Resolved images of a protostellar outflow driven by an extended disk wind

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Young stars are associated with prominent outflows of molecular gas1–2. The ejection of gas is believed to remove angular momentum from the protostellar system, permitting young stars to grow by the accretion of material from the protostellar disk2. The underlying mechanism for outflow ejection is not yet understood2, but is believed to be closely linked to the protostellar disk3. Various models have been proposed to explain the outflows, differing mainly in the region where acceleration of material takes place: close to the protostar itself (‘X-wind’4,5, or stellar wind6), in a larger region throughout the protostellar disk (disk wind7–9), or at the interface between the two10. Outflow launching regions have so far been probed only by indirect extrapolation11–13 because of observational limits. Here we report resolved images of carbon monoxide towards the outflow associated with the TMC1A protostellar system. These data show that gas is ejected from a region extending up to a radial distance of 25 astronomical units from the central protostar, and that angular momentum is removed from an extended region of the disk. This demonstrates that the outflowing gas is launched by an extended disk wind from a Keplerian disk.

We obtained high-angular-resolution millimetre-wave observations of the region surrounding the protostar TMC1A using the Atacama Large Millimeter/submillimetre Array (ALMA). We observed the $J = 2–1$ rotational transition of the carbon monoxide isotopologues $^{12}$CO, $^{13}$CO, and C$^{18}$O. TMC1A is located in the Taurus Molecular Cloud (140 parsecs from Earth), and is a protostellar system with a protostar half the mass of the Sun11 moving away from the solar neighbourhood (local standard of rest) at a systemic velocity of 6.4 km s$^{-1}$. It is surrounded by a circumstellar envelope with diameter of about 10$^3$ astronomical units (AU)12, which has a disk-like structure of radius 200 AU which is inclined 55° with respect to the plane of the sky13, and has a bipolar outflow extending at least 6$\times$10$^2$ AU (ref. 16) with position angle $\sim$165° east of north. Thus far, TMC1A has been studied at spatial resolutions ranging from several thousand astronomical units down to about 100 AU and the disk is known to exhibit a Keplerian rotation profile14 at radial distances of about 60–100 AU. The outflow, directed perpendicular to the disk, is bipolar in nature, but is most prominent on the north side of the disk16–18.

The observations (see Methods) were taken at a spatial resolution of 6 AU for TMC1A and cover the inner 200 AU of the outflow as well as the disk surrounding the protostar. The $^{12}$CO channel maps in Fig. 1 reveal the walls of the outflow cavity, whereas the $^{13}$CO and C$^{18}$O emission follows the structure of the dust continuum emission (see Extended Data Fig. 1) emanating from the 0.05M$\odot$ disk14 (where M$\odot$ is the solar mass) surrounding TMC1A. A non-disk origin for $^{12}$CO is suggested by the noticeable spatial shift of the $^{12}$CO emission relative to the $^{12}$CO, C$^{18}$O, and dust continuum emission (see Methods and Extended Data Fig. 1). The morphology of the $^{12}$CO emission changes substantially with velocity and small-scale structure (knots) is visible in the maps (Fig. 1). These knots could represent density fluctuations in the flow19,20, but additional observations at multiple epochs are needed to constrain their nature. The eastern cavity wall (to the left in all figures) of the blueshifted outflow18 is detected above the 3σ level at velocities offset by more than 2 km s$^{-1}$ from the systemic velocity, and it is clearly offset from the disk and central outflow axes indicated by the dashed lines (Fig. 1). It extends to vertical distances of more than 100 AU from the disk plane, and its direction is consistent with lower-resolution observations of TMC1A tracing 1,000–5,000 AU scales16. The western cavity wall of the red-shifted outflow is also detected, but at lower velocities compared to the source velocity and at a low signal-to-noise ratio. The northwestern and southeastern cavity walls are not detected, which implies that the radial velocities of these two components coincide with the velocity of foreground material, and therefore suggests that the outflow is rotating (at $\nu_{\phi} < 4$ km s$^{-1}$; see Methods). Alternatively, to explain their absence, the density and temperature in these regions would have to be much lower than in the two other cavity walls (see Methods), but this is unlikely given the intrinsic bipolar nature of protostellar outflows.

