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Shocks and UV radiation around low-mass protostars: the Herschel-PACS legacy

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Abstract. Far-infrared spectroscopy reveals gas cooling and its underlying heating due to physical processes taking place in the surroundings of protostars. These processes are reflected in both the chemistry and excitation of abundant molecular species. Here, we present the *Herschel*-PACS far-IR spectroscopy of 90 embedded low-mass protostars from the WISH (van Dishoeck et al. 2011), DIGIT (Green et al. 2013), and WILL surveys (Mottram et al. 2017). The 5×5 spectra covering the $\sim 50'' \times 50''$ field-of-view include rotational transitions of CO, H_2O, and OH lines, as well as fine-structure [O I] and [C II] in the $\sim$50-200 μm range. The CO rotational temperatures (for $J_\mathrm{u} \geqslant 14$) are typically $\sim$300 K, with some sources showing additional components with temperatures as high as $\sim$1000 K. The H_2O / CO and H_2O / OH flux ratios are low compared to stationary shock models, suggesting that UV photons may dissociate some H_2O and decrease its abundance. Comparison to C shock models illuminated by UV photons shows good agreement between the line emission and the models for pre-shock densities of 10^5 cm^{-3} and UV fields 0.1-10 times the interstellar value. The far-infrared molecular and atomic lines are the unique diagnostic of shocks and UV fields in deeply-embedded sources.

Keywords. Young stellar objects, outflows, jets, shocks

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1. Introduction

During the early formation of low-mass protostars, the mass accretion rates are high and thus, the feedback from the protostar on its surrounding is most spectacular. The launching of jets and winds creates outflow cavities and generates shock waves propagating in the envelope. Shocks compress and heat the gas but may also produce UV photons, which penetrate to large distances due to low densities and scattering in the outflow cavities. Characterising these processes requires spectroscopy in the far-infrared (IR), where cooling of the warm, dense gas is very efficient (Kaufman & Neufeld 1996). The question remains, how do these feedback processes influence the initial conditions (both physics and chemistry) of star and planet formation.

In this paper, we briefly summarize the survey of 90 deeply-embedded low-mass protostars observed as part of the three large *Herschel* programs: 'Water in Star forming regions with Herschel' (WISH, van Dishoeck et al. 2011), 'Dust, Ice, and Gas in Time'

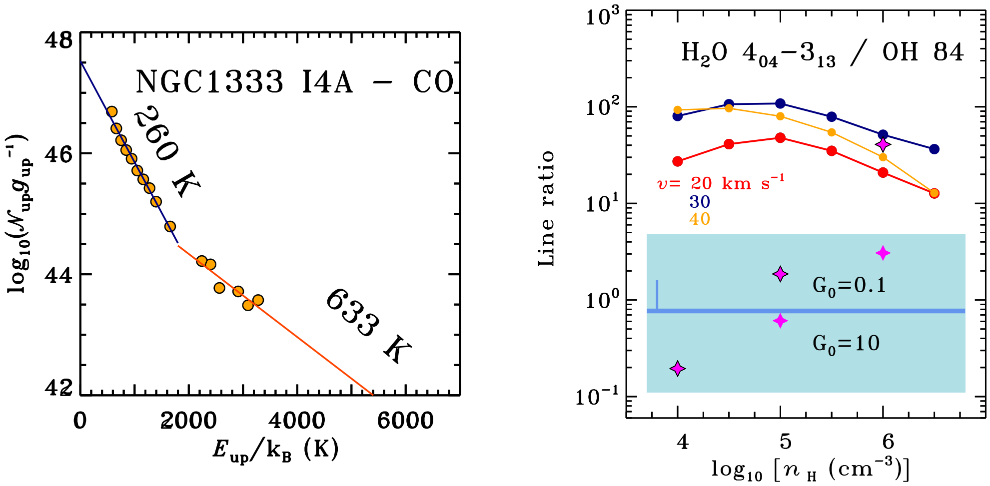

Figure 1. *Left:* CO rotational diagram of a Class 0 protostar, NGC 1333 IRAS 4A. *Right:* Line ratio of H_2O $4_{04}-3_{13}$ at 125 μm and OH at 84 μm as a function of logarithm of density of the pre-shock gas. The range observed in ~90 protostars is shown as the filled, light-blue box, and the models of C shocks are shown as solid lines (models of shielded shocks, Kaufman & Neufeld 1996) and violet stars (models of UV illuminated shocks, Melnick & Kaufman 2015).

(DIGIT, Green et al. 2013), and 'William Herschel Line Legacy' (WILL, Mottram et al. 2017). All observations were obtained using the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) that provided spectral maps consisting of 25 spatial pixels of $\sim 9.4'' \times 9.4''$, corresponding to pixel sizes of $\sim 2000 \times 2000$ AU for typical distances of 200 pc.

