The winds from HL Tau

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ABSTRACT
Outflowing motions, whether a wind launched from the disc, a jet launched from the protostar, or the entrained molecular outflow, appear to be a ubiquitous feature of star formation. These outwards motions have a number of root causes, and how they manifest is intricately linked to their environment as well as the process of star formation itself. Using the Atacama Large Millimeter/submillimeter Array (ALMA) Science Verification data of HL Tau, we investigate the high-velocity molecular gas being removed from the system as a result of the star formation process. We aim to place these motions in context with the optically detected jet, and the disc. With these high-resolution (∼1 arcsec) ALMA observations of CO (J=1−0), we quantify the outwards motions of the molecular gas. We find evidence for a bipolar outwards flow, with an opening angle, as measured in the redshifted lobe, starting off at 90°, and narrowing to 60° further from the disc, likely because of magnetic collimation. Its outwards velocity, corrected for inclination angle is of the order of 2.4 km s⁻¹.

Key words: techniques: interferometric – stars: formation – stars: winds, outflows – ISM: jets and outflows – submillimetre: ISM.

1 INTRODUCTION
Protostars accrete mass through discs, and as material moves inwards through the disc, angular momentum builds up. Without a mechanism to release this buildup of angular momentum, accretion would halt, as material reaches escape velocities. There are a number of mechanisms for dispersing angular momentum, including the launching of winds, outflows and jets. They allow the remaining material to continue moving through the disc, eventually getting to the inner edge, and becoming available for accretion by the star. All three of these large-scale phenomena are intrinsically linked with each other (see for example, Panoglou et al. 2012). Jets are generally observed in high energy, ionized (optical) tracers and in radio continuum emission. They are often associated with Herbig–Haro objects and show knotty or turbulent structures. Highly collimated, high-velocity jets are thought to entrain surrounding material forming molecular outflows, while winds are thought to be lifted directly from the disc, with the suggestion that the jets may be collimated by the wider angle magnetohydrodynamic disc winds (e.g. Frank et al. 2014). These phenomena exhibit different properties from each other (e.g. in terms of collimation, gas velocities), however the terms ‘wind’ and ‘outflow’ are often used interchangeably since their observed properties are inherently similar (e.g. they can be detected in the same tracers).

Winds, being launched from the disc, come in two forms; photoevaporative flows and molecular disc winds. The former is caused by the forming star photoionizing the disc surface (e.g. Alexander, Clarke & Pringle 2006), at which point highly energetic particles whose velocity exceeds the escape velocity will leave the system. These flows have velocities of >10 km s⁻¹ and are seen in ionized atomic species. The later, molecular disc winds, are launched from magnetic foot points within the disc, and are collimated by the magnetic field (e.g. Pudritz & Ouyed 1997). They are a key mechanism for releasing angular momentum, and have been seen in molecular CO (e.g. Klaassen et al. 2013). Molecular disc winds can self-shield such that the wind gas remains cool and thus molecular (e.g. Panoglou et al. 2012).

Outflows, generally traced with molecular line emission in the (sub-)mm, highlight the interaction between a jet/wind and its environment: as the jet or wind pushes through the ambient material, it entrains a portion of that material (through processes such as turbulence and viscosity), accelerating it to higher velocities. Because outflows trace entrained material, their flow speeds tend to be lower, and their opening angles tend to be larger than those of jets or winds. We use the term ‘outflowing material’ to describe the generalized molecular gas moving away from the disc, regardless of whether it is in a wind or an outflow.

HL Tau is an interesting region for testing the interconnectedness of these phenomena as both atomic jets (e.g. detected in Hα, Krist et al. 2008) and molecular outflows (e.g. Lumbreras & Zapata 2014) have previously been observed. HL Tau, at a distance of 140 pc (Kwon, Looney & Mundy 2011), is a young protostar of between 0.55 and 1.3 M☉ (Stephens et al. 2014; Atacama Large Millimeter/submillimeter Array (ALMA) Partnership et al. 2015).
Using Near-IR polarimetry measurements, Lucas et al. (2004) found a strongly twisted magnetic field surrounding the disc in HL Tau. They attributed the twisting to the wind from the protostar. They were unable to measure the field of the disc itself due to the high levels of extinction. Stephens et al. (2014) measured the magnetic field in the disc and found it to be dominated by a toroidal magnetic field component. They found that its structure is not consistent with either completely toroidal or completely vertical structures; the field morphology must come from a combination of these structures.

