and the significant continuum optical depth it is likely that configurations exist that would not yield absorptions or emissions that are detected in our data. A dense and warm cirumnuclear region of AGN could show these lines in emission or absorption depending on the detailed geometry and viewing angle, with contrast that is not necessarily high.

More significant, however, is the difference between the spectra presented here and the spectrum of IRAS F00183-7111, itself most likely hosting an obscured AGN (Spoon et al. 2004). Our results suggest that the CO absorption seen in IRAS F00183-7111 is not a straightforward signature of an AGN, but related to the extraordinary concentration of dense and warm gas in the nuclear region of ULIRGs. We speculate that the most heavily obscured (U)LIRGs also showing strong continuous absorption features are most likely to show similar behaviour – IRAS F00183-7111 is a prime example of this subclass among the ULIRGs (Tran et al. 2001; Spoon et al. 2004). Spoon et al. (2004) estimate from the CO absorption a colum of $10^{23.5}$ cm^{-2} of dense ~700 K molecular gas towards its nuclear region. Such gas will also emit in the mid-infrared rotational lines of molecular hydrogen. A realistic model of this emission would assume a clumpy distribution of gas in which our line of sight is not special with respect to the intercepted column density. However, for simplicity we have computed the emission from a geometrically and optically thin shell of dense gas of this column density surrounding the nuclear region. The measured flux of the H_2 0–0 S(3) line of IRAS F00183-7111 (Spoon et al. 2004) corresponds to $\sim 10^5$ $M_\odot$ of 700 K gas at the distance of F00183-7111, sufficient for a shell of radius ~2 pc shell with the column inferred by Spoon et al. (2004). This estimate indicates that the obscuring warm/dense region is likely small, but is subject to the significant opposing uncertainties of (1) obscuration of the S(3) line from this small component and (2) contributions to this line of other larger, and likely little obscured regions. A similar $r \sim 0.5$ pc scale is obtained assuming the 5 μm continuum of IRAS F00183-7111 is optically thick emission from 1000 K dust, this is likely a lower limit to the size of the CO absorbing region.

The challenge is to explain the dichotomy between spectral properties of IRAS F00183-7111 and nearby AGN: some classical models for compact tori (e.g. Pier & Krolik 1993) invoke large ($\sim 10^{24}$ cm^{-2}) columns on parsec scales, which in type 2 objects are seen in absorption against the nucleus. While there is still uncertainty on the detailed structure and columns, the presence of warm dust on such scales is directly confirmed by mid-infrared interferometry of NGC 1068 (Jaffe et al. 2004), reinforcing earlier evidence for dense parsec-scale circumnuclear gas on the basis of masers and radio continuum emission (Gallimore et al. 1996, 1997). For both nearby AGN and IRAS F00183-7111, large columns of warm gas on parsec scales are thus suggested but, still, the observed spectral signatures differ strongly. For the nearby Seyferts, the 4–5 μm emission may be dominated by relatively little obscured warm dust, even if the column through the torus towards the very nucleus is high. For an axially symmetric "torus", such dust can be seen towards parts of the inner face of the axial opening of the "torus", even in Seyfert 2 objects, or from dust extended on larger scales in the narrow line region. If NGC 1068 is representative, such little obscured regions must not be strong CO emitters. It is important to explore the role of geometric coverage in a realistic radiative transfer model including the CO lines. Models with coverage in all directions may be the key to strong features like those seen in IRAS F00183-7111. A realistic modelling of an IRAS F00183-7111-like CO absorption around a central obscured AGN/starburst could also provide better constraints on the size and structure of this region. Future Spitzer observations, in particular of moderate redshift infrared galaxies and luminous AGN, will be able to shed more light on the differences to local AGN.

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