Multiple-Line Study of NGC 1068: Hot Molecular Gas Caused by Jet-Gas Interaction in the Central 100pc?

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Abstract. A multiple molecular line and line transition study is presented for the circumnuclear disk (CND) of the proto-typical Seyfert galaxy NGC 1068. A detailed analysis of the kinematics and excitation conditions of the molecular gas, as traced by $^{12}$CO, $^{13}$CO, HCN and HCO$^+$, suggests that part of the molecular gas in the CND is shocked, expanding and heated to high kinetic temperatures most likely as a consequence of an interaction between the radio jet and the CND. We further find support for an X-ray altered chemistry of the molecular gas in the CND based on the significantly elevated abundance of HCN when compared to star-forming, starbursting or quiescent gas regions.

1. Introduction
The central 100 pc of active galaxies present fascinating laboratories to study not only the feeding mechanisms of their activities, wether in form of an accreting supermassive black hole (SMBH) or a starburst (SB), but also the feedback of these activities onto their environments. While the understanding of feeding processes enforces detailed analyses of the dynamics of the material being accreted, the disclosure of the feedback mechanisms necessitates profound knowledge of the chemical composition and physical properties of the surrounding material, i.e., mainly the molecular gas. The kinematics of the molecular gas can be best studied by $^{12}$CO(J=1–0) that traces the general characteristics of the molecular gas. Concerning the chemistry of the gas, a multitude of different molecular species, their different transitions and isotopes are necessary to understand the effect of different feedback processes, whether they are mechanical nature, i.e., via shocks, winds and/or jets, or radiative nature, i.e., via X-ray, ultra-violet or cosmic radiation.

A significant set of active galaxies exist whose $^{12}$CO emission has been observed at high angular and spectral resolution (e.g., NUGA series of papers: [1], [2], [3], [4], [5], [6], [7], [8]; see also [9], [10]) allowing to draw first conclusions on accretion mechanisms in active galaxies. Similarly high amounts of multiple line data sets do not yet exist in order to study the feedback in the centers of active galaxies: only a few case studies have been conducted so far (e.g., M82, NGC 253, IC342, and NGC 1068; see for instance: [11], [12], [13], [14]). In these studies, starburst galaxies are dominating as they are rich in molecules and hence possess bright and thus easily detectable molecular line emission. Active galaxies dominated by accretion onto a SMBH show less bright molecular emission and are hence more difficult to be detected in...
several molecular species and transitions at high angular and spatial resolution so that only the brightest and closest objects among them are being studied so far.

NGC 1068 most likely represents the most prominent nearby galaxy dominated by its SMBH. It is classified as a Seyfert type-2 galaxy and has been the posterchild for the viewing angle unification theory [15] since a long time due to the discovery of an obscured Seyfert type-1 nucleus in its center [16]. NGC 1068 was also the first galaxy to show significantly enhanced HCN emission with respect to the $^{12}$CO emission in its center as opposed to SB/star-forming galaxies such as M82 (e.g., [17, [18]). It has been already suggested early on that the enhanced HCN emission is due to an increased abundance of HCN that is caused by the strong X-ray radiation of the SMBH creating a giant X-ray dominated region (XDR) there (e.g., [17], [18], [19]). XDRs are defined in a similar way to the photon-dominated regions (PDRs) in SB galaxies (as in M82, e.g. [20]) except that the chemistry altering radiation are X-rays there and not UV-rays. After the discovery of such strong central HCN emission in NGC 1068, more Seyfert/LINER galaxies have been found to exhibit enhanced HCN emission, such as M51 and NGC 6951 for instance (e.g., [21], [22], [10], [23], [24]). A multi-transition study carried out with IRAM 30m telescope of the HCN and HCO$^+$ emission in a series of nearby active galaxies, including SB and SMBH dominated galaxies, support the idea of enhanced HCN abundances in the centers of SMBH when compared to the SB dominated galaxies in the sample [24]. Also, indications for increased kinetic temperatures were found for the SMBH galaxies in this study (e.g., NGC 1068 and M51) which in turn could lead to a hypo-excitation of the $^{12}$CO(J=1–0) emission and hence to high HCN(J=1–0)/$^{12}$CO(J=1–0) line ratios falsely simulating enhanced HCN emission.

