ALMA survey of molecular outflows in the Canis Major star forming region

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1. Introduction

- In the earliest stages of the star formation, a dense core within a molecular cloud begins to accrete the surrounding material, giving birth to a central protostar, where jets are launched at supersonic speeds, sweeping up surrounding material in large bi-polar outflows.
- The outflows weaken with time and the envelope starts to dissipate. Most continuum and line (sub)millimeter surveys have, however, focused on the brightest sources mapped at low resolution.
- In this work we undertake a survey toward an isolated molecular cloud at a distance of 0.9kpc (Figure 1), as part of the ALMA Cycle 3 project (ID: 2015.1.01339.S; PI: Luca Olmi) targeted a sample of 70 molecular clumps.

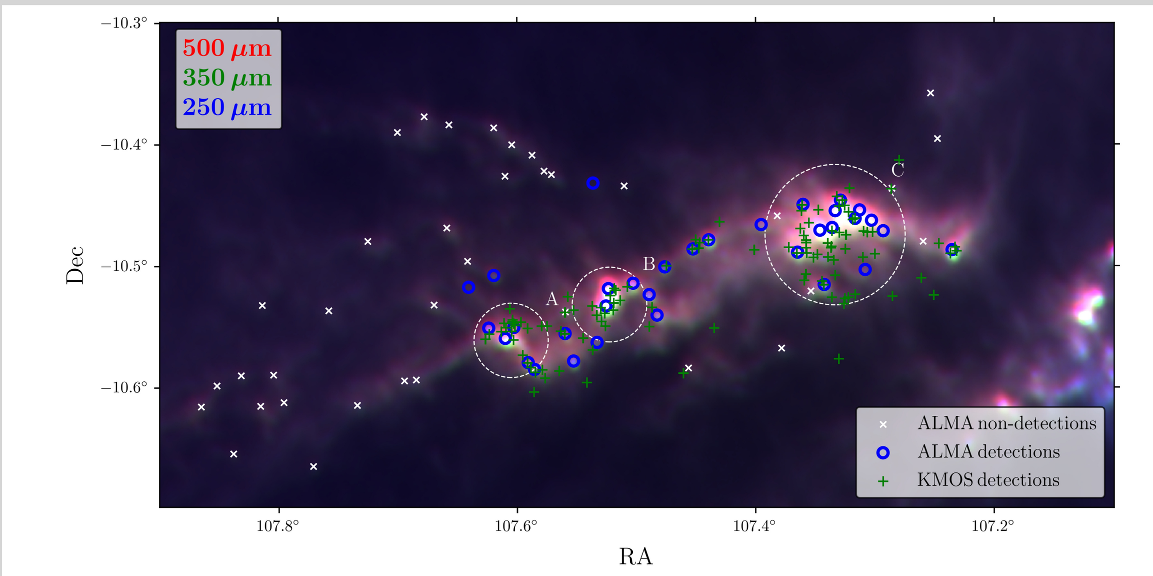


Figure 1. RGB image of the molecular cloud within the CMa-l224 star-forming region in Canis Major chosen for the ALMA observations investigated in this work, with Hi-GAL 250, 350 and 500μm in blue, green and red, respectively. 70 starless and protostellar clumps, as identified by Elia et al. (2013), were targeted, yielding 33 pointings (marked with blue circles) with a total of 60 continuum detections and 38 pointings with no continuum detections (marked with white crosses). Three circular regions, 'A', 'B' and 'C', are the approximate positions of the outflow regions associated with extended 4.5μm emission, as identified by Sewiło et al. (2019). Green crosses represent KMOS K-band detections of Itrich et al. (in prep.).

2. Data

ALMA

- ALMA Cycle 3 observations were obtained between March 27 and September 29 2016 using the 7m and 12m array. The spectral setup included three continuum spectral windows, centered on 219.5, 232, and 234GHz with bandwidths of 2GHz and channel widths of 15.625MHz, as well as two additional windows covering the 13CO J=2-1 and C18O J=2-1 lines, centered on 220.40 and 219.56GHz, respectively.

Hi-GAL

- The Herschel Infrared GALactic Plane Survey (Hi-GAL) is a Herschel open-time key-project, aiming at covering the entire Galactic disc.
- In order to classify the source as having a protostellar component, Elia et al. (2013) required it to have a detection at 70μm, giving 70 molecular clumps within the molecular cloud selected for the ALMA follow-up observations investigated in this work.