Visual inspection of the channel maps in Fig. 1 suggests that the observed outflowing gas is not launched from within a fraction of an astronomical unit from the central protostar, as would be the case in an X-wind or stellar wind scenario. The corresponding Keplerian radii (plus symbols in Fig. 1) are well outside 1 AU for each channel map. At velocities larger than about 5 km s$^{-1}$ with respect to the systemic velocity, almost no emission is detected along the central outflow axis. It is also clear that outflowing gas is present at large radial separations ($r \approx 50$ AU) from the central star and close to the disk surface. This is not easily reconcilable with a pure X-wind scenario because the wide-angle flow streamlines predicted by such a mechanism do not correspond with the observed outflowing gas with similar outflow speeds and radial separations, but a range of heights above the disk (see, for example, figure 2 of ref. 21). Consequently, the observed emission cannot be understood using a pure entrainment explanation. The channel maps also show that lower-velocity gas is present at larger distances from the central outflow axis than is higher-velocity gas. This onion-like layered structure8 is consistent with observations on larger scales19. We estimated the outflow launching radii8 (footpoint radii, $r_0$) using two different methods.

First, we fitted a first-order polynomial through all the pixels above the disk midplane in the $^{12}$CO channel maps, weighted by the flux density in each pixel (see Methods). This linear least-squares fit provides a direct and straightforward estimate of the footpoint radius for each velocity channel, assuming the gas travels along straight lines (see Methods). The best-fit results, presented in Fig. 2, reveal a range of footpoint radii between about 6 AU and about 22 AU, with a trend where $r_0$ decreases with increasing velocity. Second, we applied steady-state magnetohydrodynamic wind theory to derive the footpoint radii22. Since the same launching mechanism is responsible for the transfer of both angular momentum and kinetic energy into the wind, both in
the case of a disk wind and in the case of an X-wind, the outflow and rotational velocity components must be closely linked. Consequently, the footpoint radius can be determined for each position of the map (see Methods). The analysis shows the same trend as the first method, revealing footpoint radii between about 2 au and about 19 au (Fig. 3). Thus, the observed emission is consistent with a scenario where a magnetic wind ejects ions from a radially extended region of the disk (which is observed to be in Keplerian rotation around a central mass of $0.4 M_\odot$; see Methods and Extended Data Fig. 2), that drags molecular gas along. Indeed, the inferred range of footpoint radii is consistent with a disk wind outflow mechanism, whereas, for an X-wind or stellar wind, the footpoints should be located well inside 1 au.

In the dust continuum data, the flux density distribution reveals an excess in emission relative to the underlying Gaussian profile. The strength of this feature varies slightly with azimuthal angle (most prominent on the southern side of the disk) but is located at a relatively constant radius of around 20 au (see Extended Data Fig. 3). It is at present unclear whether this feature is related to the launching mechanism, but we note that the radius, interestingly, is very similar to the estimated maximum footpoint radius of the flow (Fig. 2). We interpret the observed dust emission excess as the result of a density enhancement (and perhaps an elevated dust temperature) at the edge of the outflow launching region.

We measure the specific angular momentum from the velocity field (deprojected from the line-of-sight velocity with respect to the systemic velocity) to be less than 200 au km s$^{-1}$ in the outflow and it appears to increase with distance from the protostar (Extended Data Fig. 4). This demonstrates that a substantial amount of angular momentum is removed from an extended region throughout the disk. The specific angular momentum of the outflowing gas is comparable to what has previously been reported for the large-scale disk of TMC1A, that is, 250 au km s$^{-1}$. Compared to other sources where large-scale emission is observed, the value is relatively low, however. Using the values of the specific angular momentum and the outflow velocity (deprojected from the line-of-sight velocity with respect to the systemic velocity), we can define a locus in the parameter space shown in figure 2 of ref. 13. That figure provides theoretical predictions for the relationship between these quantities, for different launching scenarios. The
TMC1A outflow falls in the regime where poloidal outflow velocities are relatively low and launching radii are large. This is consistent with a disk wind launching mechanism but is inconsistent with pure stellar wind or X-wind models.

