Disk-Halo interaction: The molecular clouds in the Galactic center region

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Abstract. From a large-scale study of the Galactic center (GC) region in SiO(2 − 1), HCO+ (1 − 0), and H13CO+ (1 − 0), we identify shock regions as traced by the enhancement of SiO emission. We selected 9 positions called by us as “interaction regions”, because they mark the places where gas in the GC could be interacting with gas coming from higher latitude (“disk-halo interaction”) or from larger galactocentric radius. These positions were studied using the 12C/13C isotopic ratio to trace gas accretion/ejection. We found a systematically higher 12C/13C isotopic ratio (> 40) toward the interaction regions than for the GC “standard” molecular clouds (20 − 25). These high isotopic ratios are consistent with the accretion of the gas from higher galactic latitudes or from larger galactocentric distances. There are two kinetic temperature regimes (one warm at ∼ 200 K and one cold at ∼ 40 K) for all the positions, except for the positions associated to the giant molecular loops where only the warm component is present. Relative molecular abundances suggest that the heating mechanism in the GC is related to shocks. We mapped one molecular cloud placed at the foot points of the giant molecular loops in 3-mm molecular lines to reveal the morphology, chemical composition and the kinematics of the shocked gas.

1. Introduction

To understand the formation and evolution of galaxies, one must explore their central few hundred parsecs. Observations of selected regions of the center of our Galaxy allow to study in detail the physical processes responsible for gas accretion and ejection, the role of the magnetic fields and galactic winds, in the interaction regions with a very high spatial spatial resolution. We study two kinds of phenomena which are presumably occurring in the GC region, and are believed to be partly responsible for the gas accretion toward the nuclear region of the Galaxy: the barred potential, and the Giant Molecular Loops (GMLs).

[1] showed that the large-scale gas kinematics in the central regions of the Galaxy can be explained by a barred galactic potential with two major families of orbits inside the bar: the X1 orbits parallel to the bar, and the inner X2 orbits, orthogonal to it. The gas falls from X1 to X2 orbits when it self-intersects in the X1-X2 orbits transition. The other phenomenon is
the huge loop structures (GMLs) found by [2] and thought to be formed by a Parker instability. The gas of the loops is thought to flow down along the magnetic field lines and join the Galactic plane, generating shock fronts at the “foot points” of the loops. However, so far there is no clear observational evidence of gas accretion from the X1 orbits and/or from high latitudes in the GMLs.

We performed a large-scale study of the GC region in SiO(2−1), HCO+ (1−0), and H13CO+(1−0) using the 4 m-NANTEN telescope [3]. We found an increased emission in SiO as compared to the HCO+ line intensity at the foot points of the GMLs and toward the 1.3 complex, which indicates the presence of shocks [4; 5]. From this study we selected 9 positions (see Fig. 1) where the SiO emission shows an enhancement with respect to the HCO+ emission. The positions are considered in this work as the “interaction regions”, because they mark the places where gas in the GC could be interacting with gas coming from higher latitude (“disk-halo interaction”) or from larger galactocentric radii, according to the GMLs scenario and the bar potential model, respectively. They were selected including five positions in the GMLs and two positions in the X1-X2 orbits interaction places. The positions in the GMLs were called “halo” to differentiate from the molecular clouds in the Galactic plane. Among them, 3 positions are placed where the gas in the GMLs joins the gas in the disk (foot points of the loops), and 2 positions are placed at the top of the loops. Each of the positions located at the X1-X2 orbits interaction places has two main kinematical components, one associated to the X1 orbits and the other to the X2 orbits. They were called as “disk X1”, and “disk X2”. Finally, we selected 2 positions close to b = 0 (that we called “disk”), which are not associated to neither the GMLs nor the locations of the orbits interaction, and therefore they should trace the typical GC clouds.

2. The 12C/13C isotopic ratio
To test if the GMLs scenario is correct, or if the gas is being ejected from the disk in the GC, we studied the 12C/13C isotopic ratio to trace gas accretion/ejection. Using the IRAM 30m-telescope, we observed the J = 1 − 0 rotational transition of HCO+, HCN, HNC, and their 13C isotopic substitutions toward the 9 selected positions. While 12C is predicted to be formed in first-generation, massive stars on rapid timescales, 13C is produced primarily via CNO processing of 12C seeds from earlier stellar generations, on a longer timescale. The 12C/13C isotopic ratio shows, therefore, the relative degree of primary to secondary processing in stars. Table 1 presents the results. We found a systematically higher 12C/13C isotopic ratio (> 40) toward the halo and the X1 orbits than for the GC “standard” molecular clouds (20-25). The results are consistent with a scenario where gas from the halo is accreted to the disk and with the transfer of gas from the outskirt of the disk to the GC through X1 and X2 orbits as suggested by the potential bar scenario [6].