The collimated Hα jet emission appears to be concentrated in the blueshifted lobe, which hosts a poorly collimated blueshifted molecular outflow. The [S ii] emission from the jet is seen in both the red and blue lobes (Mundt et al. 1990). Takami et al. (2007) showed that the 1.64 μm continuum emission of HL Tau exhibits a cross pattern with symmetric red and blue components on 1 arcsec scales, suggesting that the outflow is symmetric across the disc axis. They also detect a collimated jet in [Fe ii] distinct from this outflow.

The blue jet coming from HL Tau (HH 151) was first detected in the early 1980s (Mundt & Fried 1983), and curiously: (1) only becomes bright in Hα 20 arcsec from the powering source, and (2) appears at an angle to its expected direction; its observable base is along the disc axis, however from there it proceeds away from the disc at an angle. These two properties of the jet are generally ascribed to interaction with the wind from XZ Tau (e.g. Movsessian, Magakian & Moiseev 2012), because these two forming stars are indeed spatially co-located (not just projected to be close on the sky). The base of the elongated Hα emission is coincident with the [S ii] jet emission (Mundt et al. 1990), and the kink in the Hα emission can be seen in their fig. 4.

The high-velocity sub-mm emission in this region was most recently presented by Lumbreras & Zapata (2014) at a resolution of ~2 arcsec, showing collimated redshifted and blueshifted outflowing material in CO. However, these two lobes are not aligned in a classical bi-polar fashion, with the blueshifted lobe offset from the line connecting the blueshifted (optical) jet, and redshifted emission. Lower resolution CO observations (Welch et al. 2000) show that this emission is at the edge of a ‘bubble’ of blueshifted emission and likely interacting with XZ Tau, which is located within, and powering, the bubble. It should be noted that XZ Tau is thought to be a triple system (Carrasco-González et al. 2009) with two of the components being M3 and M2 Classical T-Tauri stars (Krist et al. 2008).

In this paper, we present an analysis of the ALMA Science Verification data of CO (J=1−0) taken as part of the long baseline campaign in 2014. In Section 2, we present a brief overview of the observations, in Section 3 we present the images of the largest scale CO emission recovered in these observations, highlighting the wind and outflow components. In Section 4, we analyse these results, de-project the wind velocities and constrain the wind launch radius. In Section 5, we summarize our findings.

2 OBSERVATIONS

The observations presented here come from the ALMA archive, and were taken as part of the ALMA Science Verification, long baseline campaign (project 2011.0.00015.SV). The integration times, calibrators (and their purposes), observing date and minimum and maximum baseline lengths used in each of the executions contained in this set of observations are listed in Table 1, in which each execution is identified by the last four characters of the filename given in the ALMA archive. Details about the data, and reduction can be found in ALMA Partnership et al. (2015).

We used unmodified versions of the released reference images of the Band 3 continuum and CO emission. The released spectral line data were tapered to highlight the larger scale structures, which results in a larger synthesized beam. The beam sizes and rms noise limits for the data sets are given in Table 2. Data were imaged and analysed in CASA (McMullin et al. 2007).

These observations were not designed to recover the large-scale outflowing gas, thus much of the emission has been filtered out. The shortest baselines were 15.5 m, which means the largest angular scale to which these observations could be sensitive is approximately 41 arcsec. This corresponds to approximately 77 per cent of the band 3 primary beam (53 arcsec).

Comparing our CO observations to those of Welch et al. (2000) from Berkeley-Illinois-Maryland Association (BIMA) telescope at a resolution of ~7 arcsec shows that much of the CO emission in the blueshifted emission is likely filtered out of our observations; their structures are much larger (~2.5 arcmin) than those seen with these ALMA observations. In terms of the redshifted emission lobe, the size and shape of their recovered structures (see their fig. 2) are consistent with those seen with ALMA. Because their observations are in 13CO (J=1−0), there are too many uncertainties (including an isotope ratio) to quantify the amount of missing flux in our 12CO (J=1−0) observations.

2.1 Other archival data

In addition to the ALMA Science Verification data, we make use of archival Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) data for this region, showing the Hα and [N ii] image first presented in Krist et al. (2008).

3 RESULTS

Here, we present the outflowing molecular gas properties, highlighting the morphological properties of the red (Section 3.1) and blue (Section 3.2) emission and the opening angle of the red component of the flow (Section 3.3). We further calculate the flow kinematics inferred from the emission and its velocity structure, making use of the known inclination angle on the sky (Section 3.4).

