Opening again the debate: the transient nature of the circumnuclear disk

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Abstract. Despite many investigations, the physical characteristics of the molecular gas in the Galactic center circumnuclear disk (CND) remain a topic of debate. Its mass is highly uncertain, between 10^4 (from dust) and 10^{5-6} M$_\odot$ (derived from gas tracers), and depending on the probe, density estimates for the dense clumps are 10^{5-8} cm^{-3} and gas temperatures run from 50 to a few hundred K. The range of physical parameters leaves open many questions about the nature and fate of the CND. Using several ground-based observatories, together with *Herschel* and SOFIA, we have studied the physical conditions of the dense clumps using CO, HCN and HCO$^+$, finding that most of them are transient. Their densities are not large enough for them to be gravitationally bound in the tidal field in the center of our Galaxy.

Keywords. Galactic center

1. Introduction

In the innermost region of the central molecular zone (CMZ) lies the last reservoir of molecular gas. Inside of this, UV radiation from the massive stars around the supermassive black hole in the center of our galaxy dissociate the molecules and only atomic and ionized gas share the place with the dust and stars that are observed in the infrared and optical regimes.

This disk-like structure extends from approximately 1.5 parsecs to 3 pc (Genzel *et al.* 2010) or 7 pc depending on the source (Oka *et al.* 2011). The molecular CND seems to be the source of ionized gas streamers moving toward Sgr A* on highly eccentric orbits (although see the contribution by John Lacy, in this volume), forming the so-called minispiral. Martin *et al.* (2012) show that the CND is composed of at least three different rotating structures having different inclinations that fit with the arms of the minispiral.

The analysis of the excitation of the CO molecule, using low resolution far-infrared spectra obtained with the Kuiper Airborne Observatory (KAO), yielded high densities and high temperatures (Genzel *et al.* 1985; Harris *et al.* 1985; Bradford *et al.* 2005). But the inferred densities were not high enough to maintain clump stability against the strong tidal forces in the central gravitational potential. Those conclusions were questioned when interferometric data of the HCN $J = (1-0)$ and $J = (4-3)$ transitions from OVRO and SMA (Christopher *et al.* 2005; Montero-Castaño *et al.* 2009) were interpreted in terms of densities (assuming that the observed clumps are in fact virialized) large enough for clumps to be stable in those extreme conditions.

To further investigate the nature of the gas streams within the CND we have performed in-depth CO and HCN/HCO$^+$ excitation studies. Complementing submm data from
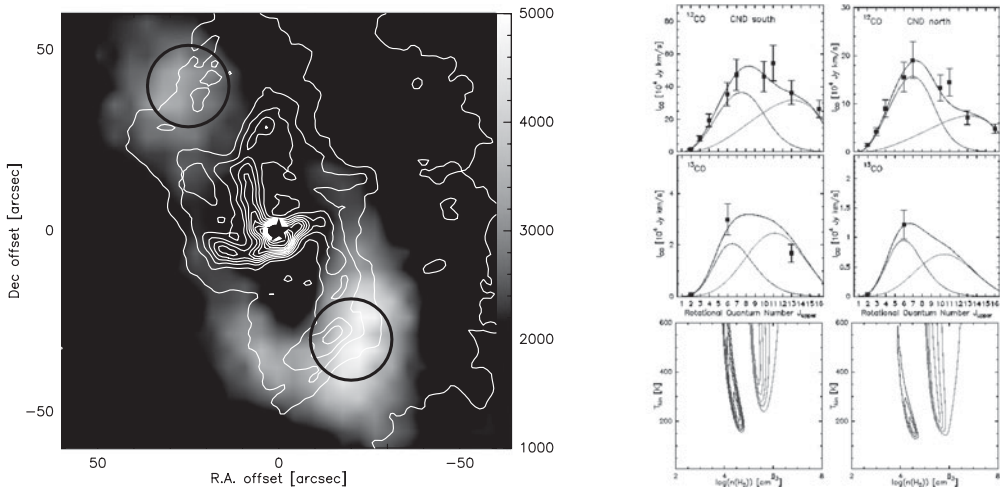
Figure 1. Left: Integrated emission of the CO $J = (6-5)$ line towards the CND, observed with the CHAMP+ receiver at APEX (MR12). **Right:** Solutions of the SED fitting in the two main lobes of the CND shown as circles in the left figure (MR12).

