High-mass Outflows Identified from COHRS CO (3–2) Survey

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Abstract

An unbiased search of molecular outflows within the region of the CO High Resolution survey has identified 157 high-mass outflows from a sample of 770 APEX Telescope Large Area Survey of the Galaxy clumps with a detection rate of 20%. The detection rate of outflows increases for clumps with higher \( M_{\text{clump}} \), \( L_{\text{bol}} \), \( L_{\text{bol}}/M_{\text{clump}} \), \( N_{\text{H2}} \), and \( T_{\text{dust}} \) compared to the clumps with no outflow. The detection rates of the outflow increase from protostellar (8%) to young stellar object clump (17%) to massive star-forming clump (29%). The detection rate 26% for quiescent clump is preliminary, because the sample of quiescent clumps is small. A statistical relation between the outflow and clump masses for our sample is \( \log(M_{\text{out}}/M_{\odot}) = (-1.1 \pm 0.21) + (0.9 \pm 0.07) \log(M_{\text{clump}}/M_{\odot}) \). The detection rate of outflows and the outflow mass-loss rate show an increase with increasing \( M_{\text{clump}} \), \( L_{\text{bol}} \), \( N_{\text{H2}} \), and \( T_{\text{dust}} \), which indicates that clumps with outflow with higher parameter values are at a more advanced evolutionary stage. The outflow mechanical force increases with increasing bolometric luminosities. No clear evidence has yet been found that higher-mass outflows have different launching conditions than low-mass outflows.

Key words: ISM: jets and outflows – ISM: molecules – stars: formation – stars: massive

Supporting material: figure sets, machine-readable tables

1. Introduction

Molecular outflows occur across the full range of stellar mass scales from brown dwarfs to massive stars, and understanding the launching mechanism is essential to understanding massive star formation (Qiu et al. 2009; de Villiers et al. 2014; Yang et al. 2018). Since the first molecular outflow was discovered observationally on Orion KL (Kwan & Scoville 1976), many other outflows have been found. Especially, low-mass outflows have increased significantly in number over the past ~40 yr, giving rise to several different models (Canto & Raga 1991; Chernin & Masson 1995; Li & Shu 1996; Lery et al. 1999). On the other hand, molecular outflows associated with massive star formation are still relatively few (e.g., Zhang et al. 2001, 2005; Beuther et al. 2002; Wu et al. 2005; López-Sepulcre et al. 2009; de Villiers et al. 2014; Yang et al. 2018). Taking into consideration that massive star-forming processes are still under active debate, it is necessary to find more high-mass outflows for detailed study in order to understand these processes.

Systematic studies of outflows associated with massive star formation started much later than studies of low-mass star processes. A search for CO (1–0) line wings toward 122 massive star-forming (MSF) regions detected moderate- to high-velocity line wings in 90% of them (Shepherd & Churchwell 1996a). CO (1–0) mapping of 10 MSF regions identified five high-mass outflows (Shepherd & Churchwell 1996b). A later CO (2–1) line survey of 69 massive protostellar candidates also showed that high-velocity gas is a common feature in massive young stellar objects (YSOs; Sridharan et al. 2002). Beuther et al. (2002) identified bipolar outflows in 21 of 26 sources. These studies show that high-mass outflows are much more massive and energetic than low-mass outflows. Kim & Kurtz (2006) found that the collimation factors of massive outflows and low-mass outflows are not significantly different, which is different from the findings of Wu et al. (2004). A study of high-mass outflows associated with 54 6.7 GHz methanol masers by de Villiers et al. (2014) found that the high-mass outflows follow the same scaling law between outflow activity and clump masses as observed for low-mass objects, which indicates a commonality in the formation processes of low-mass and massive stars. Maud et al. (2015) and Yang et al. (2018) suggested that these outflows have enough power to drive turbulence in the local environment but do not contribute significantly to the turbulence of the clouds. In this paper, we select 770 compact clumps from the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL; Schuller et al. 2009) with relatively strong CO (3–2) emission in the CO High Resolution Survey (COHRS; Dempsey et al. 2013). We (1) identify some outflow candidates and calculate outflow parameters, (2) discuss physical implications of these parameters, and (3) find some interesting phenomena for further interferometric studies. In Section 2 we describe the ATLASGAL and COHRS surveys and present our sample. In Section 3, we identify 157 high-mass outflows and calculate the physical properties of 84 sources with both blue and red lobes. Section 4 discusses the correlation between outflow parameters and properties of their corresponding clumps and presents a comparison between the outflow force and bolometric luminosities for low-mass stars and high-mass stars. A summary is presented in Section 5.
2. Archival Data and Our Sample