For our analysis, we have made extensive use of integrated intensity (zeroth moment), and intensity weighted velocity (first moment) maps of the CO emission. These maps were clipped at 3σ and 5σ, respectively, using the noise level quoted in Table 2 and were integrated over the velocity ranges of 0–5.5 km s~1 and 7–20 km s~1, respectively, for the blueshifted and redshifted emission. We note that the spatial extent of the redshifted emission detected in these observations is consistent with that of Lumbreras & Zapata (2014) observed with the Submillimeter Array (SMA). To clarify, what Lumbreras & Zapata (2014) call a ‘wide-angle outflow’, we discuss as an ‘outflow entrained by a wide-angle wind’ (which we shorten to ‘flow’), to be more consistent with the terminology in Arce et al. (2007).

Fig. 1 shows the first moment map of the CO emission, highlighting the positions of the redshifted and blueshifted emission lobes. The colour scale shows the velocities of the outflowing material in CO. This map already shows the complex morphology of the CO emission. It highlights the sharp transition between red and blue emission, and that redshifted emission is present towards the
Table 1. Calibrators and observing parameters.

| Execution | Time on science source (min) | Phase | Calibrators bandpass | Flux | Observing date | Baseline lengths Max (m) Min (m) |
|-----------|------------------------------|-------|----------------------|------|----------------|----------------------------------|
| X5fa      | 30                           | J0431+2037 | J0510+1800          | J0510+1800 | 2014-10-28 | 15 238 15.5                      |
| X845      | 30                           | J0431+2037 | J0423—0120          | J0510+1800 | 2014-10-28 | 15 238 15.5                      |
| X3b2      | 20                           | J0431+2037 | J0510+1800          | J0423—0120 | 2014-11-11 | 15 238 15.5                      |
| X220      | 21                           | J0431+2037 | J0423—0120          | J0510+1800 | 2014-11-13 | 15 238 15.2                      |
| X693      | 30                           | J0431+2037 | J0423—0120          | J0510+1800 | 2014-11-11 | 15 238 15.5                      |
| X5b2      | 30                           | J0431+2037 | J0510+1800          | J0423—0120 | 2014-11-14 | 15 238 15.2                      |

Table 2. Properties of the ALMA observations used in this study.

| Species (incl. transition) | Frequency (GHz) | Synthesized beam \( B_{\text{maj}} \times B_{\text{min}} \) (arcsec) \( B_{\text{pa}} \) (°) | rms noise |
|---------------------------|-----------------|-------------------------------------------------|-----------|
| CO \((J=1-0)\)             | 115.271         | 0.98 × 0.90                                     | 8.1       |
| Continuum                 | 115.136         | 0.09 × 0.06                                     | 0.01      |

Note. rms noise levels have units of mJy beam\(^{-1}\) per 1 km s\(^{-1}\) channel for the CO line emission, and mJy beam\(^{-1}\) for the continuum.

Figure 1. First moment map of the CO emission from HL Tau (cut at 10σ, integrating over 0–20 km s\(^{-1}\)). The black contours show the 5σ to 25σ levels of the continuum emission to highlight the position of the disc. Note that the emission (CO and continuum) at the left edge of the map is that from XZ Tau, as indicated. The green lines through the red lobe correspond to the white lines in Fig. 2, which are then transposed on to the blue lobe.

3.1 Redshifted emission

Because the redshifted lobe appears to be limb brightened (the edges of the outflow appear to have the greatest intensities, see Fig. 2), it is likely that the red emission is primarily coming from the conical edges of a flow, possibly with an excavated central cavity. The red outflowing material has an ‘hourglass’ morphology which could be suggestive of magnetic collimation (see for instance Stephens et al.

3.2 Blueshifted emission

Fig. 3 shows the moment maps of the blueshifted CO emission. The brightest blueshifted emission comes from quite near the disc, where the H\(\alpha\) emission is strongest as well. As can be seen in Fig. 4, towards the centre of the flow axis (which arises between the two peaks in the blueshifted material, and is labelled as ‘Jet’), there is a small jet-like structure protruding from the H\(\alpha\) emission.

The blueshifted emission is not as collimated as the red, probably due to a combination of effects including the interaction with the XZ Tau bubble (which is expanding within the blueshifted CO emission from HL Tau, see for instance Welch et al. 2000).