Observationally, younger outflows are found to be more collimated, have smaller opening angles, and show higher gas velocities than their older counterparts. In this regard, TMC1A does not fall into the category of the very youngest protostars, but rather into the transition period between young and old, where there is still a considerable amount of material available for accretion onto the central protostar. Theoretically, X-winds naturally produce fast, well collimated outflows, and stellar winds are effective at spinning down the central protostar, whereas slow outflows and wide opening angles are most easily explained by disk wind models.

The observations presented here demonstrate that the observed TMC1A CO outflow is launched from radial distances substantially displaced from the central protostar, but, since the observations do not resolve the emission on scales below 6 AU, we cannot exclude the possibility of an additional, confined and high-velocity component not probed by these observations. It has in fact been suggested that a combination of different mechanisms is needed to match all of the observations, within which the disk wind might be important for driving a wide-angle outflow capable of removing a large portion of the infalling envelope. In general, the most promising theories proposed for protostellar outflow ejection (X-winds, stellar winds and disk winds) have difficulties explaining both large opening angles and bow-shaped structures simultaneously.

A well known observational fact in meteoritics is that part of the chondritic material found throughout the Solar System has a composition consistent with having undergone thermal processing at very high temperatures expected only in the inner Solar System. If the disk wind observed in this work extends to smaller radii (at which the disk wind cannot currently be resolved), it could form the first link in a chain that could transport thermally processed solid material outwards in a protostellar system by allowing it to rain down on the outer part of the disk, whereas an X-wind-type outflow could not. The TMC1A system has an age of at most a few hundred thousand years. Although these observations do not probe the very smallest scales, they show that it is possible to drive such a mechanism at times sufficiently early to correspond to the formation epoch of various, chondritic components in a young analogue of the Solar System.

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to P.B. (per.bjerkeli@bjerkeli.se).

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METHODS

ALMA observations and data processing. TMCI was observed with ALMA on 2015 October 23 and 30. The observations presented here are part of the Cycle 3 programme 2015.1.01415.S. The primary beam of the ALMA 12-m dishes covers a field of 22 arcsec in diameter around TMCI and the source was observed in the $J = 2 - 1$ rotational transitions of $^{13}$CO, $^{13}$CO and C$^{18}$O at 230.5 GHz, 220.4 GHz and 219.6 GHz, respectively. 49 antennas in the 12-m array were used during the observations providing baselines in the range 85 m to 16,196 m. The CO observations were carried out at a spectral resolution of 244 kHz (0.32 km s$^{-1}$) and the total bandwidth is 117 MHz. In addition to these baselines, one baseline was used for continuum observations where the spectral resolution was set to 976 kHz (1.35 km s$^{-1}$) and the total bandwidth was 1.875 MHz. The precipitable water vapour during the observations was between 0.28 mm and 0.63 mm. The phase centre of the observations was right ascension $\alpha_{2000} = 04h 39m 35.2s$, declination $\delta_{2000} = +25\degree 41\arcmin 44.27\arcsec$. The peak of the continuum emission is slightly offset from this coordinate, that is, by $+0.03\arcsec$, $-0.05\arcsec$ ($+$5 AU, $-$7 AU corresponding to $\alpha_{2000} = 04h 39m 35.2s$, $\delta_{2000} = +25\degree 41\arcmin 44.23\arcsec$). The X-ray source J0440+2728 was used as phase calibrator and the blazar J0510+1800 was used as bandpass calibrator. The flux calibration uncertainty is estimated to be less than 10%.

