Hot water in low-mass protostars

Dominika Itrich[1], Agata Karska[1] and Monika Matuszak[2]

1. Centre for Astronomy, Nicolaus Copernicus University, Grudziądzka 5, 87–100 Toruń, Poland
2. Institute Astronomical Observatory, Adam Mickiewicz University, Słoneczna 36, 60–268 Poznań, Poland

During the formation of low-mass stars, the collapse of the dense envelope is accompanied by ejections of jets and outflows extending even up to parsec scales. Recent far-infrared spectroscopy with *Herschel*/PACS revealed hot molecular gas (> 100 K) extending along the outflows from several nearby protostars. Here, we analysed emission from highly-excited rotational lines of water ($E_{\rm up}/k_{\rm B} \sim 1000$ K) in a sample of 90 low-mass protostars (Karska et al., 2018). Such hot water is detected in 9 sources. We calculated water rotational temperature using Boltzmann diagrams and looked for correlations with highly excited CO lines and various sources properties. The sources with hot water are ideal candidates for follow-up studies with the James Webb Space Telescope, which will access hot water lines at mid-IR with ~ 50 times higher spatial resolution than *Herschel* mission.

1 Introduction

Stars are formed in dense cores within molecular clouds. As the star builds up its mass, part of available material is ejected as powerful and collimated outflow. The outflows interact with the dense medium, creating shocks that compress and heat the gas (Kaufman, 1996). H_2O is a dominant coolant of the outflow-envelope interactions (Herczeg et al., 2012).

We used data from the *Herschel*/PACS instrument collected as a part of WISH, DIGIT and WILL surveys (Karska et al., 2018). The *Herschel* Space Observatory was a space-based telescope to study the Universe at the far-infrared and submillimeter wave bands. It was launched in May 2009 and it has been operating until 2013. It's primary targets were clouds of gas and dust where new stars are being born, protoplanetary disks and cometary atmospheres. The spacecraft carried three instruments: two cameras (PACS, SPIRE) and a very high-resolution spectrometer (HIFI). The telescope's primary mirror was 3.5 m in diameter and allowed *Herschel* to collect almost 20 times more light than any previous infrared space telescope.

The Photoconductor Array Camera and Spectrometer (PACS) observed the wave range from 55 to 210 μm covering many atomic and molecular transitions. PACS with 25 spacial pixels ($9.4'' \times 9.4''$ each) provides the 8 times improvement in spatial resolution as compared to ISO/LWS (Infrared Space Observatory/Long Wavelength Spectrometer). The range spectroscopy mode provided the spectral resolution of $R = \lambda/\Delta\lambda \sim 1000 - 1500$ over the full spectral range (Poglitsch et al., 2010).

2 Results

We identified 9 out of 90 objects with the detection of the highly-excited H_2O line ($8_{18} - 7_{07}$) at $63.32\,\mu$m. Rotational diagrams for sources with at least 4 detections

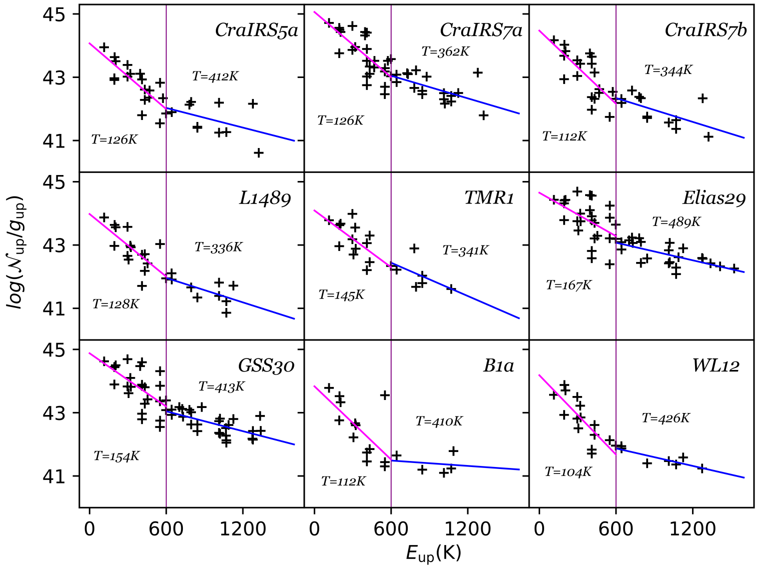

Fig. 1: Rotational diagrams for objects with identified hot water emission, where $E_{\rm up}$ is excitation energy of upper level, N – the populacy and $g_{\rm up}$ is degeneracy of that level. For these objects two components are visible: hot and warm.

Table 1: Rotational temperatures and total numbers of emitting water molecules calculated for the warm and hot components on Boltzmann diagrams (Fig. 1).

Object	$T_{\rm warm}$(K)	$T_{\rm hot}$(K)	$N_{\rm warm}$	$N_{\rm hot}$
CraIRS5a	126	412	5.89e+45	1.25e+45
CraIRS7a	126	362	5.80e+46	1.34e+46
CraIRS7b	112	344	1.28e+46	2.69e+45
L1489	128	338	5.17e+45	1.10e+45
TMR1	145	341	7.42e+45	1.81e+45
Elias29	167	489	4.09e+46	1.38e+46
GSS30	154	413	5.01e+46	1.29e+46
B1a	111	410	2.94e+45	4.68e+44
WL12	104	426	5.84e+45	7.92e+44

revealed the existence of two components with average temperatures of $T_{\rm warm} = 130 \pm 21$ K and $T_{\rm hot} = 390 \pm 46$ K (Fig. 1). The temperatures and numbers of emitting water molecules calculated for all protostars with hot water are shown in Tab. 1. No correlation was found between hot water emission at 63.32 μm and source bolometric luminosity and temperature. We found only a correlation between H_2O and CO (30 – 29) emission with the Pearson coefficient of 0.99 (Fig. 2).

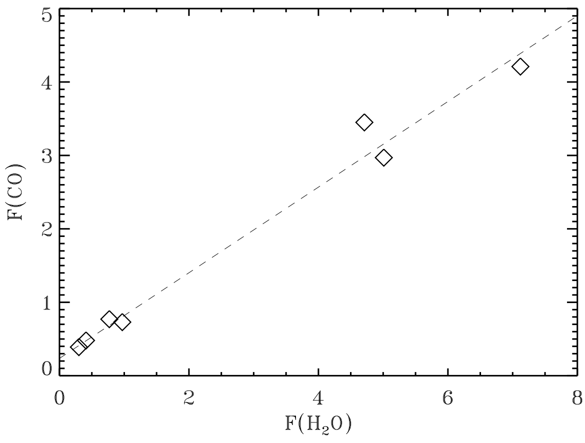

Fig. 2: Correlation between H_2O ($8_{18} - 7_{07}$) at 63.32 μm and CO ($30 - 29$) at 87.19 μm emission. Fluxes are given in 10^{-20} W cm^{-2} units.

3 Conclusions

Hot H_2O was detected in only 10% of low-mass protostars observed in our sample. The average rotational temperature of this very rare component is 390 K. The origin of the hot H_2O is unclear but a correlation with CO lines suggests that both are produced in the same energetic processes, likely related to shocks. Further work is needed to find out all characteristics and properties of the hot water emission and star formation. Next instrument to follow up this work is James Webb Space Telescope. It will observe hot H_2O at mid-IR with unprecedented sensitivity. The formation of stars and planetary systems is one of main goals of the JWST mission.

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