3.3 Opening angle

The left-hand panel of Fig. 2 shows the opening angle of the redshifted flow. Its morphology can be decomposed into two components: one with a small-scale opening angle of 90°, and a larger scale (collimated) opening angle of 60°. This hourglass morphology could be due to magnetic collimation, like is the case for L1157-mm (Stephens et al. 2013). The magnetic field directions found by Lucas et al. (2004) and Stephens et al. (2014) are suggestive of field orientations which could collimate the flow. Under the assumption...
Figure 3. Blueshifted CO moment maps integrated over 0–5.5 km s\(^{-1}\). Note that both the integrated intensity and intensity weighted velocity increase significantly towards the centre (northern edge) of the blueshifted emission. This is likely due to interaction with the jet (not plotted).

Figure 4. Blueshifted wind (blue contours, starting at 15 per cent of the peak intensity, increasing in levels of 10 per cent), overlaid on HST ACS grey-scale image of a combination of H\(\alpha\) and [N ii].

that we are not observing a special orientation on the sky, we expect this limb brightened morphology to be representative of a conical morphology in 3D.

Additionally, we note that the 60\(^\circ\) lines from Fig. 2 are drawn in Figs 1 (in green) and 7 (in white) to help guide the eye in these plots. Note that in these two figures, the lines have been transposed onto the blue emission as well.

3.4 Flow energetics

From the line wing CO emission, we quantified the mass, momentum and energy in the flow. The intensity in each velocity channel was summed, and/or multiplied by the velocity of that channel to determine the mass (\(M \propto \int T dv\)), momentum (\(P \propto M \times v\)) and energy (\(E \propto M \times v^2/2\)). Here, we assume the CO is optically thin, and that there is likely missing flux from the largest scale structures in these data, therefore our column density and mass estimates are lower limits. Using the extent of the red flow (20 arcsec), and the maximum velocity of the redshifted emission (5 km s\(^{-1}\)), we estimate a kinematic age of approximately 2600 yr, with which we quantify the mechanical luminosity (\(L = E/\dot{t}\)), and mass-loss rate (\(M = \dot{M}/\dot{t}\)) of the flow. We note that this is an extreme lower limit to the age of the flow. The constants of proportionality in the first few equations are related to the abundance of CO (taken to be 1 \times 10\(^{-4}\)), the ambient temperature (\(T = 50\) K) and a multiplicative constant for CO related to the energy of the J=1\(\rightarrow\)0 transition, the partition function, and the degeneracy of the state (see Appendix A2). We note that since the inclination angle of the flow is known (see Section 4.1), the velocities used in the calculation have been corrected for inclination, and the results are given in Table 3. Changing our assumed temperature by 20 K up or down changes our mass estimates by \(\sim\)35 per cent. We note that our derived outflowing gas mass is approximately half that found in Lumbreras & Zapata (2014), while our momentum and kinetic energies are <10 per cent of their values. The mass comparison gives an estimate of our missing flux, since we used the same local thermodynamic equilibrium (LTE) (\(T = 50\) K) assumption. Without knowing their velocity integration methods or limits, we cannot comment on the discrepancies between the momentum and energy calculations.

4 DISCUSSION

4.1 Flow inclination angle

As discussed in Section 3.3, and shown in the left-hand panel of Fig. 2, the flow has an opening angle of \(\sim\)90\(^\circ\) at its base. We analyse this opening angle using the assumption of conical symmetry about the flow axis. This assumption is supported by the observation that the flow is limb brightened (left-hand panel of Fig. 2).

ALMA Partnership et al. (2015) fit the \(uv\) plane visibilities of the dust continuum emission, and found an inclination angle of 46\(^\circ\) \pm\) 0.2 for the disc in the plane of the sky. If the flow axis is perpendicular to the disc axis, then it should have an inclination angle of 44\(^\circ\) with respect to the line of sight. This, coupled with the flow opening angle of 90\(^\circ\) suggests part of each wind lobe should exhibit some ‘counter-flow’ emission, i.e. emission within a certain lobe that, due to the large opening angle, has crossed the plane of the sky and therefore appears to be flowing in the opposite direction. As shown in the cartoon of Fig. 5, there should be a small portion of the blue flow which has red velocities – labelled as ‘rs’ (redshifted) blue’. Similarly for the red flow, there is a small component labelled ‘bs (blueshifted) red’. These ‘counter-flows’, because they are close the plane of the sky, will have very small line-of-sight velocities.