Together with the detection of other species such as SiO and CN in the CND of NGC 1068 (see [25]), a quite complicated puzzle started to form for the chemistry, dynamics and excitation conditions of the molecular gas. This article discusses the interferometric observations of several $^{12}$CO, $^{13}$CO, HCN and HCO$^+$ line transitions at high angular and spectral resolution (see also [14]) in order to shed more light onto the complex nature of the molecular gas in the CND of this source.

2. The Molecular Gas Emission in NGC 1068’s CND

The low-J transitions (J=1–0 and J=2–1) of the $^{12}$CO, $^{13}$CO, HCN and HCO$^+$ line emission in the CND of NGC 1068 have been observed with the IRAM Plateau de Bure Interferometer (PdBI) while the higher-J transitions (J=2–1 and higher) with the Submillimeter array (SMA). A detailed description of the observations can be found in [14]. The velocity integrated line emission of each observed molecule is shown in Fig.1. All molecules are more or less detected along the ring-like structure of the CND in NGC 1068 that splits up into a western and eastern knot. The weaker molecules mostly show up in the northern “bridge” part of the CND. The J=1–0 transition of HCN and HCO$^+$ is not plotted here as they will be published later by Usero et al.. However, their integrated intensities have been used to calculate the line ratios for HCN and HCO$^+$.

2.1. Dynamics of the Molecular Gas

At first sight, the kinematics of the molecular gas within the CND seems to follow normal Keplerian rotation (see grey line profiles of the molecules in Fig.2 and Fig.5 in [14]). However, by looking in more detail into the dynamics of the different molecules, i.e., separating the eastern and western knot, one finds that redshifted and blueshifted emission is found towards both knots (see also Fig. 3) indicating a much more complex underlying kinematics. Standard Keplerian rotation leads to well spatially separated red- and blueshifted emission. [9] argued early on that the CND in NGC 1068 might be warped. Standard (symmetric) tilted ring models, however, cannot explain such an overlap of red- and blueshifted emission. Elliptical orbits, or more precisely non-circular motions, could be one possible explanation. However, given that the
Figure 1. Velocity integrated line emission of $^{12}$CO(J=3–2) (a–g), HCN(J=3–2) (a), HCO$^+$(J=3–2) (b), HCO$^+$(J=4–3) (c), $^{12}$CO(J=2–1) (d), $^{13}$CO(J=2–1) (e), $^{15}$CO(J=3–2) (f), C$^{18}$O(J=2–1) (g), $^{12}$CO(J=1–0) (h) and $^{13}$CO(J=1–0) (i) in NGC 1068, observed with the SMA and the IRAM PdBI (taken from [14]). Contour levels are: $^{12}$CO(J=3–2) – from 10σ by 6σ with 1σ=4.8 Jy km s$^{-1}$; HCN(J=3–2) – from 3σ by 1σ with 1σ=2.6 Jy km s$^{-1}$; HCO$^+$(J=3–2) – from 2σ by 1σ with 1σ=3.4 Jy km s$^{-1}$; HCO$^+$(J=4–3) – from 3σ by 1σ with 1σ=2.4 Jy km s$^{-1}$; $^{12}$CO(J=2–1) – from 5σ by 5σ with 1σ=1.2 Jy km s$^{-1}$; $^{13}$CO(J=2–1) – from 3σ by 1σ with 1σ=0.9 Jy km s$^{-1}$; $^{13}$CO(J=3–2) – from 5σ by 1σ with 1σ=3.5 Jy km s$^{-1}$; C$^{18}$O(J=2–1) – from 3σ by 1σ with 1σ=0.9 Jy km s$^{-1}$; $^{12}$CO(J=1–0) – from 5σ by 3σ with 1σ=0.4 Jy km s$^{-1}$; $^{13}$CO(J=1–0) – from 1σ by 1σ with 1σ=0.1 Jy km s$^{-1}$.