2.1. Archival Data

ATLASGAL is the largest and most sensitive systematic survey of the inner Galactic plane at 870 μm. This unbiased database of dense clumps provides a comprehensive sequence of massive star formation regions, from quiescent to H II, for investigating high-mass outflows at different stages. ATLASGAL has an FWHM beam size of 19′′, and the typical pointing rms error is ~4 arcsec at 345 GHz. The survey sensitivity of 0.3–0.5 Jy beam−1 (5σ) allows the detection of all cold dense clumps (<25 K) with masses >1000 M⊙ out to a heliocentric distance of 20 kpc (Urquhart et al. 2014). A total of ~10,163 compact clumps have been detected in the region |l| < 60° and |b| < 1°5, and Urquhart et al. (2018) present the detailed physical properties of these MSF clumps. We will use these data to compare the relation between outflow parameters and the properties of their corresponding clumps.

COHRS (Dempsey et al. 2013) has been taken using the Heterodyne Array Receiver Programme on the James Clerk Maxwell telescope in Hawaii. When complete, this survey will cover |b| ≤ 0.5 between 10° < |l| < 65°. A first data release covers |b| ≤ 0.5 between 10°:25 < |l| < 17°:5 and 50°:25 < |l| < 55°:25 and |b| ≤ 0.25 between 17°:5 < |l| < 50°:25, which totals 29 square degrees. The survey has an angular resolution of 13″8 and an approximate rms of ~2 K per 0.42 km s−1 channel. At this frequency, the main-beam efficiency is 0.61. The CO (3–2) data from COHRS serve as a tracer of outflow activity and as a classic indicator of the very early stages of star formation (Banerjee & Pudritz 2006).

2.2. The Source Sample

The massive clump catalog of ATLASGAL (Urquhart et al. 2014) contains 1869 clumps that are located in the regions covered by COHRS (Dempsey et al. 2013). A total of 770 of these clumps are associated with detected CO (3–2) emission, and their physical properties from Urquhart et al. (2018) are given in Table 1. The average values of Tdust, log[NH( cm−2)], [log[MC[ cm−2]]], and [log[Lbol/Lc[ cm−2]]], and [log[Lbol/Mc[ cm−2]]] for these 770 clumps are 21.61 ± 5.15, 22.37 ± 0.34, 2.87 ± 0.68, 3.50 ± 0.98, and 0.63 ± 0.33, respectively.

Figure 1 shows the distributions of Tdust, NH, Lbol, Mc, and Lbol/Mc of 1869 ATLASGAL clumps and the selected 770 COHRS sample clumps. Among the sample, the detection rate of clumps with the warm dense gas tracer CO (3–2) increases rapidly with increasing Tdust, Lbol, and Lbol/Mc, which indicates evolving star formation activity. However, Mc and NH display little change in the detection rate, which confirms that Mc and NH do not change after the evolution of the clumps has started (Urquhart et al. 2018). On the whole, the average values of Tdust, Mc, [Lbol/Lc], and NH for the 770 clumps associated with CO (3–2) are slightly larger than those of all 1869 clumps (see Table 4). Kolmogorov–Smirnov (K-S) tests for these two samples suggest that they are from different parent distributions for bolometric luminosity (statistic = 0.18, p-value ≲ 0.001; a p-value > 0.05 would indicate that two samples come from the same parent distribution), bolometric luminosity-to-mass ratio (statistic = 0.2, p-value ≲ 0.001), and dust temperature (statistic = 0.19, p-value ≲ 0.001). These results support the above idea that clumps with CO (3–2) are relatively more evolved and are currently forming stars. The relatively large p-values for the peak column density (statistic = 0.07, p-value = 0.02) and the clump mass (statistic = 0.05, p-value 0.07) indicate that these two parameters are not sensitive to the evolution of the clumps (Urquhart et al. 2018).