2. Results

Rich molecular line emission is commonly detected in Class 0/I protostars including highly-excited H_2O ($E_{\rm up} \sim 1000$ K) and CO lines ($E_{\rm up} \sim 5000$ K), see Herczeg et al. 2012 and Goicoechea et al. 2012. The line fluxes of molecular species correlate strongly with each other and show similar extent of emission, typically following the outflow direction. Multiple transitions of CO lines are used to determine rotational temperatures of the gas (see left panel of Figure 1). A ~ 300 K component is universally seen in almost all protostars, whereas the hotter gas component shows a broad distribution with a median at 720 K (detected in 27% of sources). These two physical components are identified in the spectrally-resolved CO 16-15 lines obtained with HIFI (Kristensen et al. 2017). The ~ 300 K component in the PACS CO ladder corresponds to the broad, Gaussian component in the line profiles originating in outflow cavity shocks or disk winds. The hotter component is associated with the "offset" component (i.e. offset in velocity) likely produced in the irradiated shocks (see Kristensen et al. 2017, for discussion).

The right panel of Figure 1 shows a comparison of the measured H_2O / OH line ratios and the predictions from stationary (1D plane-parallel) C shock models from Kaufman & Neufeld (1996). Clearly, these models overestimate the observed line ratios by 1-2 orders of magnitude. Low H_2O / OH line ratios require partial photodissociation of H_2O into OH and O. Predictions from C shock models illuminated by UV photons (Melnick & Kaufman 2015) reproduce the observed ranges of H_2O / OH for pre-shock densities of 10^5 cm^{-3} and UV fields 0.1-10 times the interstellar value. These preliminary comparisons show that UV radiation influences the chemistry in the inner envelopes around deeply-embedded

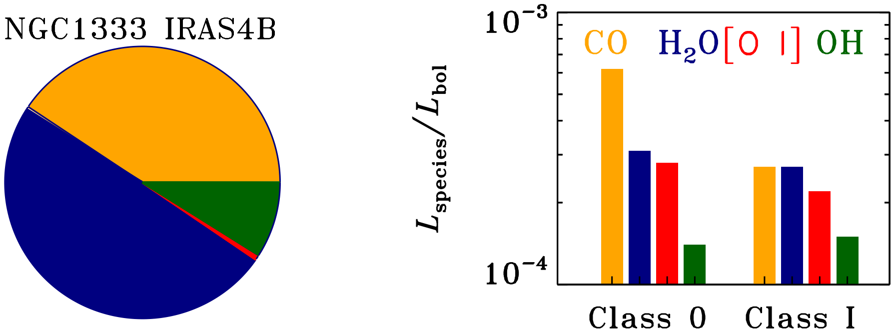

Figure 2. *Left:* Fractions of gas cooling contributed by CO (orange), H_2O (blue), OH (green), and [O I] (red), to the total far-infrared line cooling in the Class 0 protostar NGC 1333 IRAS 4B. *Right:* Median line cooling in CO, H_2O, [O I], and OH over bolometric luminosities for Class 0 and Class I sources.

protostars, as also evidenced by observations of light ionised hydrides (Kristensen et al. 2013, Benz et al. 2016).

Low abundances of H_2O are also confirmed by relatively low total line cooling in H_2O versus other molecules at far-IR wavelengths. Kaufman & Neufeld (1996) predict that H_2O should account for 70-90% of total molecular line cooling in the far-IR (H_2O+CO+OH, Karska et al. 2014). At the same time, the observed H_2O emission is typically below 30% and at most about 50% in the most H_2O-rich source NGC1333 IRAS4B (left panel of Figure 2, data from Herczeg et al. 2012). Clearly, some H_2O is missing and the UV photodissociation is a possible mechanism to decrease its abundance.

Far-IR molecular line cooling decreases from Class 0 to Class I (right panel of Figure 2), but the differences are significant only in CO and not in H_2O (Karska et al. subm.). Proper interpretation of these trends requires the analysis of velocity-resolved profiles, which reveal multiple kinematic components with varying contributions depending on the transition (e.g., Kristensen et al. 2017).

The far-IR data presented here demonstrate the necessity for excellent space-based facilities to quantify the chemistry and excitation of warm molecular and atomic gas. The next major step will occur when the *James Webb Space Telescope* (JWST) is launched in 2018; this telescope will provide crucial data on not only the mid-IR cooling species, but most importantly on the dominant gas coolant: molecular hydrogen, H_2. Direct measurements of the atomic and molecular abundances will be performed and tested against sophisticated shock models.

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