THE HOT GAS AND THE COLD DUST IN THE GALACTIC CENTER CLOUDS AS SEEN BY ISO *

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ABSTRACT

We present the first results of the LWS and SWS ISO observations of 18 molecular clouds in the Galactic center (GC) region. H_2 emission from several rotational lines in the ground vibrational state has been detected toward all molecular clouds. The rotational temperatures derived from these lines are between 150 and 500 K. Remarkably, the derived column densities of the hot H_2, $\sim 2\ 10^{22}$ cm^{-2}, are similar to those obtained for the cold gas. From the non-detection of the S(3) line at 9.7 μm, we find that the hot gas must be located behind more than 30 mag of visual extinction of cold gas and dust. The LWS continuum spectra indicate that the cold dust has temperatures of 25-35 K and column densities similar to those required to explain the extinction of the H_2 emission. Observations of the J=2-1 and J=1-0 lines of $C^{18}O$ (J=2-1/J=1-0 line ratios of 0.7-1.4) seem to sample only the cold gas located in front of the hot gas. This indicates that the low J transitions of $C^{18}O$ does not trace the total molecular gas in the GC. The LWS continuum spectra impose stringent limits ($\lesssim$ 1 per cent) to the hot dust associated to the hot H_2.

Toward most of the clouds we also detected emission from the fine structure lines of ionized species such as SIII and NeII, and in some cases lines from NeIII and OIII. In contrast with the previous idea that the heating of the GC clouds is dominated by shocks, our data suggest that photoelectric heating by UV radiation can be the dominat mechanism. The effective temperature of the ionization radiation derived from the NeIII/NeII ratio is 35.000 K (typical of an O7 star). Our ISO data when combined with the upper limits to the intensities of the recombination lines measured at millimeter wavelengths indicate that the UV radiation is very diluted. Cavities with sizes larger than 2 pc surrounding the ionizing star(s) are required to explain the dilution. The origin of the ionized cavities and the implications of these findings on the heating of the molecular clouds in the GC are briefly discussed.

Key words: ISO; infrared astronomy; Galactic Center; ISM; shock waves.

1. INTRODUCTION

The molecular clouds in the GC exhibit unusual characteristics with widespread high gas kinetic temperatures and relatively low dust temperatures (see e.g. Güsten 1989). Unlike the warm and hot cores in the molecular clouds of the Galactic disk where the UV photons from young stars heat the grains and the gas is heated by dust-gas collisions, the low dust temperatures observed in the GC require a different heating mechanism which acts directly on the gas. So far, the main heating mechanism invoked to explain the particular properties of the molecular clouds in the GC is shocks (Wilson et al. 1982). The chemistry in the GC clouds also seems to be unusual. The abundance of refractory molecules like SiO is relatively large, supporting the shock scenario (Martín-Pintado et al. 1997; Hüttemeister et al. 1998). Due to the large extinction towards this region most of our view of the GC clouds has been obtained from radio observations. Obviously, a complete picture of the energetics of these clouds will only be obtained when the main cooling lines in the IR are measured. We have used ISO to obtain a complete view of the ionized, hot and cold gas and dust in the GC clouds. These data will allow to fully characterize the GC clouds, and will help to understand the heating in the GC.

2. OBSERVATIONS, DATA REDUCTION AND RESULTS

We have observed 18 molecular clouds in the GC selected from the sample of Hüttemeister et al. (1993) and Martín-Pintado et al. (1997) with the LWS and the SWS of ISO. We have measured with the SWS

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several rotational line of H_2 (S(0), S(1), S(3) , S(4) and S(5)), the 18.7 and 33.5 μm lines of SIII, the 12.8 μm of NeII, and the 15.6 μm line of NeIII. The reduction of the SWS data was carried out with the Interactive Analysis programs at the ISO Spectrometer Data Centre at MPE. We also took full LWS spectra of all sources. Observations of the recombination line H41α and of the J=1-0 and J=2-1 lines of $C^{18}O$ have also been obtained with an angular resolution similar to that of the SWS aperture using the IRAM 30-m telescope.