3. Results

3.1. Outflow Identification

The identification of outflows among the source sample has been made mainly by checking the line wings of CO (3–2) spectra and the PV diagrams with a cut along the galactic latitude and longitude. In Figure 2, the PV diagram of the source G15.558–0.462 shows clear outflow features, which determines the velocity range of the red and blue lobes. Figure 3 displays the CO (3–2) integrated intensity images of the outflow lobes in the same source, where the blue dotted and red solid contours representing the blue and red outflow lobes are overlaid onto the CO (3–2) integrated intensity image of the clump (in gray scale). Table 2 lists the contour levels for the identified outflow sources, and Table 3 lists the velocity range of the integrated emission.

A total of 157 high-mass outflows has been identified among the 770 candidate clumps, and all of their PV diagrams are displayed in the online version of Figure 2. Shepherd & Churchwell (1996b) noted that certain outflow lobes may be indistinguishable from high-velocity components of adjacent sources in the field of view. Some 39 out of 157 high-mass outflow candidates have only one clearly defined red lobe or red lobe, while the other lobe is contaminated. In addition, the red and blue lobes of nine sources overlap with each other, and 24 sources have one lobe completely missing. Therefore, we retain 85 high-mass outflows with distinct red and blue lobes that are spatially separated. Excluding one further clump without a distance estimate, further analysis in this paper
concentrates on 84 high-mass outflows. The CO (3–2) integrated intensity maps of these 84 high-mass outflows similar to Figure 3 are displayed online.

3.2. Outflow Parameters

The physical properties of the 84 outflows are calculated following the procedure of Garden et al. (1991). The total

Figure 1. Distributions of $M_{\text{clump}}$, $L_{\text{bol}}$, $L_{\text{bol}}/M_{\text{clump}}$, $N_{\text{H}_2}$, and $T_{\text{dust}}$ for the selected 770 clumps associated with detected CO (3–2) emission (yellow filled histogram) compared to the total 1869 clumps (blue filled histogram). The red filled histograms represent detection rate of clumps associated with detected CO (3–2) emission in the corresponding bin.
ET = MM t n FP t in the online journal. Emission is integrated are listed in Table 3. The centroid of the ATLASGAL contour and contour spacing are listed in Table 2. Velocities over which the linearly increase from three times the rms noise to the maximum; the minimum k column density of the outflow is obtained by summing over all spatial pixels defined by the lowest (3σ) contour. The total mass (M) of each outflow is obtained by summing over all spatial pixels defined by the lowest contour. The momentum and kinetic energy per velocity channel for each pixel in the defined outflow lobe area is computed by

\[ P_{\text{pixel}} = M_{\text{pixel}} \times \nu \]  

\[ E_{\text{pixel}} = (1/2) M_{\text{pixel}} \times \nu^2 \]

where \( \mu_{\text{H}_2} = 2.72 \) is the mean molecular weight (Brunt 2010), \( m_{\text{H}} = 1.67 \times 10^{-24} \text{ g} \) is the mass of a hydrogen atom, \([\text{CO/\text{H}_2}]\) is assumed to be \( 10^{-4} \), and \( A_{\text{pixel}} \) is the area of each pixel within the outflow lobe defined by the lowest \( (3\sigma) \) contour. The total mass (M) of each outflow is obtained by summing over all spatial pixels defined by the lowest contour. The momentum and kinetic energy per velocity channel for each pixel in the defined outflow lobe area is computed by

\[ P_{\nu,\text{pixel}} = M_{\nu,\text{pixel}} \times \nu \]  

\[ E_{\nu,\text{pixel}} = (1/2) M_{\nu,\text{pixel}} \times \nu^2 \]

where \( \nu \) is the velocity of each channel relative to the systemic velocity, and \( M_{\nu,\text{pixel}} \) corresponds to the emission in that channel. The total momentum (P) and kinetic energy (E) of each outflow are calculated by summing over all velocity channels and all spatial pixels defined by the lowest contour. Finally, the mass rate of the outflow, mechanical luminosity, and mechanical force are calculated as

\[ M_{\text{out}} = M_{\text{out}} / t_{\text{dyn}} \]  

\[ L_{\text{out}} = E_{\text{out}} / t_{\text{dyn}} \]

where \( t_{\text{dyn}} \) is the dynamical time, \( t_{\text{dyn}} = l / V \), where \( l \) is the separation between the centers of the blue and red lobes and \( V \) is the mean outflow velocity defined as \( P / M \).