Table 3. Derived flow kinematics (assuming a kinematic age of 2650 yr).

| Quantity | Units | Red | Blue |
|----------|-------|-----|------|
| Mass     | \((\times 10^{-4} M_\odot)\) | 0.73 \pm 0.00 | 11.14 \pm 0.00 |
| Momentum | \((\times 10^{-4} M_\odot \, \text{km s}^{-1})\) | 2.21 \pm 0.05 | 14.77 \pm 0.51 |
| Energy   | \((\times 10^{45} \text{erg})\) | 1.52 \pm 0.05 | 4.74 \pm 0.25 |
| Luminosity | \((\times 10^{-4} L_\odot)\) | 4.72 \pm 0.15 | 14.70 \pm 0.76 |
| Mass-loss | \((\times 10^{-8} M_\odot \, \text{yr}^{-1})\) | 2.73 \pm 0.00 | 41.96 \pm 0.00 |
| Velocity integration limits | 9 \sim 20 | -4 \sim 6 |

Note: The uncertainties on the mass and mass outflow rates are smaller than the precisions listed here. The method for calculating these uncertainties is presented in Section A2, which takes into account the rms noise of the observations, but not things like CO opacity or abundance and ambient temperature assumptions.
The Winds from HL Tau

Figure 5. Cartoon of the relationship between the flow, its 90° opening angle at the base, and the inclination angle of the disc (which is assumed to be perpendicular to the outflow). This representation explains why there is blueshifted emission coincident with the red flow, and redshifted emission coincident with the blue flow.

Figure 6. Channel map of the CO emission from 4 to 10 km s\(^{-1}\). Note that there is very little emission detected at the systemic velocity (~6.5 km s\(^{-1}\)), which may be due to filtering. The integrated intensities of the blueshifted and redshifted emission are shown as contours (from 10 per cent to 70 per cent of the peak intensity) in the two channels at 5.5 and 7.5 km s\(^{-1}\), where the counter-flow emission is strongest. The intensity contours are taken over the same velocity intervals as the moment 0 maps shown in Figs 2 and 3. These ‘rs blue’ and ‘bs red’ counter flows are highlighted in the channel maps of Fig. 6 in the 5.5 and 7.5 km s\(^{-1}\) channels. In these two channels, the integrated emission of the blueshifted and redshifted winds is overplotted (respectively) with blue and red contours. This is to demonstrate where the blue and red wind lobes are, and highlight that there is additional emission in these channels spatially co-incident with the opposite wind lobe. The ‘counter-flow’ emission components at 5.5 and 7.5 km s\(^{-1}\) are also shown in Fig. 7 as blue and red contours (respectively). Fig. 8 shows the overlap in redshifted and blueshifted emission in the, respectively, ‘other’ side of the flow. The red contours consist of redshifted emission at 7.5 km s\(^{-1}\), while the blue contours show blueshifted emission at 5.5 km s\(^{-1}\). The labels show the predominant flow velocity within each cone; opposite to the low-velocity contamination shown here. The contours cover 10σ–15σ in 1σ steps. Note that the bulk of the outflow material is not captured in these two channels, but exists at higher velocities from systemic (6–7 km s\(^{-1}\)). The white lines correspond to the green ones in Fig. 1, and cross at the position of the disc. The background grey-scale shows the integrated intensity of the CO emission taken over the velocity range of the channel map in Fig. 6. The two ellipses used in Fig. 8 come from regions of high ‘contamination’ of red/blue emission within the two yellow circles shown here.