The data calibration and imaging was carried out in CASA31 (version 4.5.0) and followed standard procedure. The continuum is subtracted in the Fourier plane ($uv$ domain) by fitting a constant to the line-free calibrators. The calibrated visibilities for the continuum are transformed into the image domain using the CLEAN algorithm$^{22}$ with Briggs weighting and the robust parameter set to 0.5. For the line emission, natural weighting is used to provide the highest signal-to-noise ratio. To improve the signal-to-noise ratio, we used a visibility taper at 0.04 arcsec for the continuum and $^{13}$CO maps (shown in Fig. 1) and a visibility taper at 0.10 arcsec for the $^{13}$CO and C$^{18}$O maps. (Extended Data Fig. 1). All spectral line output images have a spectral resolution of 0.35 km s$^{-1}$. The interferometric nature of the observations leads to spatial filtering of large-scale structures, which, for these observations, leads to a maximum recoverable scale of 0.4 arcsec (about 60 AU at a distance of 140 parsecs). This implies that we do not detect any emission that is extended over scales larger than 60 AU and we do not detect emission at velocities below 2 km s$^{-1}$ relative to the systemic velocity of 6.4 km s$^{-1}$. Hence, we probe material moving with a velocity offset from any extended emission in the system$^{31}$ and we do not recover any foreground emission from the envelope.

Analysis of the continuum and spectral line maps. Each velocity channel is analysed individually using MATLAB. For the presented maps, the first contour is set at 1.3 times the root-mean-square level of each map, which is calculated in a 1.3 arcsec by 1.3 arcsec emission-free region located at a distance of 1.5 arcsec from the continuum peak. The presented data has not been corrected for the primary beam response. This has no effect on the maps presented, since the correction is less than 1% within 2 arcsec of the phase centre of the observations.

Origin of the emission. A crucial part of the analysis is to identify the molecular emission that arises from the disk. This can be done through direct comparison of the $^{13}$CO, $^{13}$CO and C$^{18}$O emission. The line ratios between the isotopologues are close to one, suggesting that the medium is optically thick in $^{12}$CO. To estimate the optical depths, the emission of the isotopologues at $\nu = 9$ km s$^{-1}$ is used. Assuming a kinetic temperature of 100 K and adopting isotopic ratios of 60 and 550 for $^{13}$CO and C$^{18}$O, we calculate the optical depths ($\tau$) to be 0.04, 0.2 and 25 for $^{13}$CO, $^{13}$CO and C$^{18}$O, respectively. Even in the line wings, the optical depth of $^{12}$CO is much greater than 10. The spatial distribution of $^{13}$CO differs noticeably from that of $^{13}$CO and C$^{18}$O; the latter two roughly trace the rotation of the disk (Extended Data Fig. 1). Furthermore, $^{13}$CO is not detected in the outer parts of the disk, whereas $^{12}$CO and C$^{18}$O are. This implies that the $^{12}$CO in the disk is invisible. In Extended Data Fig. 1, the extent of the disk is derived from integrating the line wings, away from the region of $^{13}$CO emission. To test the robustness of our results, we also fitted a first- and second-order polynomial to the emission ($z = A(r - r_0)^2$). The derived footprint radii are similar and we conclude that the choice of exponent does not affect our scientific conclusions. If we instead assume an intercept of zero during the fitting procedure (that is, $z = A r^2$; ref. 38), the goodness of fit decreases because the observed geometry is considerably steeper than can be modelled by any simple polynomial with a zero intercept (such as $z = A r^2$).

In an independent analysis, we estimate the footprint radius for each detected pixel in the $^{13}$CO map, using equation (4) of ref. 22. The characteristic velocity in each position is taken from the computed velocity field (Fig. 1) and in each position the velocity is decomposed into the rotation component along the systemic velocity; the rotational velocity and the outflow velocity. We note that the estimated footprint radius can be affected by entrained gas and/or asymmetries in the flow, since this increases the uncertainty on the magnitude of the velocity components. Further, such an analysis can only be carried out in the ballistic regime,
and for that reason, we mask out all pixels where the local escape velocity exceeds the outflow velocity. The estimated footpoint radius for each position is presented in Fig. 3. An illustration of where the outflow is launched is shown in Extended Data Fig. 5. In both figures, straight lines point towards the launching point.