As the inclination angle of the outflow cannot be easily determined, we adopted an average inclination angle of 57°3 to 59°3 to conform with similar studies (Bontemps et al. 1996). Table 3 lists the outflow mass, momentum, energy, dynamical time, mechanical force, mechanical luminosity, and mass rate of high-mass outflows. Typical values of these variables for our sample are more than two orders of magnitude larger than typical for low-mass outflows (e.g., Bachiller 1996; Bontemps et al. 1996; Hatchell et al. 2007; Bontemps et al. 2011). This is consistent with the previous result, i.e., massive star formation can drive powerful outflows (Cabrit & Bertout 1992; Shepherd & Churchwell 1996; Beuther et al. 2002; Wu et al. 2004; de Villiers et al. 2014; Yang et al. 2018). Compared with the outflows detected with the CO (1–0) and CO (2–1) lines, the CO (3–2) line wings often have a smaller spatial extent, suggesting that CO (3–2) traces the warmer gas closer to the site of massive star formation.

\[ M_{\text{pixel}} = N_{\text{tot}}^{12}\text{CO} \left[(\text{H}_2)/\text{CO}\right] \mu_{\text{H}_2} m_{\text{H}} A_{\text{pixel}}, \]  

\[ \text{where } \mu_{\text{H}_2} = 2.72 \text{ is the mean molecular weight (Brunt 2010), } m_{\text{H}} = 1.67 \times 10^{-24} \text{ g} \text{ is the mass of a hydrogen atom, } \left[\text{CO/\text{H}_2}\right] \text{ is assumed to be } 10^{-4} \text{, and } A_{\text{pixel}} \text{ is the area of each pixel within the outflow lobe defined by the lowest (3σ) contour. The total mass (M) of each outflow is obtained by summing over all spatial pixels defined by the lowest contour. The momentum and kinetic energy per velocity channel for each pixel in the defined outflow lobe area is computed by } \]

\[ P_{\nu,\text{pixel}} = M_{\nu,\text{pixel}} \times \nu \]  

\[ E_{\nu,\text{pixel}} = (1/2) M_{\nu,\text{pixel}} \times \nu^2 \]  

\[ \text{where } \nu \text{ is the velocity of each channel relative to the systemic velocity, and } M_{\nu,\text{pixel}} \text{ corresponds to the emission in that channel. The total momentum (P) and kinetic energy (E) of each outflow are calculated by summing over all velocity channels and all spatial pixels defined by the lowest contour. Finally, the mass rate of the outflow, mechanical luminosity, and mechanical force are calculated as } \]

\[ M_{\text{out}} = M_{\text{out}} / t_{\text{dyn}} \]  

\[ L_{\text{out}} = E_{\text{out}} / t_{\text{dyn}} \]

\[ \text{where } t_{\text{dyn}} \text{ is the dynamical time, } t_{\text{dyn}} = l / V \text{, where } l \text{ is the separation between the peaks of the blue and red lobes and } V \text{ is the mean outflow velocity defined as } P / M. \]

\[ \text{As the inclination angle of the outflow cannot be easily determined, we adopted an average inclination angle of 57°3 to 59°3 to conform with similar studies (Bontemps et al. 1996). Table 3 lists the outflow mass, momentum, energy, dynamical time, mechanical force, mechanical luminosity, and mass rate of high-mass outflows. Typical values of these variables for our sample are more than two orders of magnitude larger than typical for low-mass outflows (e.g., Bachiller 1996; Bontemps et al. 1996; Hatchell et al. 2007; Bontemps et al. 2011). This is consistent with the previous result, i.e., massive star formation can drive powerful outflows (Cabrit & Bertout 1992; Shepherd & Churchwell 1996; Beuther et al. 2002; Wu et al. 2004; de Villiers et al. 2014; Yang et al. 2018). Compared with the outflows detected with the CO (1–0) and CO (2–1) lines, the CO (3–2) line wings often have a smaller spatial extent, suggesting that CO (3–2) traces the warmer gas closer to the site of massive star formation.} \]
4. Discussion

4.1. Comparison between Clumps with and without Outflows

The 770 massive clumps selected from the ATLASGAL and COHRS surveys may be divided into a sample of 157 high-mass outflow source with detected CO (3–2) emission and a sample of 613 clumps that are not. Figure 4 presents the distribution of the physical properties of the two subsamples, and the corresponding typical values are summarized in Table 4. It is evident that the clumps associated with outflows are significantly more massive, have higher column densities and temperatures, and host more luminous and evolved objects. K-S tests suggest that these two samples are significantly different from each other, which implies that clumps with more luminous and evolved central sources are much more likely to be associated with outflows than their lower-luminosity and less evolved counterparts (see also Yang et al. 2018).