Figure 7. Spectra taken from two regions within the blueshifted (blue line) and redshifted (red line) portions of the wind, where contamination from gas at the opposite velocities is strongest. The black vertical line represents the LSR velocity (6.5 km s\(^{-1}\)) suggested by ALMA Partnership et al. (2015). CO spectra within the two black circles in Fig. 7 to highlight that there is significant ‘counter-flow’ emission at these positions. Note that these circles were chosen a few arcsec from the disc to avoid contamination from the rotationally symmetric disc emission. This shows that there is ‘rs blue’ and ‘bs red’ emission in this flow, which confirms that the opening angle is large, and that the flow is indeed perpendicular to the disc, as expected.
With the inclination angle known (with respect to the plane of the sky), the line-of-sight velocities of the red and blue emission known, and the opening angle of the cone assumed to be circularly symmetric (i.e. the opening angle measured in Fig. 2 is consistent along the line of sight as well), we can estimate the true velocities of the red and blue flows solving
\[
\cos(\Gamma) \times V_{\text{blue}} = V_{r} - V_{\text{LSR}} \tag{1}
\]
\[
\sin(\Gamma) \times V_{\text{blue}} = V_{b} - V_{\text{LSR}}, \tag{2}
\]
where \(V_{\text{blue}}\) is the average velocity of the blue flow, \(V_{\text{LSR}}\) is the local standard of rest (LSR) velocity, \(V_{r}\) and \(V_{b}\) are the peak velocities redshifted and blueshifted emission of the two components shown in the spectrum. Solving equation (1) for \(V_{\text{LSR}}\) and putting that into equation (2), the only unknown becomes \(V_{\text{blue}}\), since \(V_{r}\) and \(V_{b}\) can be read from Fig. 8. The same method was used to calculate the redshifted flow velocity. From these analyses, we find redshifted and blueshifted wind velocities of 2.5 and \(-2.3\) km s\(^{-1}\).

5 CONCLUSIONS
We find, and quantify, evidence for an outflow entrained from a wide-angle wind from the HL Tau system using high-resolution ALMA Science Verification observations of CO (J=1–0). We find that the wind is indeed perpendicular to the disc, and that its inclination angle (44°), combined with the wind opening angle (90°) requires the wind to cross the plane of the sky. This crossing is seen in ‘counter-flow’ emission at 5.5 and 7.5 km s\(^{-1}\). From these angles, we were able to quantify a characteristic wind velocity (\(\sim 2.4\) km s\(^{-1}\)) in both lobes.

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REFERENCES
Alexander R. D., Clarke C. J., Pringle J. E., 2006, MNRAS, 369, 216
ALMA Partnership et al., 2015, ApJ, 808, L3
Arce H. G., Shepherd D., Gueth F., Lee C.-F., Bachiller R., Rosen A., Beuther H., 2007, in Reipurth B., Jewitt D., Keil K., eds, Protostars and Planets V. Univ. Arizona Press, Tucson, AZ, p. 245
Beck T. L., Bary J. S., McGregor P. J., 2010, ApJ, 722, 1360
Carrasco-González C., Rodríguez L. F., Anglada G., Curiel S., 2009, ApJ, 693, L86
Frank A. et al., 2014, in Beuther H., Klessen R. S., Dullemond C. P., Henning T., eds, Protostars and Planets VI. Univ. Arizona Press, Tucson, AZ, p. 451
Klaassen P. D. et al., 2013, A&A, 555, A73
Krist J. E., Stapelfeldt K. R., Hester J. J., Healy K., Dwyer S. J., Gardner C. L., 2008, AJ, 136, 1980
Kwon W., Looney L. W., Mundy L. G., 2011, ApJ, 741, 3
Lucas P. W. et al., 2004, MNRAS, 352, 1347
Lumbrañas A. M., Zapata L. A., 2014, AJ, 147, 72
McMullin J. P., Waters B., Schiebel D., Young W., Golap K., 2007, in Shaw R. A., Hill F., Bell D. J., eds, ASP Conf. Ser. Vol. 376, Astronomical Data Analysis Software and Systems XVI. Astron. Soc. Pac., San Francisco, p. 127
Movsessian T. A., Magakian T. Y., Moiseev A. V., 2012, A&A, 541, A16
Mundt R., Fried J. W., 1983, ApJ, 274, L83
Mundt R., Buehrke T., Solf J., Ray T. P., Raga A. C., 1990, A&A, 232, 37
Panoglou D., Cabrit S., Pinaux des Forêts G., Garcia P. J. V., Ferreira J., Casse F., 2012, A&A, 538, 2
Padrón R. E., Ouyed R., 1997, in Reipurth B., Bertout C., Proc. IAU Symp. 182, Herbig-Haro Flows and the Birth of Stars. Kluwer, Dordrecht, p. 259
Stephens I. W. et al., 2013, ApJ, 769, L15
Stephens I. W. et al., 2014, Nat, 514, 597
Takami M., Beck T. L., Pyo T.-S., McGregor P., Davis C., 2007, ApJ, 670, L33
The Astropy Collaboration et al., 2013, A&A, 558, A33
Welch W. J., Hartmann L., Helfter T., Briceño C., 2000, ApJ, 540, 362

APPENDIX A: CALCULATING OUTFLOW MASS AND KINEMATICS
Here, we present the methods used to quantify the energetics of the outflowing molecular material from the HL Tau disc. We stress that the line emission, especially the blueshifted emission, is likely to be spatially filtered by the observations. There exist no publicly available single dish CO J=1–0 observations by which we can quantify the amount of filtered flux.