APEX with airborne (SOFIA) and space (*Herschel*) observations, the new spectral energy distributions cover now a much wider range of excitation conditions. We present results of our CO (Requena-Torres *et al.* 2012, MR12), and of the HCN and HCO$^+$ excitation studies (Mills *et al.* 2013, M13) towards the two main lobes of the CND.

2. Observations

For the study of the conditions of the molecular material in the CND we have used a combination of millimeter and submillimeter telescopes.

Early observations mapped the CO $J = (2-1)$ emission in the Sgr A complex with the IRAM 30-m telescope. Those were complemented by maps of the CO $J = (4-3)$ transition with the CSO, and more recently with all the submm transitions accessible to the APEX instruments (CO $J = (3-2)$, $J = (4-3)$, $J = (6-5)$, and $J = (7-6)$). With HIFI onboard the *Herschel* satellite we observed the CND region in the CO $J = (10-9)$ transition, and with SOFIA, the Stratospheric Observatory for IR Astronomy, we made use of the GREAT instrument to observe the $J = (11-10)$, $J = (13-12)$, and $J = (16-15)$ transitions in the two main lobes of the CND, where the CO $J = (7-6)$ emission peaks. We observed as well ^{13}C isotopologues with APEX ($J = (3-2)$, $J = (6-5)$) and SOFIA ($J = (13-12)$). As a parallel project, we mapped the CND in the high-J lines of HCO$^+$ and HCN accessible from APEX ($J = (3-2)$, $J = (4-3)$, $J = (8-7)$, $J = (9-8)$), together with some of their isotopologues (see M13 for details).

3. CO SED in the main lobes of the circumnuclear disk

Using the CND maps of the CO transitions, from $J = (2-1)$ to $J = (16-15)$, we model the CO spectral energy distribution (SED) from the line resolved observations, convolving all the maps to the same beam size of $22.5''$ (the beam of the CO $J = (11-10)$ observations with GREAT). We used the ^{13}C isotopologues to constrain the optical depths of the CO lines. The non-LTE models used in the analysis are large velocity gradient models, similar to the ones described in Weiss *et al.* (2007).
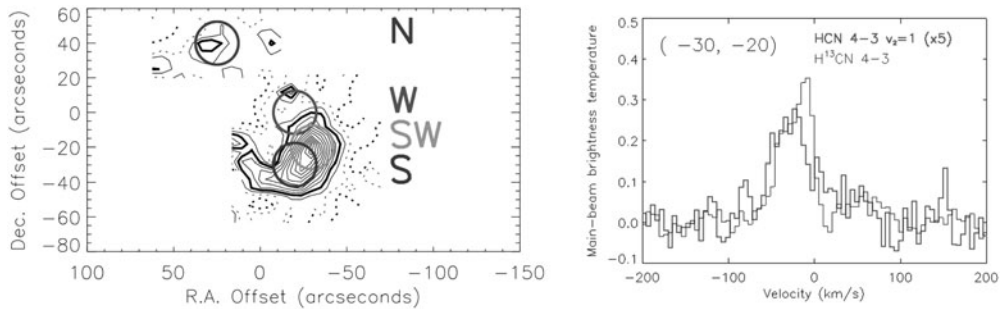
Figure 2. Left: Contour map of the $J = (8 - 7)$ transition of HCN observed with the APEX telescope. Circles show positions that have been studied (M13, their Figure 2). **Right:** Detection of the vibrationally excited HCN transition in the SW region, see M13.