4.2. Detection Rate of Outflows

The detection rate of outflow sources among massive clumps is only 20%, which is much lower than previous results, i.e., 66% (Yang et al. 2018), 66% (Maud et al. 2015), 57% (Zhang et al. 2001, 2005), and 39%–50% (Codella et al. 2004). This may be attributed to both the weaker CO (3–2) emission as compared to the other CO transitions and to the location of our sources in the inner region of the Galactic plane, where higher interstellar extinction toward the molecular ring and contamination of different velocity components along the line of sight make it difficult to detect outflows. Moreover, the internal extinction of the objects also affects these results (Zhang et al. 2001, 2005). In the same region (28° ≤ l ≤ 46° and |b| ≤ 0°25) covered by both COHRS and CHIMPS, 66 outflows may be identified in 298 clumps with CO (3–2) detected, while Yang et al. (2018) identified 187 outflows in 261 clumps with detected 12CO and C18O. A total of 36 outflows were identified by both this study and Yang et al. (2018). Taking into consideration that COHRS has a mean rms of 2 K and the CHIMPS 12CO and C18O survey has a median rms of 0.6 K, the low detection rate of outflows in our sample probably results from the lower sensitivity of COHRS.

ATLASGAL clumps were classified into four evolutionary stages by König et al. (2017) and Urquhart et al. (2018): (a) the youngest quiescent phase (a starless or pre-star phase with weak 70 μm emission), (b) protostellar (clumps with weak mid-infrared 24 μm emission but far-infrared bright), (c) YSO-forming clumps (bright mid-infrared 24 μm emission), and (d) MSF clumps (radio-bright H II regions, massive YSOs, and methanol masers), some of which were identified as H II regions using Kalcheva et al. (2018). Among our 770 clumps, there are 19 quiescent clumps, 93 protostellar clumps, 386 YSO-forming clumps, 269 MSF clumps, and 3 clumps that have not yet been classified. Outflows were identified in 5 quiescent clumps (5/19 or 26%), in 7 protostellar clumps (7/93 or 8%), in 67 YSO clumps (6/386 or 17%), and in 78 MSF clumps (78/269 or 29%), respectively. The detection rate increases from protostellar sources to MSF sources. However, the detection rate of 26% for the quiescent stage is higher than for the protostellar and YSO stages, which may be unreliable considering that the sample of quiescent clumps is small.

Within the sample, 754 of 770 clumps with 156 of 157 outflows have measured distances, and their physical parameters have been obtained from Urquhart et al. (2018). The detection rate is displayed in Figure 5 as a function of clump mass, bolometric luminosity, luminosity-to-mass ratio, peak H2 column density of the clumps (N(H2)), and dust temperature. The outflow detection rate increases with Mclump, Lbol, Lbol/Mclump, and N(H2), and increases to 56% when N(H2) > 1023 cm−2. These results indicate that more massive, more luminous, denser, and more evolved sources show a higher outflow detection rate, which agrees with the 12CO results of Yang et al. (2018). The detection rate as a function of dust temperature also shows a similar variation. Urquhart et al. (2018) found that dust temperatures, bolometric luminosities, and Lbol/Mclump ratios increase with advancing evolutionary stage. These results suggest that also outflow detection rates increase with advancing evolutionary stage.

4.3. Comparison of Outflow Parameters to Clump Properties

A strong correlation is found between the outflow mass and the clump mass for our 84 high-mass outflows (see Figure 6), showing a best-fit power-law of Mout ∝ Mclump0.07, which is consistent with previous results (Beuther et al. 2002; López-Sepulcre et al. 2009; Sánchez-Monge et al. 2013; de Villiers et al. 2014; Yang et al. 2018). The ratio Mout/Mclump ranges from 0.004 to 0.296 with an average value of 0.06, and only 2 of 84 sources are below this range. Approximately 6% of the core gas is entrained in the molecular outflow, which is comparable to the entrainment ratio of 4% given by Beuther et al. (2002) and 5% by Yang et al. (2018).