A1 Data processing
The data cube was masked at 3σ, which was internally derived using line free channels, and corresponds to the rms noise levels listed in Table 2. Within the masked data cube, using velocity limits listed in Table 3, we determined the flux in, and noted the velocity of, each channel. The measured fluxes were converted from mJy beam\(^{-1}\) km s\(^{-1}\) to K km s\(^{-1}\) using the size of the synthesized beam (0.98 arcsec × 0.9 arcsec), and observing frequency (115 GHz).

When calculating quantities from these measured intensities and velocities, we used the PYTHON package uncertainties to propagate the measured uncertainties through our calculations. This includes the uncertainty in the flux (taken as the rms noise in each channel) and velocity (taken as half the width of a velocity channel).

A2 Calculating physical quantities
With the intensities in each channel, we determined the column density in the upper state (J=1) level of CO. Then, assuming LTE and a temperature of 50 K, this was then scaled using the partition function to calculate the total column density of CO we are observing using
\[
N_{I} = \frac{8 \pi k \nu_{I}^{2}}{h c^{3}} \frac{1}{A_{10}} \int T \, dv \tag{A1}
\]
\[
N_{\text{tot}} = Z(T) \times N_{I} / (2J + 1) \times e^{-E_{J} / kT}, \tag{A2}
\]
where \(N_{I}\) is the column density in the J = 1 level, and \(A_{10}\) is the Einstein A coefficient for the J = 1–0 transition of CO. With the
assumption of LTE, we extrapolated this to the total CO column density using the second equation above, where \( Z(T) \) is the partition function, \( J \) is the upper state quantum number, and \( E_1 \) is the energy of the \( J = 1 \) state.

The column density calculated above corresponds to the column density within each velocity channel. The total column density integrated over the velocity ranges listed in Table 3, was calculated by summing the column densities in each channel.

The integrated redshifted and blueshifted masses were calculated from the column densities under the assumption of optically thin emission:

\[
M_{\text{ch}} = N_{\text{tot}} \times n_{\text{beams}} \times A_{\text{beams}} \times m_{\text{H}_2} / X,
\]

where \( n_{\text{beams}} \) is the number of beams the column density is being summed over, \( A_{\text{beams}} \) is the area of each beam (in cm\(^2\)), \( m_{\text{H}_2} \) is the mean molecular mass of hydrogen, and \( X \) is the abundance of CO, which we assume to be \( 10^{-4} \). Subsequently, we determined the total blueshifted and redshifted outflowing masses by summing over the velocities listed in Table 3.

One of the key reasons for calculating the mass in each channel independently is to best quantify the momentum and energy in the flow. For each velocity channel, we multiplied the derived mass by the LSR-corrected gas velocity \( (v_{\text{ch}} = v_{\text{means}} - v_{\text{LSR}}) \) to determine the momentum in that channel. Then, the absolute values of the momenta in each channel were summed to determine the total momentum in both the redshifted and blueshifted emission. Similarly, to determine the total outflow energy:

\[
E = \sum 0.5 \times M_{\text{ch}} \times v_{\text{ch}}^2.
\]

The outflow mechanical luminosity and mass-loss rates were determined by dividing the total outflow energy and mass (in each lobe) by the dynamical age of the outflow. This age was determined by dividing the extent of the wind by the maximum velocity of the gas in the flow. Given a wind length of 20 arcsec, and a maximum velocity of 5 km s\(^{-1}\), at a distance of 140 pc, we derive an outflow age of approximately 2650 yr.

The ‘wind length’ corresponds to the approximate ends of the redshifted emission along the limb brightened edges of the wind. For scale, 20 arcsec corresponds to the distance between the disc and the ends of the green lines in Fig. 1. This outflow age estimate is subject to a number of caveats, chief amongst which are the lack of short spacing information likely filtering out how large the outflowing material is, the possibility that the wind could be accelerating (or decelerating) with time, and there being emission at higher velocities which are not detected due to the sensitivity limits of the observations.