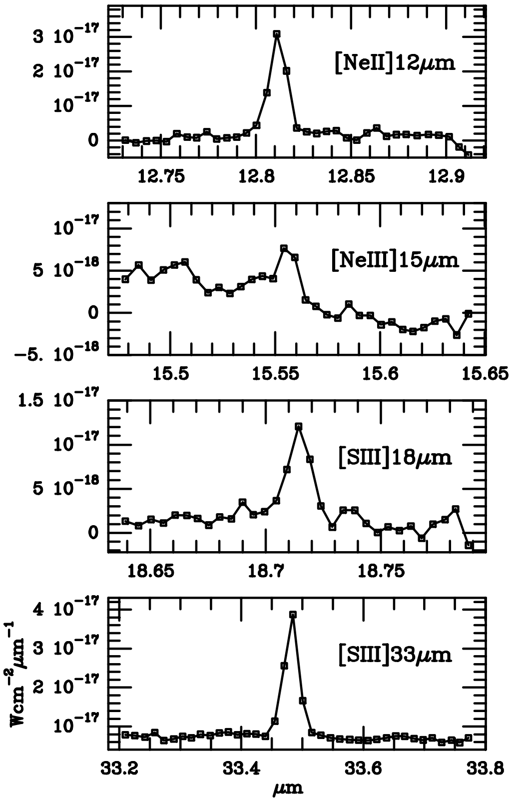

Figure 1. Fine structure lines observed with the SWS towards the cloud M+0.16-0.10. The spectra are averaged to one half of the instrument's resolution.

3. THE STRUCTURE IN THE GC CLOUDS

From the combination of all these data, a new picture of the GC clouds emerges. We find that all the sources in our sample show the presence of three different components: the ionized gas, the hot molecular gas and the cold gas and dust.

3.1. The ionized gas

Basically all the sources observed in the GC show emission from fine structure lines of ionized species like NeII and SIII (see Fig. 1). The ratio between the 18.7 and the 33.5 μm lines of SIII are $\lesssim$0.2. This is much smaller than the lower limit of 0.5 obtained from the excitation at very low density. This low ratio indicates that the ionized gas must be located behind more than 40 mag of visual extinction even in the case that the source of the ionized emission is extended. In the sources with the strongest NeII line, we also detect emission from the NeIII line. For those sources the ratios between the NeIII and the NeII lines, 0.05-0.2, suggest effective temperature for the ionization radiation of at least 35000 K (Sellmaier et al. 1996), typical of an O7 star. This is in contrast with the recombination line data at millimeter wavelengths, for which we find an upper limit to the emission of $\sim$ 15 mK. Assuming the typical linewidths of $\sim$ 30 kms^{-1}, and a LTE electron temperature of 10000 K, our upper limits indicates that the Lymann continuum photons in the SWS aperture must be $\leq$4 10^{47} s^{-1}, typical of a B0 star. The effective temperature of the ionization radiation derived from the NeIII/NeII ratio is inconsistent with ionization by main sequence OB starts exciting HII regions with sizes of $\lesssim$2 pc. As discussed in Section 4, the presence of large cavities surrounding the ionizing stars can explain the discrepancies.

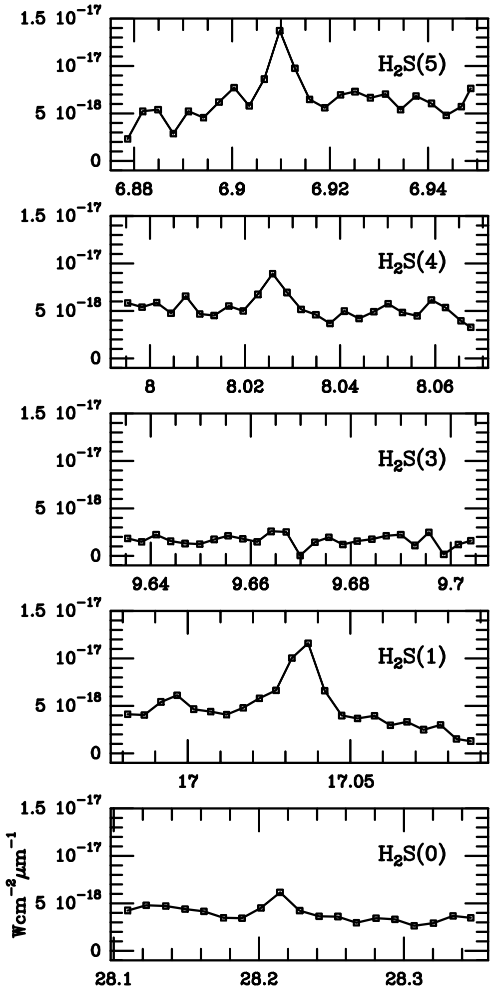

Figure 2. Pure rotational transitions of H_2 as observed with the SWS towards M+0.16-0.10. The spectra are averaged to one half of the instrument's resolution. Note that the S(3) line is not detected because of the absorption by the 9.7 μm silicates feature.