In Figure 7, the outflow mass-loss rate Mout has been plotted against Mclump, Lbol, Tdust, and N(H2), and although the dispersion in the data is relatively large, a clear positive trend may be
Figure 4. Histograms of the cloud sample indicators. The blue histogram boxes are for the current sample of 157 outflow sources among the CO (3–2) sample, and the gray histogram boxes are for the nonoutflow sample of 613 sources. Top left to bottom left: logarithmic distributions of the clump mass, bolometric luminosity, luminosity-to-mass ratio, peak H$_2$ column density, and dust temperature. The bin size is 0.5, 0.5, 0.3, 0.2, and 0.08 dex from top left to bottom left.
Table 4
Summary of Physical Parameters of Clumps and Outflows

| Parameter | Mean ± std | Median | Min | Max |
|-----------|------------|--------|-----|-----|
| \( T_{\text{dust}}(K) \) | 19.5 ± 5.5 | 19.0  | 7.9 | 56.1 |
| \( \log(M_{\text{clump}}(M_\odot)) \) | 2.83 ± 0.61 | 2.85 | −0.40 | 5.04 |
| \( \log(L_{\text{bol}}(L_\odot)) \) | 3.10 ± 1.00 | 3.06 | 0.30 | 6.91 |
| \( \log(L_{\text{out}}/M_{\text{clump}}(L_\odot)/M_\odot)) \) | 0.27 ± 0.79 | 0.30 | −2.40 | 2.83 |
| \( \log(N_{\text{HI}}(\text{cm}^{-2})) \) | 22.34 ± 0.28 | 22.30 | 21.60 | 23.92 |

| Parameter | Mean ± std | Median | Min | Max |
|-----------|------------|--------|-----|-----|
| \( T_{\text{dust}}(K) \) | 21.6 ± 5.2 | 21.2 | 9.7 | 46.4 |
| \( \log(M_{\text{clump}}(M_\odot)) \) | 2.87 ± 0.68 | 2.90 | −0.30 | 5.04 |
| \( \log(L_{\text{bol}}(L_\odot)) \) | 3.50 ± 0.98 | 3.49 | 0.46 | 6.91 |
| \( \log(L_{\text{out}}/M_{\text{clump}}(L_\odot)/M_\odot)) \) | 0.63 ± 0.65 | 0.68 | −1.42 | 2.53 |
| \( \log(N_{\text{HI}}(\text{cm}^{-2})) \) | 22.37 ± 0.34 | 22.31 | 21.76 | 23.92 |
| Distance(kpc) | 6.5 | 5.9 | 1.3 | 15.4 |

| Parameter | Mean ± std | Median | Min | Max |
|-----------|------------|--------|-----|-----|
| \( T_{\text{dust}}(K) \) | 23.1 ± 5.1 | 22.6 | 10.7 | 37.0 |
| \( \log(M_{\text{clump}}(M_\odot)) \) | 3.06 ± 0.64 | 3.12 | 1.15 | 5.04 |
| \( \log(L_{\text{bol}}(L_\odot)) \) | 3.91 ± 1.03 | 3.89 | 1.71 | 6.91 |
| \( \log(L_{\text{out}}/M_{\text{clump}}(L_\odot)/M_\odot)) \) | 0.84 ± 0.61 | 0.89 | −1.11 | 2.19 |
| \( \log(N_{\text{HI}}(\text{cm}^{-2})) \) | 22.55 ± 0.40 | 55.51 | 21.88 | 23.92 |
| Distance(kpc) | 6.4 | 5.4 | 0.3 | 15.9 |

Outflow Properties for 84 Clumps with Further Analysis

| Parameter | Mean ± std | Median | Min | Max |
|-----------|------------|--------|-----|-----|
| \( M_{\text{out}}(M_\odot) \) | 140.18 ± 211.05 | 54.72 | 0.69 | 1040.29 |
| \( \rho(10 M_\odot \text{ km s}^{-1}) \) | 163.52 ± 288.12 | 43.20 | 0.36 | 1614.77 |
| \( E(10^{45} \text{erg}) \) | 212.52 ± 425.34 | 35.67 | 0.19 | 2499.60 |
| \( t(10^6 \text{year}) \) | 7.91 ± 6.76 | 5.58 | 0.81 | 32.39 |
| \( M_{\text{out}}(10^{-4} M_\odot \text{ yr}^{-1}) \) | 32.17 ± 67.96 | 8.73 | 0.23 | 490.88 |
| \( F_{\text{out}}(10^{-4} M_\odot \text{ km s}^{-1} \text{ yr}^{-1}) \) | 38.07 ± 92.49 | 6.94 | 0.11 | 677.99 |
| \( L_{\text{out}}(L_\odot) \) | 46.65 ± 129.98 | 5.17 | 0.05 | 931.07 |