Intercepting blue- and redshifted parts of the emission are well aligned with the axis of the jet (compare Fig.4) we propose an alternative scenario. Assuming and interaction of the jet with
Figure 2. Spatially integrated spectrum of the \(^{12}\text{CO}(J=1–0)\), taken from [9], \(^{12}\text{CO}(J=2–1)\) and \(^{12}\text{CO}(J=3–2)\) (left column) and HCN\((J=3–2)\) and HCO\(^+\)\((J=4–3)\) emission over the E-knot (dotted blue) and W-knot (solid red) component of NGC 1068.

the CND so that the jet has to “digg” its way through this larger scale disk, parts of the gas can be easily shocked and hence blown outward of the disk. The dynamics will therefore be a mix of outwards moving gas and Keplerian rotating gas with the latter being the dominating mechanism. A toymodel of this hypothesis is shown in Fig. 5 and a more sophisticated dynamical model can be found in [14]. The possibility of the jet hitting parts of the disk in NGC 1068 has been also found by other studies (e.g., [25], [26], [27], [28]). Also in M51, that exhibits similar characteristics to NGC 1068, indications have been found for an interaction of the jet with the surrounding CND (see [22], [10]). However, we cannot entirely exclude at this point that the molecular gas is moving inwards and not outwards although the nature of the emission points more toward an outward motion.
2.2. Excitation and Chemical Conditions of the Molecular Gas

Given all the different molecular species and transitions obtained in this study a significant set of independent line ratios can be derived in order to form the basis for a detailed simulation of the excitation and chemical conditions of the molecular gas (for the different line ratio maps and values please see [14]). In this study, we used the RADEX code to conduct a large velocity gradient (LVG) modelling (for more details on the analysis see [14]; the code was developed by [29]). The results of the modelling (see Fig.6-7) support previous findings by [24] that the molecular gas is hot in the bridge of the CND in NGC 1068, assumed to be the interaction zone of the jet and the disk. As can be seen, the HCN(J=3–2) emission follows nicely that of the H$_2$ emission that further indicates an expansion of the gas. Furthermore, we find HCN abundances that are significantly elevated when compared to star-forming/starbursting or quiescent regions. This leads to the conclusion that the excitation and chemical conditions are influenced by a complex combination of different mechanisms including shocks and strong X-ray radiation from the SMBH. Indeed, significant X-ray radiation has been found within the center of NGC 1068 that extends toward the CND (see Fig.12 in [25], and [30]).

3. Conclusions

In this article we discussed a multi-species, multi-transition study of the molecular emission in the CND of NGC 1068 at high spatial resolution. Supporting previous results, we find strong
Figure 4. Comparison of the $^{12}$CO(J=2–1) and HCN(J=3–2) emission with the radio jet as observed by [28] and the H$_2$ emission as observed by [26].

Figure 5. Toy model to explain the merging of a normal disk rotation with an expanding gas component on top.

indications of an interaction between the jet and CND in NGC 1068 that does not only lead to shocked gas that seems to be blown outwards of the CND but also to high kinetic temperatures within the bridge (northern part) of the CND. Furthermore, modelling of the excitation and chemical conditions of the molecular gas within the CND of NGC 1068 suggests an enhancement of the HCN abundance with respect to starforming/SB and quiescent galaxies. This is thought to be a consequence of the strong and large X-ray radiation field from the SMBH that penetrates deep into the CND of NGC 1068 and alters the chemistry of the molecular gas there.
Figure 6. $\chi^2$-fit results obtained from the RADEX simulations of the excitation conditions of the molecular gas. Shown are four different $^{12}\text{CO}/^{13}\text{CO}$ abundance ratios ($=10,26,52,110$) for three different $^{12}\text{CO}$ column densities respectively. The middle panel shows the best $\chi^2$-fit found for each abundance ratio.

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Figure 7. $\chi^2$-fit results obtained from the RADEX simulations of the excitation conditions of the molecular gas. Shown are four different [HCN]/[HCO$^+$] abundance ratios around the standard galactic value of [HCN]/[HCO$^+$] $\approx 10$ for three different HCN column densities respectively. The middle panel shows the best $\chi^2$-fit found for each abundance ratio.

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