3. Continuum and line detections

- 60 ALMA Band 7 continuum objects were found in 36 molecular clumps of Elia et al. (2013). For the 33 sources with Herschel counterparts identified, we have derived envelope parameters, including the bolometric temperatures and luminosities, as well as envelope masses (Figure 2).
- In Figure 3 we show the envelope mass as a function of the bolometric luminosity. It can be seen that the mass tends to decrease with increasing temperature. This is consistent with the scenario in which the dust envelopes tend to decrease in size (and mass), as the source evolves due to its gravitational collapse. At the same time, the gas and dust heats up resulting in an increase in the bolometric temperatures.
- Following Stephens et al. (2018), we investigate how does the detection rate of N_2D^+ J=3-2 emission line near a protostar changes with evolution. N_2D^+ J=3-2 emission line is expected to disappear at T_{bol} > 20K (e.g. Jørgensen et al. 2011). It can be seen in Figure 4 that as we go towards higher values of T_{bol}, the detection rate of N_2D^+ J=3-2 decreases.

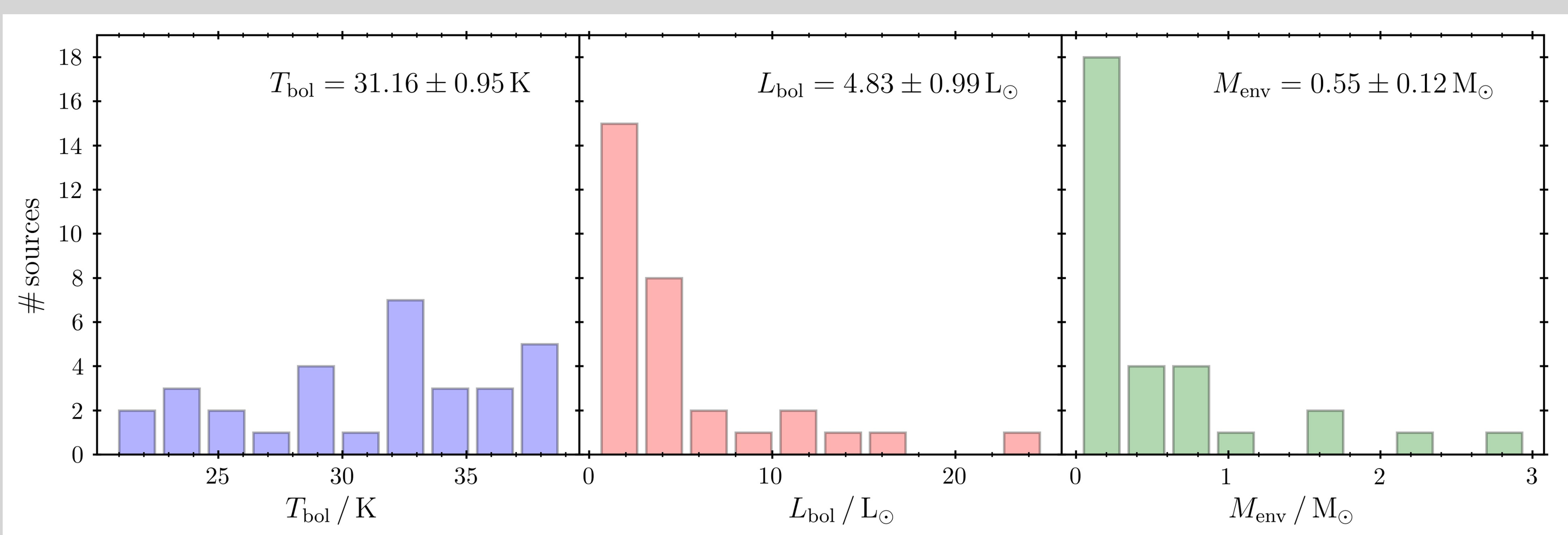


Figure 2. Histograms of the envelope parameters with the mean values quoted in each panel.

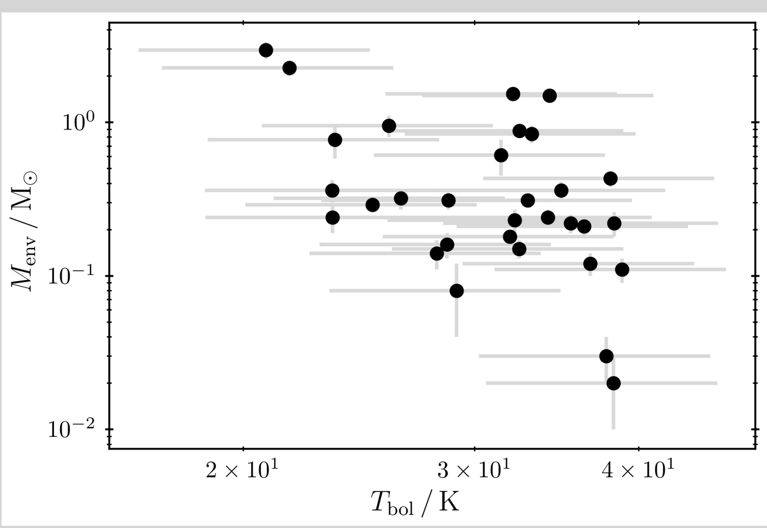


Figure 3. Envelope mass as a function of the bolometric temperature for the sample studied in this work.