Note. The physical parameters of clumps derive from Urquhart et al. (2018). We list the mean ± standard deviation, median, minimum, maximum values of these parameters for each subsample in Columns (2)–(5).

found in all cases. The correlation between the outflow mass-loss rate and the dust temperature will even be stronger if the two quiescent points on the left in panel (c) are ignored. On the other hand, if the MSF clumps are removed in panel (d), the dispersion of the clump distribution will increase and there would barely be any correlation. Our results indicate that \( M_{\text{out}} \) also increases with dust temperature (Figure 7(c)), suggesting that clumps with a higher outflow mass-loss rate are also at a more evolved stage, which confirms the findings of Urquhart et al. (2018) that the dust temperatures may increase with advancing evolutionary stage.

More massive clumps with higher luminosity and higher column density (\( N_{\text{HI}} \)) are the hosts of protostars with a higher outflow mass-loss rate (\( M_{\text{out}} \)). Furthermore, the relationship between outflow mass-loss rate and accretion rate of \( M_{\text{acc}} \sim M_{\text{out}}/6 \) (Beuther et al. 2002; de Villiers et al. 2014) would indicate that more massive clumps with higher column densities increase their mass more rapidly and form H II regions much more rapidly than clumps with lower mass and lower column density (McKee & Tan 2003; de Villiers et al. 2014; Urquhart et al. 2014). The above results suggest that the clumps with outflows having a higher \( M_{\text{out}} \) are in advanced evolutionary stages. With a mean outflow mass-loss rate of \( 3.2 \times 10^{-3} M_\odot \text{ yr}^{-1} \) for our sample, the mean mass accretion rate would be \( 5.4 \times 10^{-4} M_\odot \text{ yr}^{-1} \).

The outflow force \( F_{\text{out}} \) for our high-mass outflows has been plotted against the bolometric luminosity in Figure 8, together with low-mass bipolar outflow sources from the literature (Bontemps et al. 1996). For consistency, all outflow mechanical force values have been inclination-corrected using a factor derived for the mean inclination angle of 57°3. The outflow force \( F_{\text{out}} \) for all low-mass and high-mass sources lies well above the radiative force line, \( F = L_{\text{bol}}/c \), and increases systematically with increasing bolometric luminosity as
Separate linear fits for the low-mass and high-mass outflows give a slight difference in slopes of 0.65 and 0.58, which is smaller than those for the sample of Yang et al. (2018). On the other hand, the slopes for our sample sources below and above $L_{bol} = L_{104}$ are significantly different at 0.42 and 0.71. However, our source sample is sensitivity limited and is increasingly incomplete for $L_{bol} < L_{104}$ as can also be deduced from Figure 1. Therefore, the shallower fit for the high-mass sources in that range remains misleading until the sample is augmented.

The systematic increase of the outflow force $F_{out}$ with increasing bolometric luminosity and the similar fits for the low-mass sources and the high-mass sources with $L_{bol} < 10^4L_\odot$ would suggest that the launching mechanism outflows are similar for all sources. On the other hand, the spread in data points is also too large to discern any differences in the $F_{out}-L_{bol}$ relation for sources at different $L_{bol}$. Taking the (misleading) slope for sources at face value would also be inconsistent with the expectation that the conditions would be different for the highest-mass sources.

Alternatively, in high-mass sources in denser groups and clusters, the stars would increase faster in mass and form HII regions much more quickly than in lower-density regions (McKee & Tan 2003; de Villiers et al. 2014; Urquhart et al. 2014). Similarly, they would produce a collective outflow and increase the effective opening angle of this (chaotic) outflow, leading to feedback, the destruction of outflow signatures, and momentum loss that would give a shallower $F_{out}-L_{bol}$ relation (Peters et al. 2014; Bally 2016; Goddi et al. 2018).

On the other hand, stellar winds of massive stars and UV radiation fields from HII regions will push circumstellar material and impede the formation of other cluster members (Bally 2016). In Figure 8, the few sources with HII regions show a steeper slope, indicating more outflow power. Maud et al. (2015) suggest that low/intermediate-mass protoclusters can explain single outflows from cores with $L < 6400 L_\odot$, and that the most massive protostars in cores with higher luminosities dominate over the outflows and persist powering outflows. N-body interactions (i.e., coupled magnetic field; Moscadelli et al. 2016) may also be a dominant effect in massive star formation, resulting in a larger dispersion for the outflow parameters during the YSO stage (Reipurth 2000; Reipurth & Mikkola 2012).