**Dust continuum emission.** To examine the continuum emission from the disk, we fitted a Gaussian profile to the emission as a function of the radius, deprojected by the inclination angle of the system, for all azimuthal directions. This reveals an enhancement in the emission around 20 au at the 1 mJy per beam level (see Extended Data Fig. 3), which is consistent with the estimated footpoint radius for the lowest-velocity channels. Since the emission cannot easily be explained by an analytical function, we exclude all data points from the Gaussian fit where the enhancement is most prominent, that is, between 12 au and 33 au. The variation with azimuthal angle of the distance to the peak position of this enhancement is smaller than the resolution element in these observations (see Extended Data Fig. 3).

**Angular momentum of the outflowing gas.** To estimate the specific angular momentum of the outflowing gas, we use the $^{12}$CO velocity field. The specific angular momentum is calculated as the product of the rotational velocity, and the distance to the central axis of the blueshifted outflow (see Extended Data Fig. 4). The uncertainty on the rotation velocity is dominated by the uncertainty on the inclination angle (about 10°), since the uncertainty in observed velocity is negligible in comparison.

**Code availability.** The code RADMC-3D, used for the Keplerian disk modelling, is available at: http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/. We have opted not to make the molecular excitation code available owing to the lack of documentation and the non-trivial nature of its usage.

**Data availability.** This paper makes use of the following ALMA data: ADS/JAO. ALMA#2015.1.01415.S. The datasets generated and/or analysed during the current study are available in the ALMA archive (http://almascience.eso.org/aq/?project_code=2015.1.01415.S) and are also available from the corresponding author upon reasonable request.

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Extended Data Figure 1 | Comparison of integrated emission for $^{12}$CO, $^{13}$CO and $^{18}$O. Contours are from $3\sigma$ in steps of $3\sigma$ for $^{12}$CO (a) and $1\sigma$ for $^{13}$CO (b) and $^{18}$O (c). $\sigma = 4$ mJy per beam for $^{12}$CO and $\sigma = 5$ mJy per beam for $^{13}$CO and $^{18}$O. Redshifted (red) and blueshifted (blue) emission is integrated from 2.5 km s$^{-1}$ to 10 km s$^{-1}$ with respect to the systemic velocity. The corresponding integrated emission from the power-law disk model is shown in greyscale. RA, right ascension; Dec, declination.
Extended Data Figure 2 | Position–velocity diagram for $^{13}\text{CO}$ and $^{18}\text{O}$. Velocity of $^{13}\text{CO}$ (a), and $^{18}\text{O}$ (b) versus position, using an inclination angle of $55^\circ$. The dashed curve is indicative of Keplerian rotation around a 0.4$M_{\odot}$ star. The red and blue colours indicate the redshifted and blueshifted components, respectively. Error bars show the standard deviations of the Gaussian fits in position and the velocity resolution. au, astronomical units.
**Extended Data Figure 3 | Enhancement in dust continuum emission.**

**a–d.** Observed radial continuum brightness profile (square data points) at the four position angles indicated in the inset at top right. ‘Position’ angle 76° corresponds to the long axis of the disk on the northeastern side where the blueshifted northern outflow is launched. A Gaussian fit is overlaid as a dashed line. 

**e–h.** Residual intensity after subtracting the fits shown in the left column (square points), and a Gaussian fit (dashed line) to determine the peak location of the enhancement. The grey-filled area denotes the 2σ root-mean-square noise in the continuum map.
Extended Data Figure 4 | Specific angular momentum derived from the velocity field. The colour map shows the specific angular momentum and black dashed lines show the position angle of the outflow and the disk.
Extended Data Figure 5 | Inferred launching region of the disk wind. This illustrative figure is overlaid on a three-colour background image, showing the blueshifted (blue) and redshifted (red) $^{12}\text{CO}$ emission together with the continuum emission (green). The outflow emission is integrated from $\pm(2.5-10)\ \text{km s}^{-1}$ with respect to the systemic velocity $6.4\ \text{km s}^{-1}$. The outlines of the disk and the outflow and the axes of the disk and the outflow are indicated with white lines. Dashed blue lines are the same as in Fig. 3.