The first result is that one needs two different excitation components of the gas to fit the CO SED. For both, we need high temperatures ranging from 175 to 500 K, and densities from $10^4 - 10^5$ cm^{-3}. The densities are tightly constrained in the reduced parameter space. The analysis implies that the gas cannot be gravitationally stable against tidal shear, as the densities are significantly below the Roche limit of 10^7 cm^{-3}.

4. Excitation of the high density tracers: HCN and HCO$^+$

To study the conditions in the denser gas, we observed the high-J HCN and HCO$^+$ lines observable with APEX (HCN $J = (3 - 2)$, $J = (4 - 3)$, and $J = (8 - 7)$, as well as HCO+ $J = (3 - 2)$, $J = (4 - 3)$, and $J = (9 - 8)$). Small maps were observed in all the transitions in order to study the two positions studied in CO (N, S) and to extend the analysis to other two positions (W, SW, see M13).

Using the non-LTE radiative transfer code RADEX, the analysis was done in two ways, one using a wide velocity range for determining the average excitation, and the other probing individual clumps, assuming their emission is restricted to a relatively narrow velocity range (20 km s^{-1}) based on the spectral profile of the peaks observed in HCN $J = (4 - 3)$ with interferometers (Montero-Castaño *et al.* 2009).

In both cases, all the solutions for the excitation of HCN and HCO$^+$ except one are consistent with those based on the CO (though on average, the densities are slightly higher), and indicate that densities are below the Roche limit. However the RADEX analysis of HCN emission in a small velocity range covering the so-called S1 source (v_{LSR}: -115 to -95, from S in Figure 2), shows a larger density that could hold a gravitationally bound clump in the CND.

But, toward one position in the CND (SW) we also detected the $J = (4 - 3)$ $v_2 = 1$ vibrational excited line of HCN, at a velocity of -20 km s^{-1}. This line is not likely to be excited by collisions as this requires densities of the order of 10^{11} cm^{-3}, many orders of magnitude higher than any observed in the region. It is more likely that this line is excited by infrared pumping via rovibrational transitions, at 14 μm. Using a modified RATRAN code to model this pumping, we find that the most likely source of the excitation is warm (T$\sim$150 K) dust embedded within the gas clump. This pumping also lowers the density inferred from the HCN excitation analysis. Due to the physical proximity of clumps S1 and SW, it is possible that HCN in S1 could also be subject to radiative excitation, which would lower its inferred density as well, potentially making it so this clump cannot be tidally stable. However, as the $v_2 = 1$ line is not detected at the velocity of clump S1, it is not clear how significant this effect may be.

5. Conclusions

Using a combination of observations from ground-based telescopes, *Herschel*, and the GREAT instrument on-board SOFIA, we have obtained high-spatial and spectral resolution ($22.5'' - 8''$ and $\sim 1\,\mathrm{km\,s^{-1}}$) CO maps of the circumnuclear disk (CND). The gas densities derived from our CO excitation analysis clearly imply that the CO-emitting clumps in the CND cannot be gravitationally stable against tidal shear, as they are well below the Roche limit of 10^7 cm^{-3}. As such, our models strongly suggest the CND consists of gravitationally-unbound, transient clumps.

An analysis of the denser gas component of the CND using multi-transition observations of HCN and HCO$^+$ from the APEX telescope also finds low densities (10^5-10^6 cm^{-3}) which supports the transient nature of the CND everywhere except in one position. In this specific position, the densities may be large enough to allow the material to be gravitationally bound. However, the discovery of vibrationally-excited HCN in a nearby clump indicates that warm embedded (T$\sim$150 K) dust may contribute to radiative excitation of HCN, and reduce the densities derived using this molecule.

Very recent works from Liu *et al.* (2013) and Smith & Wardle (2013) using old and new interferometric data, also find that clumps in the CND are unlikely to be virialized, and agree that densities based on the assumption of virialization are overestimated. Upcoming observations with ALMA will allow for high resolution studies of the excitation of individual clumps, and should conclude this debate by determining if there truly are any individual clumps that are stable, or if the structure in the CND is entirely transient.

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