3. The kinetic temperatures towards the interaction regions
We derived the physical conditions of the molecular gas in the interaction regions of the GC. Using the Effelsberg 100m-telescope, we measured the metastable inversion transitions of NH3 from (1, 1) to (6, 6) in 6 positions that can be observed from this site. Using rotational diagrams and large velocity gradient calculations, we estimated for the first time, the kinetic temperatures of the molecular clouds in these regions (Table 2). The kinetic temperatures are high, not only in the typical GC clouds, but also in the high latitude and high velocity clouds observed in this paper. Therefore, the heating mechanism of the molecular clouds are likely to be a general characteristics of the molecular gas throughout the GC region. We derive two kinetic temperature regimes (one warm at ∼ 200 K and one cold at ∼ 40 K) for all the positions, except for the halo where only the warm component is present. Using the 30m-telescope, we also observed molecular tracers of different physical processes like SiO, HNCO, CS, C18O, and 13CO (shocks, photodissociation, dense gas) to derive the densities, and to reveal the
heating mechanisms affecting the molecular gas in these regions. From the high gas kinetic temperature, and by the increased SiO abundance, our results support the shock origin of the heating mechanisms in the GC. The high kinetic temperature in the X1 orbits and in the foot point of the GMLs seems to support to the large scale dynamics induced by the bar potential and the GMLs scenario as origins for the shocks.

4. 3 mm mapping of the foot point of the GMLs
We used the Mopra telescope to map one molecular cloud (M−3.8 + 0.9) at the foot points of the GMLs in 3mm lines. The maps reveal structures at small scales in the SiO emission, and large differences between the spatial distribution of the SiO and the HCO+ emission. The SiO emission in the M−3.8 + 0.9 cloud has narrow profiles (20 km/s) in comparison with the HCO+ profiles (50 km/s), thus, shocked gas is dynamically more confined than the HCO+ emission (Riquelme et al 2012b, in prep.).


Table 1. Intensity ratios from the observed $^{12}$C and $^{13}$C isotopomers. Table from [6].

| Source   | Velocity Component LSR [km s$^{-1}$] | Velocity Range [km s$^{-1}$] | HCO$^+$/H$^{13}$CO$^+$ ratio of $\int T_A^d$ dv | HCN/H$^{13}$CN ratio of $\int T_A^d$ dv | HNC/HN$^{13}$C ratio of $\int T_A^d$ dv |
|----------|-------------------------------------|-------------------------------|-----------------------------------------------|------------------------------------------|-------------------------------------------|
| Halo 1   | 100                                 | [50, 190]                     | 45.5±5.4                                      | 13.5±0.2                                 | ≥ 25.6                                   |
|          | 87                                  | [50, 97]                      | ≥73.9                                         | 25.8±2.0                                 | ≥7.5                                     |
|          | 117                                 | [97,135]                      | 32 ± 3.7                                      | 11.3±0.1                                 | ≥37.5                                    |
|          | 144                                 | [135,190]                     | 39.1±24.7                                     | 16.7±1.8                                 | ≥2.7                                     |
| Halo 2   | −62                                 | [−115,−20]                    | 73.1±36.5                                     | 14.6 ± 1.0                               | ≥15.4                                    |
|          | left wing                           | [−115,−70]                    | ≥34.4                                         | 21.2±3.3                                 | ≥8                                       |
|          | right wing                          | [−70,−20]                     | 53.2±26.1                                     | 11.6±0.9                                 | ≥13.6                                    |
| Halo 3   | −60                                 | [−120,−30]                    | 38 ± 5.0                                      | 13 ± 0.3                                 | ≥40.1                                    |
|          | left wing                           | [−120,−80]                    | 54.2±37.7                                     | 19.2±1.9                                 | ≥10.4                                    |
|          | central peak                        | [−80,−30]                     | 35.7±4.0                                      | 12 ± 0.2                                 | 48.3 ± 21.8                              |
| Halo 4   | 200                                 | [150,250]                     | 28.3±5.4                                      | 11.8±0.9                                 | 14.9 ± 3.1                               |
|          | peak                                | [150,210]                     | 29.2±7.5                                      | 11.7±0.8                                 | 17.9 ± 3.9                               |
|          | right wing                          | [210,250]                     | ≥10.6                                         | 12.4±4.0                                 | 7.1 ± 3.4                                |
| Halo 5   | −50                                 | [−100,−40]                    | 13.8±5.0                                      | 6.9 ± 0.3                                | 22.8 ± 12                                |
| Disk X1-1| 180                                 | [140,230]                     | 56 ± 6.4                                      | 10.8±0.1                                 | 25.5 ± 7.5                               |
|          | left wing                           | [140,180]                     | 57.2±7.5                                      | 11.6±0.1                                 | ≥8                                       |
|          | right wing                          | [180,230]                     | 54.4±11                                       | 9.9±0.2                                  | 15.7 ± 4.4                               |
| Disk X2-1| 95                                  | [50,140]                      | 29 ± 1.6                                      | 12.1±0.2                                 | 22.1 ± 2.7                               |
|          | left wing                           | [50,92]                       | 32.4±3.7                                      | 13.9±0.4                                 | 22.8 ± 4.0                               |
|          | right wing                          | [92,140]                      | 27.3±1.7                                      | 11.3±0.2                                 | 21.7 ± 8.6                               |
| Disk X1-2| 67                                  | [0,100]                       | 42.1±8.6                                      | 9.4±0.1                                  | 9.9 ± 1.3                                |
| Disk X2-2| −43                                 | [−80,−20]                     | 21.7±1.9                                      | 6.6±0.1                                  | 13.1 ± 1.0                               |
| Disk 1   | 66                                  | [35,105]                      | 14.0±2.8                                      | 13.1±1.0                                 | 15.8 ± 3.6                               |
|          | central peak                        | [35,70]                       | 16.4±4.6                                      | 23.1±3.8                                 | ≥11.4                                    |
|          | right wing                          | [70,105]                      | 11.6±3.4                                      | 7.8±0.7                                  | 11.7 ± 2.7                               |
| Disk 2   | −55                                 | [0,43]                        | ≥29.1                                         | 9.1±0.2                                  | ≥21.9                                    |
|          | left wing                           | [43,97]                       | 4.1±0.1                                       | 3.5±0.1                                  | 3.7 ± 0.1                                |
|          | right wing                          | [97,135]                      | 16.1±2.3                                      | 13.8±1.3                                 | ≥2.6                                     |