Any differences in the slopes of the $F_{out}-L_{bol}$ relation may thus reveal differences in the star formation processes in...
clusters and dense groups, or alternatively suggest a different formation mechanism.

5. Summary

A search for outflows has been conducted toward 770 ATLASGAL clumps located in the region covered by COHRS with detected CO (3–2) emission and satisfying the conditions for forming massive stars.

1. A total of 157 high-mass outflows have been identified within the complete sample with a detection rate of 20%, and the properties of 84 outflows with well-defined bipolar outflows and reliable distances have been calculated and considered for further study. This low detection rate is likely due to interstellar extinction and internal absorption of the objects, contamination of CO emission from the Galactic molecular ring, and a lower signal strength of the CO (3–2) line relative to lower-excitation lines used in other surveys.

2. Outflows were identified in 7 quiescent clumps (5/19 or 26%), in 7 protostellar clumps (7/93 or 8%), in 67 YSO clumps (67/386 or 17%), and in 78 MSF clumps (78/269 or 29%), respectively. The detection rate 26% for quiescent clumps is very preliminary because of the small sample size.

3. The clumps with outflows have higher values for $M_{\text{clump}}$, $L_{\text{bol}}$, $L_{\text{bol}}/M_{\text{clump}}$, $N_{\text{H}_2}$, and $T_{\text{dust}}$ compared to clumps with no outflow, and also the detection rate increases with increasing values for these parameters, in agreement with Yang et al. (2018).

4. A statistical relation between the outflow mass and the clump masses for our sample is $\log(M_{\text{out}}/M_\odot) = (-1.1 \pm 0.21) + (0.9 \pm 0.07)\log(M_{\text{clump}}/M_\odot)$. This relation is in agreement, within uncertainties, with earlier
Figure 8. Outflow force vs. the bolometric luminosity of the central sources. The black stars represent low-mass outflow sources from Bontemps et al. (1996). The red circles and blue squares represent our outflow sample with \( L_{\text{bol}} < 10^4 L_\odot \) and \( L_{\text{bol}} > 10^4 L_\odot \), respectively. The blue squares with a black cross indicate MSF clumps with an \( \text{H}_\text{II} \) region. The black solid line (\( \log F_{\text{out}} = -4.90 + 0.70 \log(L_{\text{bol}}) \)) represents the best fit to all outflow sources. The blue dashed line (\( \log F_{\text{out}} = -5.04 + 0.65 \log(L_{\text{bol}}) \)) indicates the best fit to low-mass outflows (Bontemps et al. 1996). The red dashed line (\( \log F_{\text{out}} = -4.47 + 0.58 \log(L_{\text{bol}}) \)) denotes the best fit for all massive outflows in our study. The blue dotted line (\( \log F_{\text{out}} = -3.98 + 0.42 \log(L_{\text{bol}}) \)) and red dotted line (\( \log F_{\text{out}} = -5.07 + 0.71 \log(L_{\text{bol}}) \)) show the best fit to our outflow sample with \( L_{\text{bol}} < 10^4 L_\odot \) and \( L_{\text{bol}} > 10^4 L_\odot \), respectively. The black dotted line (\( \log F_{\text{out}} = -6.12 + 0.88 \log(L_{\text{bol}}) \)) is the best fit for MSF clumps with \( \text{H}_\text{II} \) regions. The red solid line represents \( F = L_{\text{bol}}/c_\text{s} \).

5. The mass-loss rate of the outflows shows an increase with increasing \( M_{\text{clump}}, L_{\text{bol}}, N_{\text{H}2}, \) and \( T_{\text{dust}} \). This indicates that the clumps with outflow with higher values for these parameters are at advanced evolutionary stages.

6. The mechanical outflow force \( F_{\text{out}} \) increases systematically with increasing bolometric luminosity as \( \log F_{\text{out}} = -4.90 + 0.70 \log(L_{\text{bol}}) \). Sectional fitting also shows that the relations for low-mass sources and for higher-mass sources are very similar. This suggests that the sources along the whole range of \( L_{\text{bol}} \) have the same launching mechanisms, and there is no evidence yet that cluster and dense groups deviate from this relation.

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