The Galactic center interstellar medium as seen by ISO

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This paper deals with the heating and the ionization of the interstellar medium (ISM) in the 500 central pc of the Milky Way (hereafter Galactic center, GC). We review the results of Infrared Space Observatory (ISO) observations of a sample of GC molecular clouds located far from thermal radiocontinuum or far-infrared sources. For the first time, we have been able to study in detail the dust continuum spectra from 40 to 190 $\mu$m founding a warm (30-40 K) dust component in addition to the well known 15-20 K component. Fine-structure lines observations have revealed the presence of diffuse ionized gas associated with the molecular clouds. The effective temperature of the ionizing radiation is higher than 33000 K. ISO has also allow us to measure the fraction of warm ($\sim$ 150 K) H$_2$ in the GC clouds, which is on average of 30 %. The observations of the warm (a few 100 K) neutral gas are compatible with a Photon Dominated Region (PDR) scenario.

1 Dust

We have been able to study the full spectrum of the dust continuum emission from 40 to 190 $\mu$m. Two gray bodies are needed to model the spectra: a cold component with similar temperature for all the sources of 15-18 K and a warmer component with a temperature of 26 K to 39 K depending on the source (see Rodriguez-Fernandez et al. 2004). The cold dust is a well known component of the GC ISM from previous far-infrared and sub-millimeter studies. On the contrary, this is the first time we observe the warm dust component. As shown in Fig. 1, the warm component temperature and luminosity are well correlated with the 20 $\mu$m intensity in the images taken by Midcourse Space Experiment (MSX).

2 Ionized gas

We have detected fine structure lines of ionized species as [C II] 158 $\mu$m and [Si I] 34 $\mu$m in all the sources. In most of them we have also detected lines like [N II] 122 $\mu$m, [Ne II] 13 $\mu$m or [S III] 34 $\mu$m. In 11 of the 18 sources we have even
Fig. 1. Sources positions (black dots) overlaid on the 20 µm image by MSX. For each source numbers separated by a colon represent the temperature of the warm dust component in K and the [O III] 88 to [N II] 122 µm flux ratio detected the [O III] 88 µm (with excitational potential of 35 eV). (Rodriguez-Fernandez et al. 2001b; Rodriguez-Fernandez & Martin-Pintado 2004). The lines observed with the LWS Fabry-Perot (velocity resolution of ∼30 km s$^{-1}$) are very broad, with linewidths up to 150 km s$^{-1}$. Left panel of Fig. 2 shows the [N II] spectra overplotted on the $^{13}$CO(1-0) data of Rodriguez-Fernandez et al. (2001a). Taking into account the rather different spectral resolutions, for most of the sources the Fabry-Perot lines profiles are similar to those of the $^{13}$CO(1-0) lines. [S III] and [O III] lines ratios imply that the electron densities are lower than a few 10 cm$^{-3}$. Therefore, line profiles and electron densities are consistent with the ionized gas arising in the low density envelopes of the molecular clouds. The good correlation between the the [C II] 158 µm and the [N II] 122 µm fluxes (right panel of Fig. 2) implies that part of the [C II] flux also arises the ionized gas component (Heiles 1994).

Figure 1 shows one of the lines ratios sensitive to the effective temperature of the ionizing radiation that can be derived for most of the sources ([O III] 88/[N II] 122) over the 20 µm MSX image. The higher lines ratios are measured in those sources with the higher dust temperature (Section 1) which are those located in the surrounding of the 20 µm emission features. The association of warm dust and ionized gas imply heating by stars radiation. The ionizing sources are probably located in the vicinity of the 20 µm peaks but the radiation reach large distances due to the inhomogeneity of the medium, i.e., the general scenario is probably similar to that found by Rodriguez-Fernandez et al. (2001b) in the Radio Arc region. CLOUDY models show that the effective temperature of the radiation is higher than 33000 K (Rodriguez-Fernandez & Martin-Pintado 2004).

3 Warm neutral gas

Observations of $^{12}$H$_2$ pure-rotational lines have allow us to measure the total column density of warm gas in the GC clouds. The column density of warm
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Fig. 2. Left panel: comparison of the [N II] 122 μm and the 13CO(1-0) line profiles. Right panel: [C II] 158 μm versus [N II] 122 μm fluxes and least squares fit.

(∼ 150 K) H$_2$ is ∼ 10$^{22}$ cm$^{-2}$. In addition there is a ∼ 500 K gas component with a column density lower than 1% of that at 150 K. Comparing with the H$_2$ column density derived from CO we see that the fraction of warm H$_2$ is on average of 30% but it is as high as ∼ 100% for some of the sources. The H$_2$ line intensities can be reproduced both by shocks or PDRs models. In particular, the observed temperature gradient is in perfect agreement with both model predictions and ISO observations of well-known PDRs (Rodriguez-Fernandez et al. 2001a).

In addition, we have observed the warm (a few 100 K) neutral medium by means of fine structure lines of species like O, C$^+$ or Si$^+$, which are the main cooling lines in these medium. The lines to continuum ratio (∼ 0.3%) is typical of PDRs. Indeed, the discovery of ionized gas associated with the molecular clouds implies that PDRs are expected in the interface between the ionized and the molecular gas. From the PDRs diagnostic diagrams of Wolfire et al. (1996) we estimate a density of 10$^3$ cm$^{-3}$ and an incident field 10$^3$ times higher than the local interstellar radiation field.

We have also found that the ratio of warm to cold H$_2$ increases with an increasing fine-structure lines to far-infrared continuum ratio. This fact points to a common origin for the warm H$_2$ and the fine structure lines. (Rodriguez-Fernandez et al. 2004).

4 Discussion and conclusions

The heating of the GC clouds is a long-standing problem. The discrepancy of the dust and gas temperatures and the apparently lack of ionized gas associated to the molecular clouds are usually invoked to rule out radiative heating mechanisms. However, the picture arising from the ISO observations is a complex medium where the molecular clouds are irradiated from the exterior by hot radiation arising from relatively hot and distant sources. The
surfaces of the clouds are ionized and there is a warm (150 K) neutral gas component in the interface between the ionized and the molecular gas. The 30-40 K dust component should be associated with the 150 K gas component and both heated in PDRs. It is noteworthy that the discrepancy of gas and dust temperatures only rules out gas heating by collisions with hot dust but it does not rule out any radiative heating mechanisms as photoelectric effect on the dust grains in a PDR. Indeed a gas temperature of 150 K and a dust temperature of $\sim 35$ K as measured in the GC clouds it is exactly what it is expected in a $10^3$ cm$^{-3}$ and $G_0=10^3$ PDR (Hollenbach et al. 1991).

On the other hand, the extended distribution and high abundances of fragile molecules when illuminated by ultra-violet radiation (see for instance Martin-Pintado et al. 2001) and the large line-widths are the best probe of the presence of turbulence or low velocity shocks in the GC clouds. Shocks, turbulence and PDRs probably coexist in the GC. Unfortunately, it is still not clear how much gas is heated in PDRs and how much is heated by other mechanisms. In any case, the new ISO data show that the importance of radiation in the heating of the GC clouds should be revisited and that a significant fraction of the warm gas in the GC clouds arise in standard PDRs.

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