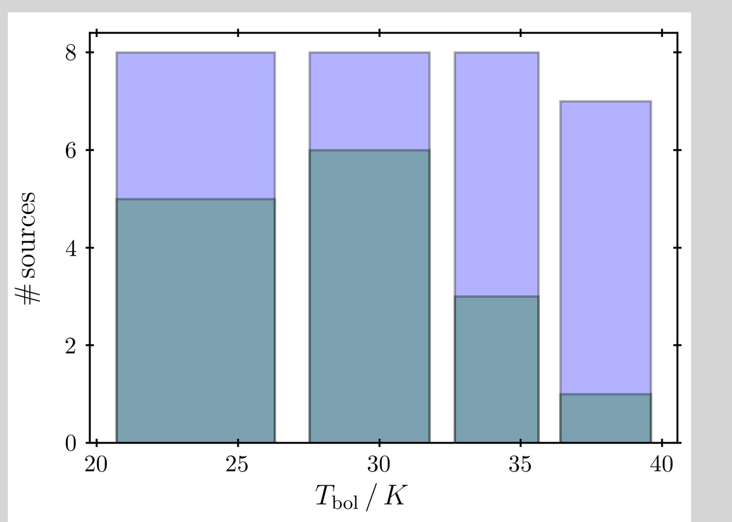
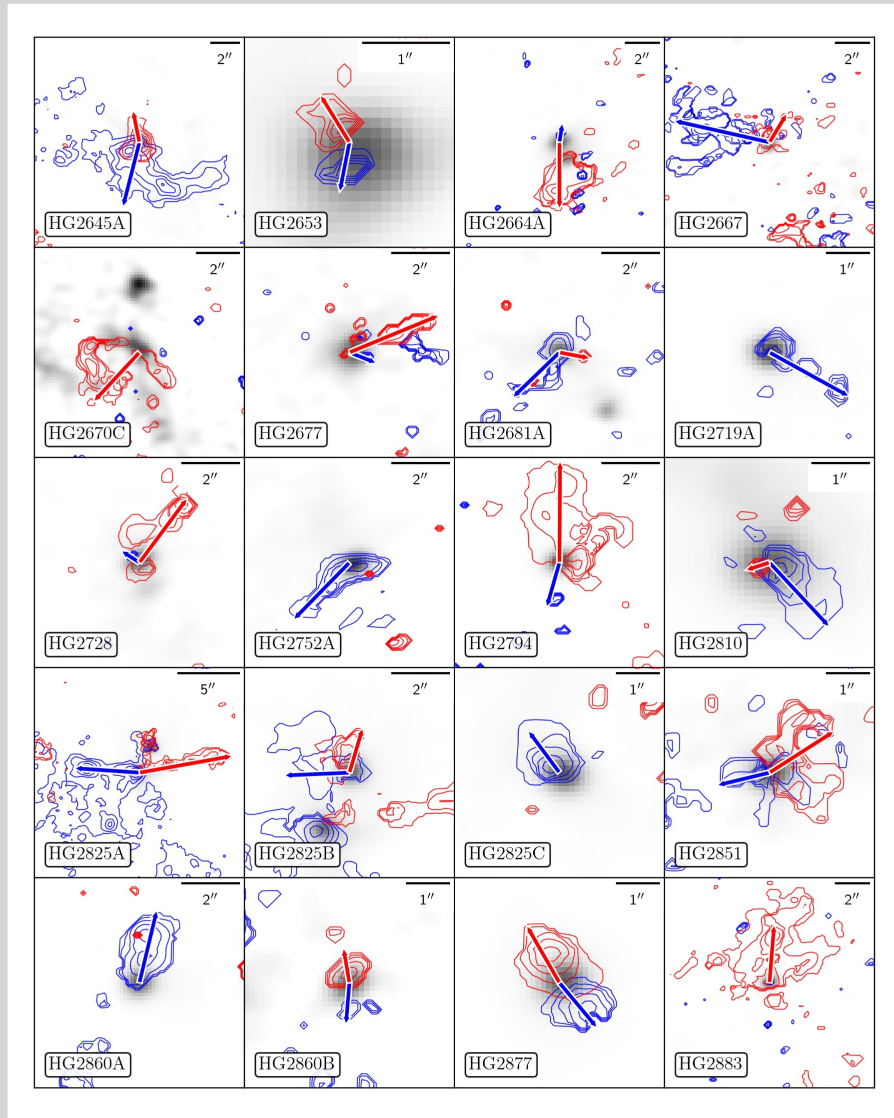


Figure 4. Histogram of bolometric temperatures for the whole sample of this work (blue) and for the sub-sample with N_2D^+ J=3-2 detections (green).