3.2. The hot molecular gas

All the clouds show emission in several rotational lines in the ground vibrational state of H_2 (see Fig. 2). In all sources the S(3) at 9.7 μm is weaker than expected, indicating that the hot gas is also behind of more than 30 mag of visual extinction. The rotational temperatures derived from the line intensity ratios vary from 150 K (S(1)/S(0)) to 500 K (S(5)/S(4)) (see Fig. 3). This indicates the presence of large temperature gradients within the hot gas. Ortho-to-para ratios different from LTE will only change the kinetic temperature from 150 to 180 K.

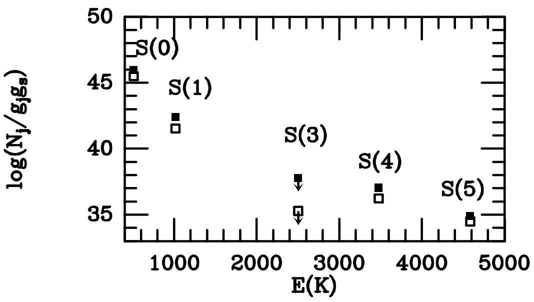

Figure 3. Rotational plot for H_2 rotational states J=2-7 obtained for M+0.16-0.10. The filled squares have been obtained after correcting the measured values (open squares) for 29 magnitudes of visual extinction using the extinction law of Draine 1989. The assumed ortho-to-para ratio is 3. Note that the values for the S(3) line are upper limits.

The total column densities of hot (150 K) H_2 corrected by extinction are at least 1-2 10^{22} cm^{-2}. These column densities of hot molecular gas must be considered as lower limits since the lowest kinetic temperatures sampled by the S(0) and S(1) lines are $\geq$ 140 K. If warm gas with kinetic temperatures of $\sim$ 80 K is present, the column densities of the hot gas must be increased by a factor of more than 5.

3.3. The cold molecular gas and dust

The line ratios between the J=2-1 and the J=1-0 lines of $C^{18}O$ towards all ISO sources are 0.7-1.4. This seems to be a general characteristic in the GC molecular clouds (see e.g. Hüttemeister et al. 1998) and indicates that the molecular gas sampled by these lines is relatively cold with kinetic temperatures much lower than the 140 K derived from the H_2 lines. The total H_2 column densities derived from the $C^{18}O$ emission towards the ISO clouds are 3-5 10^{22} cm^{-2}. These column densities are similar to those of the warm and the hot gas, but the measured line ratios of $C^{18}O$ are inconsistent with those expected for the hot gas, namely 3-4. This suggests that the $C^{18}O$ emission only samples the cold component. It is interesting to note that the column density of the hot component can be even larger than the column densities of the cold component measured from the $C^{18}O$ lines.

As mentioned in the previous section, the hot H_2 is located behind more than 30 mag of visual extinction. This material must be associated with relatively cold dust since it is outside of the region emitting the hot H_2. The H_2 column densities associated with the material in front of the hot gas are similar to the estimated from the $C^{18}O$ emission. This suggests that both are associated. Further support for this idea comes from the spectrum measured with LWS. The continuum spectrum between 40 and 190 μm indicates that most of the luminosity in the FIR is emitted by cold dust with temperatures between 25 and 35 K, and H_2 column densities of 3-8 10^{22} cm^{-2}. The column densities and the temperatures derived from the dust emission are consistent with those derived from the low J $C^{18}O$ data.

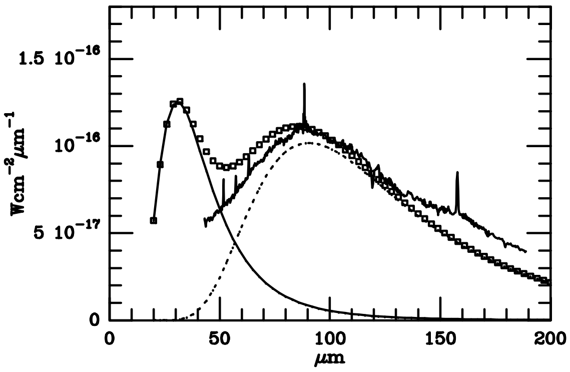

Figure 4. LWS spectrum of M+0.16-0.10. It has been superimposed a two component grey-body (squares) where a cold (33 K) dust component (dashed line) of N_{H_2} $\sim$ 3 10^{22} cm^{-2} is attenuating a warm (120 K) dust component with N_{H_2} 1000 times smaller (solid line). Note that even such an small amount of hot dust should have been detected.