We identified four main velocity components: from −140 to −70 km s$^{-1}$, from −70 to −40 km s$^{-1}$, from −40 to −20 km s$^{-1}$, and from −20 to 20 km s$^{-1}$. In these velocity ranges, we identify five main molecular complexes, which are indicated with green boxes in Fig. 2 on the HCN maps. In Fig. 3 we show the integrated intensity ratio of the SiO to HCO$^+$ in velocity ranges of 10 km s$^{-1}$. While it is clear that both, the complex 3 and 4 are intense in both molecules; HCO$^+$ dominates towards the complex 2, showing the lowest ratio, and the SiO dominates in complex 1 (which almost does not present HCO$^+$ emission) and in complex 5. There are differences up to a factor 25 between the region where the HCO$^+$ dominate in the complex 2, and where the SiO dominates in the complex 5 and in complex 1.

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Table 2. Kinetic temperatures derived from LVG calculations.

| Source | Cloud number | low temperature | high temperature | single temperature from p−NH₃ |
|--------|--------------|-----------------|------------------|-------------------------------|
|        | T<sub>kin</sub> N(NH₃) | T<sub>kin</sub> N(NH₃) | T<sub>kin</sub> N(NH₃) |
|        | [K] cm<sup>−2</sup>  | [K] cm<sup>−2</sup>  | [K] cm<sup>−2</sup>  |
| Halo1  | 1            | 175 × 10<sup>14</sup> | >115              | 1.20 × 10<sup>15</sup> |
|        | 2            | 90              | >115              | >1.99 × 10<sup>14</sup> |
|        | 3            | 135             | >115              | >6.6 × 10<sup>13</sup> |
| Halo4  | 1            | 90              | >115              | 1.99 × 10<sup>14</sup> |
| DiskX1-1 | 1       | 38              | 1.99 × 10<sup>14</sup> | >300<sup>a</sup> |
| DiskX2-1 | 1       | 38              | 4.47 × 10<sup>14</sup> | 100 |
| DiskX1-2 | 1       | 52              | 1.66 × 10<sup>14</sup> | 215 |
| DiskX2-2 | 1       | 28              | 1.90 × 10<sup>14</sup> | 95 |
| Disk1  | 1            | 23              | 3.98 × 10<sup>13</sup> | >154<sup>b</sup> |
|        | 2            | 38              | 6.31 × 10<sup>13</sup> | >82<sup>b</sup> |
| Disk2  | 1            | 68              | 1.41 × 10<sup>15</sup> | 200 |
|        | 2            | 50              | 1.41 × 10<sup>15</sup> | >145 |
|        | 3            | 50              | 1.41 × 10<sup>15</sup> | 80 |

<sup>a</sup> LVG gives a T<sub>kin</sub> greater than 300 K which is the value allowed by the collisional rates given by [7].

<sup>b</sup> Due that the values for the (4,4)-(5,5) metastable inversion transitions are upper limits to the actual T<sub>MB</sub>, the modeled curve in the LVG plot is outside the allowed range, and we give a lower limit to the kinetic temperature using the rotational temperature form the LTE plot.

Figure 2. Position of the five molecular complexes discussed in the text.
Figure 3. Ratio of the integrated intensity of SiO(2 − 1) to HCO⁺, in velocity intervals of 10 km s⁻¹.
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