4. Outflow detections



- The minimum (or inner) velocity of the gas, v_{in}, that is being carried by a high-velocity outflow, is defined as the velocity at which the Gaussian fit to the $C^{18}O$ J=2-1 data falls below 5% of the peak value. Outflows are then found by integrating ^{13}CO J=2-1 data cubes between v_{in} and the maximum detected velocity, v_{max} (Figure 5).
- The outflow parameters of interest are the mass, M, the velocity, v_{CO}, the projected size of the lobe, R_{lobe}, and, ultimately, the outflow force, F_{13CO}.

Figure 5. High-velocity ^{13}CO J=2-1 outflows, with red- and blue-shifted ^{13}CO J=2-1 emission, integrated between inner velocity, v_{in}, and maximum velocity, v_{max}, are shown in red and blue contours equally spaced between 0.1 and 0.9 times the peak value, respectively, with the ALMA continuum in the background.

5. Outflows from low to high-mass YSOs

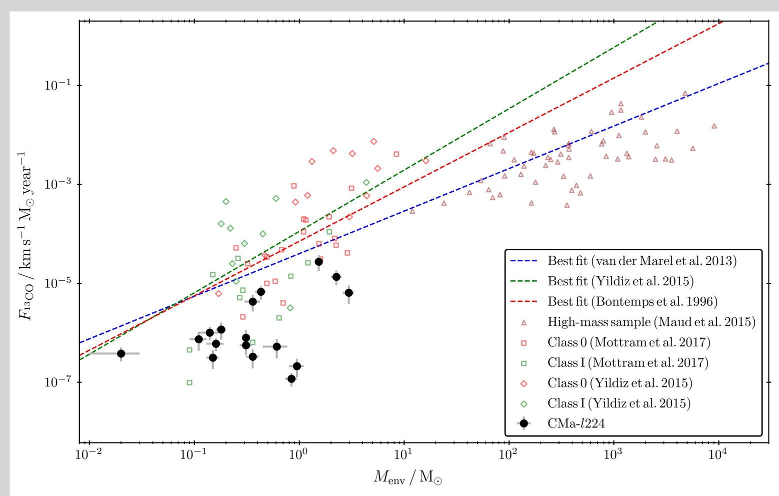


Figure 6. The outflow force as a function of the envelope mass for the ALMA sample studied in this work (black circles). Overplotted with diamonds and squares are the low-mass samples of Yildiz et al. (2015) and Mottram et al. (2017), respectively, divided into Class 0 YSOs in red and Class I YSOs in green. High-mass YSO sample of Maud et al. (2015) is also shown with brown triangles. The red, blue and green dashed lines represent the functional forms for the F13CO-Menv correlation derived by Bontemps et al. (1996), van der Marel et al. (2013) and Yildiz et al. (2015), respectively.

- In Figure 6 we show F_{13CO} as a function of Menv for our sample with black circles. In addition, we plot two low- and high-mass samples, as indicated in the caption. The decrease of the outflow force with the decreasing envelope mass reflects the decrease of the outflow force with evolution (e.g. Saraceno et al. 1996).
- It is interesting to note that our low-mass sample tends to fall somewhat below the correlation. These outflow parameters are based on ^{13}CO J=2-1 observations, which are likely missing the highest-velocity material.

6. Outflow activity in the CMa-*l*224 region

- Lin et al. (2021) conducted ^{12}CO J=1-0, ^{13}CO J=1-0 and $C^{18}O$ J=1-0 observations of CMa OB1 complex, of which CMa-l224 region is a part, using the 13.7-m millimeter-wavelength telescope of the Purple Mountain Observatory (PMO) in Delingha, China, with the beam size of ~50 arcsec.
- ^{12}CO J=1-0 molecular outflows were identified as shown in Figure 7. It can be seen that the single-dish outflows have significantly larger areas than the outflows found in this work. This is most likely due to both, the resolution difference between the two studies and the fact that Lin et al. (2021) used the ^{12}CO J=1- 0 data, while we have adopted the ^{13}CO J=2-1, being much less sensitive to the highest-velocity material.

