From Interstellar Clouds to Star-Forming Galaxies: Universal Processes?, E45, 1 of 2
Proceedings IAU Symposium No. 315, 2016
P. Jablonka, Ph. André, & F. van der Tak, eds.
doi:10.1017/S1743921316008061

Warm dust and gas of massive young stellar objects revealed by Herschel PACS spectroscopy

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Abstract. We present results of Herschel PACS imaging spectroscopy data toward ten massive young stellar objects taken as part of the WISH project. Our sample consists of four high mass protostellar objects (HMPOs), two hot molecular cores (HMCs), and four ultracompact HII regions (UCHIIs), and the spectra cover a broad range of wavelengths (55 to 210 μm) imaged over an $\sim 50''$ field with 5×5 spaxels. By fitting the continua utilizing a modified black-body formula we estimate mass-weighted dust temperature and column density distributions of warm dust and find that UCHII regions are hottest and HMCs are most deeply embedded. We also estimate rotational temperature and column density distributions of warm CO gas using the rotational diagram analysis, which are comparable over targets in contrast to continuum results. By comparing high J CO line fluxes to the RATRAN estimates of centrally heated envelope models, we find that majority of warm CO originates from bipolar outflow shocks.

Keywords. astrochemistry, stars: formation, stars: pre–main-sequence, HII regions

1. Introduction

Warm dust collision is the main heating mechanism of gas in quiescent molecular clouds (Doty & Neufeld 1997). However, when stars form, various heating mechanisms are added: energetic bipolar outflows and strong UV photons. We investigate physical properties of dust and gas (temperature and column density distributions) around massive young stellar objects and discuss whether the properties are explained by centrally heated envelope models (van der Tak et al. 2013).

Ten massive young stellar objects, which consist of four high mass protostellar objects (HMPOs: DR21(OH), W3 IRS5, W33A, AFGL 2591), two hot molecular cores (HMCs: G327-0.6, NGC 6334-I), and four ultra compact HII regions (UCHIIs: G5.89-0.39, G34.26+0.15, NGC 7538-IRS1, W51N-e1), have been observed by the Photodetector Array Camera and Spectrometer (PACS, Poglitsch *et al.*2010) of the Herschel Space Observatory (hereafter *Herschel*), as part of the *Herschel* guaranteed time key program, Water in star-forming regions with Herschel (WISH, van Dishoeck et al. 2011). The PACS imaging spectroscopy data offer broad spectra of 55 to 210 μm in 5×5 spatial pixels (hereafter spaxels, $9.4'' \times 9.4''$ each), which include dust continua and various atomic and molecular lines. The central spaxel data of our dataset have been employed in Karska et al. (2014a) for studying molecular cooling in star formation.

2. Warm dust

First, we estimate deconvolved sizes of dust continuum at 170 μm using the 2D Gaussian function and find that they are smaller than those at 450 μm. This implies central heating: cold dust grains are farther distributed.

In addition, we fit individual continua of 25 spaxels over the PACS wavelengths using the modified blackbody radiation formula for constraining mass-weighted temperature and column density distributions. The mass-weighted dust temperatures and column densities are broadly ranged: e.g., $T_d = 35$–60 K and $N = 0.5$–4.0 g cm^{-2} at the center. However, we find that UCHIIs have the highest mass-weighted dust temperatures and HMCs have the highest column densities implying the most deeply embedded state.

We also compare the temperature and column density distributions with centrally heated envelope models (van der Tak et al. 2013). Such passive envelope models well explain the *Herschel* PACS observations, but the outer regions appear to be warmer than the models, which suggests an external heating.

3. Warm CO

We obtain CO rotation temperatures and column densities using the rotational diagram analysis based on CO ladders of $J_{up} \geqslant 14$. Rotation temperatures of CO (T_{rot} = 150–350 K at the center) are much higher than the mass-weighted dust temperatures. In addition, they are comparable over radius and objects unlike dust temperatures. Column densities of CO ($N_{CO} = 0.1$–1×10^{16} cm^{-2}) do not indicate a significant variation over objects either, differently from dust continuum estimates. The discrepancy suggests that the components traced by warm CO differ from what continuum tracks.

In addition, we calculate CO fluxes of centrally heated envelope models using RATRAN (Hogerheijde & van der Tak 2000) and compare them with data. The comparison shows that majority of warm CO cannot be explained by envelope heating. The fraction of warm CO understood by envelope heating is about 20% at the central regions of all the three type objects (HMPOs, HMCs, UCHIIs). When the whole PACS 5×5 spaxel area is taken into account, the fraction is only about 10% or less. This indicates that the main heating mechanism of warm CO is more extended than an envelope. Outflow activities like UV photons through bipolar outflow cavities and outflow shocks are thought to be the main excitation mechanisms of warm CO (Karska et al. 2014b).

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