From the continuum data at short wavelengths, we derive an upper limit to the column density of the hot dust with similar temperatures to that of the hot gas of $\leq 10^{20}$ cm^{-2}, more than 100 times smaller than that obtained from the H_2 lines (see Fig. 4). Our data support the idea that the dust associated with the hot gas is much colder than the gas.

4. DISCUSSION

Since the discovery of the relatively uniform high temperatures in the envelope of Sgr B2 and in other molecular clouds in the GC, a detailed understanding of the thermal balance in these molecular clouds has been a challenge. The most accepted idea is that shock heating explains the large column densities of hot gas associated with relatively cold dust (Wilson et al. 1982; Güsten 1989).

4.1. The heating mechanisms

Our ISO data show that the material along the line of sight towards the GC molecular clouds has a complex structure. The presence of an ionized component requiring an effective temperature for the ionization radiation of $\sim$35000 K indicates that shock heating is not the only mechanism which heats the large column densities of hot molecular gas in the

GC clouds. If shocks are responsible for all of the heating, the presence of the NeII and NeIII lines would imply J type shocks with shock velocities $\geq$ 100 kms^{-1}. This is contradiction with the profiles of the ammonia lines arising from the hot and the cold gas (see Hüttemeister et al. 1993) which do not show the displacement in radial velocities expected if the hot ammonia were heated by J-shocks. Furthermore, the ratio of the total line cooling rate to the FIR dust continuum is typically 0.006, far too low for the expected values from fast J shocks (Hollenbach & McKee 1989).

On the other hand, photoelectric heating will account for most of the observed characteristics of the ionized and the hot molecular components. For typical photodissociation regions (PDRs) in the Galaxy, photoelectric heating heats the gas to temperatures above those of the dust in a region with typical column densities of $\sim 3\ 10^{21}$ cm^{-2} (see Hollenbach & Tielens 1997). Several typical Galactic PDRs along the line of sight are then required to account for the large H_2 column densities of hot gas observed with ISO.

4.2. Wind blown ionized bubbles

Further support for the presence of several PDRs along the line sight of the GC comes from the inconsistencies between the Lyman continuum photons and the effective temperature of the ionization radiation. This can be reconciled if the ionized gas fills relatively large cavities surrounding the ionizing stars. Assuming a main sequence O star, our upper limit to the recombination line emission sets a lower limit to the size of the cavities of 2.5 pc. Hot (60-130 K) shells of molecular gas with sizes of 1-2.5 pc have recently been observed in the envelope of Sgr B2 molecular cloud (Martín-Pintado et al. 1999), and approximately 300 shells with sizes between 5 and 10 pc have been also identified from the CO survey of the GC (Hasegawa et al. 1998). From the number and the sizes of the shells detected in the GC, it is very likely that basically any line of sight towards the GC intersect at least two shells. In fact, Hasegawa et al. (1998) claim that the most likely occurrence of shells along the line of sight is ~ 20 shells. This would easily explain that the large column densities of hot H_2 observed with ISO can be produced by PDRs at the inner edges of a number of shells.

Although photoelectric heating can explain the ISO observations, the presence of a relatively large column density of hot ammonia ($\sim$ 30 per cent of the cold ammonia, see Hüttemeister et al. 1993) indicates that the Far UV radiation in not the only heating mechanism acting in the GC clouds. This is due to the fact that ammonia is a very fragile molecule and would be easily photo-dissociated in typical PDRs (Fuente et al. 1990). Martín-Pintado et al. (1999) have found that the hot ammonia shells in the Sgr B2 molecular cloud are expanding at relatively low velocities, 6-10 kms^{-1}. They proposed that the hot ammonia shells are produced by shocks associated with wind blown bubbles driven by evolved massive stars such us Wolf-Rayet stars or Luminous blue variables. These wind blown bubbles can explain the large cavities around the stars, the rather high effective temperature of the ionization radiation, and the shock chemistry in the GC molecular clouds.

In summary, the ISO data show that the energetic of the GC molecular clouds is dominated by FUV radiation that ionizes and heats the gas by photoelectric effect and to less extent by low velocity shocks, caused by the wind of evolved massive stars, that contribute to the selective heating of the gas maintaining the dust at lower temperatures.

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