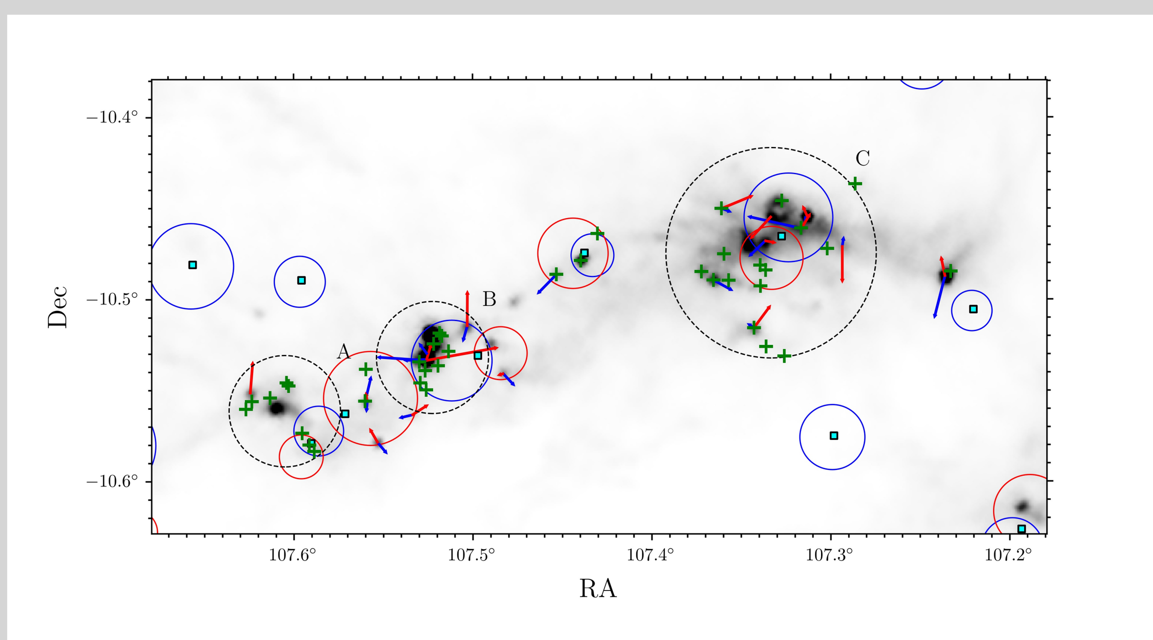


Figure 7. Map of high-velocity blue- and red-shifted (indicated with color arrows) ^{13}CO J=2-1 outflows, as identified in this work, with the Hi-GAL 250μm image in the background. The lengths of the arrows, representing given outflow lobe length, were multiplied by 20 to make them visible. The blue and red circles show the CO J=1-0 outflows found by Lin et al. (2021), centered on the outflow lobe peaks, with the size of the circles representing the area of the outflow. The cyan squares show the outflow sources. The black dashed circles represent the outflow regions identified in Sewilo et al. (2019). Green crosses show KMOS H_2 2.12μm detections as identified by Itrich et al. (in prep).

7. Summary

We have undertaken a survey toward an isolated molecular cloud at a distance of 0.9kpc. The main findings can be summarized as follows:

- Envelope mass anti-correlates with the bolometric temperature.
- Detection rate of N_2D^+ decreases with increasing evolutionary stage.
- Outflow properties from ^{13}CO observations fall below literature values; the entire outflow is not captured.

Baldeschi, A., et al. 2017, MNRAS, 466, 3682, Bontemps, S., et al. 1996, A&A, 311, 858, Elia, D., et al. 2013, ApJ, 772, 45, Ho, P. T. P., et al. 2004, ApJL, 616, L1, Jørgensen, J. K., et al. 2011, A&A, 534, A100, Lin, Z., et al. 2021, ApJS, 252, 20, Maud, L. T., et al. 2015, MNRAS, 453, 645, Molinari, S., et al. 2010a, A&A, 518, L100, 2010b, PASP, 122, 314, 2011, A&A, 530, A133, Mottram, J. C., et al. 2017, A&A, 600, A99, Sewilo, M., et al. 2019, ApJS, 240, 26, Stephens, I. W., et al. 2018, ApJS, 237, 22, Stephens, I. W., et al. 2019, ApJS, 245, 21, van der Marel, et al. 2013, A&A, 556, A76, Yıldız, U. A., et al. 2015, A&A, 576, A109,