Snapshot of a magnetohydrodynamic disk wind traced by water maser observations

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The formation of astrophysical objects of different nature, from black holes to gaseous giant planets, involves a disk-jet system, where the disk drives the mass accretion onto a central compact object and the jet is a fast collimated ejection along the disk rotation axis. Magnetohydrodynamic disk winds can provide the link between mass accretion and ejection, which is essential to ensure that the excess angular momentum is removed and accretion can proceed. However, until now, we have been lacking direct observational proof of disk winds. Here we present a direct view of the velocity field of a disk wind around a forming massive star. Achieving a very high spatial resolution of about 0.05 au, our water maser observations trace the velocities of individual streamlines emerging from the disk orbiting the forming star. We find that, at low elevation above the disk midplane, the flow co-rotates with its launch point in the disk, in agreement with magneto-centrifugal acceleration. Beyond the co-rotation point, the flow rises spiralling around the disk rotation axis along a helical magnetic field. We have performed (resistive-radiative-gravito-)magnetohydrodynamic simulations of the formation of a massive star and record the development of a magneto-centrifugally launched jet presenting many properties in agreement with our observations.

Magnetohydrodynamic (MHD) disk winds have been proposed to be the engines of the powerful jets observed at varying length scales in many diverse sources, from young stellar objects (YSOs) to black holes. According to the classical model of an ideal MHD disk wind, in the reference frame co-rotating with the launch point, the flow streams along the magnetic-field line anchored to the accretion disk. An observer at rest sees magneto-centrifugal acceleration: the magnetic field keeps the flow in co-rotation with its launch point while its radial distance increases, until reaching the Alfvén point where the poloidal kinetic and magnetic energies are equal. Beyond the Alfvén point, the flow spirals outwards along the rotation axis with a stably increasing ratio of the streaming onto the rotational velocity, until it gets eventually collimated into a fast jet. So far, the best observational evidence for an MHD disk wind has been the finding of line-of-sight velocity gradients transversal to the jet axis, which are interpreted in terms of jet rotation and the imprint of the magneto-centrifugal acceleration. However, this is indirect evidence, and the derivation of key parameters, such as the launch radius and the magnetic lever arm, can be seriously affected by systematic biases. On scales of ~100 au, a few studies based on very long baseline interferometry (VLBI) maser observations have revealed rotating disk-like, conical or cylindrical maser distributions at the jet root, but the streamlines of a disk wind have been never traced, until now.

IRAS21078+5211 is a star-forming region of high bolometric luminosity, $5 \times 10^3 L_\odot$ (ref. 13) at a distance of 1.63 ± 0.05 kpc (ref. 16), and harbours a cluster of forming massive stars. On scales of a few 100 au, by employing the Northern Extended Millimeter Array (NOEMA), a disk is observed in high-density molecular tracers (CH$_3$CN and HC$_3$N; Fig. 1a) rotating around a YSO of mass $5.6 \pm 2 M_\odot$. Interferometric observations at radio wavelengths (5 cm) using the Jansky Very Large Array (JVLA) have revealed a jet directed northeast–southwest (position angle from north to east, $P A \approx 44^\circ$) emerging from the YSO, whose position at the centre of the disk is pinpointed by compact thermal emission observed with the JVLA at 1.3 cm. During 2010–2011, we have performed multi-epoch Very Long Baseline Array (VLBA) observations of the maser emission at 22 GHz. These observations have discovered a cluster of masers placed up to 100 au northeast from the YSO, whose proper motions are collimated northeast–southwest ($P A = 49^\circ$) and trace the base of the jet from the YSO (Fig. 1b). The analysis of the three-dimensional (3D) maser motions, specifically the local standard of rest (LSR) velocity ($V_{\text{LSR}}$) gradient transversal to the jet axis and the constant ratio between the toroidal and poloidal velocities, suggested that the jet could be launched from an MHD disk wind.

In October 2020, we performed novel observations (Fig. 2a) of the water maser emission in IRAS21078+5211 by including all telescopes available in the VLBI network, with the aim to simulate next-generation radio interferometers that will improve current sensitivities by more than an order of magnitude (see ‘Observations’ in Methods). In the following, we show that these observations prove that the water masers trace magnetized streams of gas emerging from the YSO’s disk (see Fig. 2b and ‘Simulation snapshot of a forming massive star’ in Methods). The maser emission concentrates in three regions to the northeast, north and southwest, inside the three dotted rectangles of Fig. 2a. Along the jet axis (the dashed red line in Fig. 2a), whose sky projection is known from previous observations of the maser proper motions and radio jet (see ‘Shock type and corresponding flow kinematics of water masers’ in Methods), we observe two elongated structures, blue- and redshifted (with respect to the systemic $V_{\text{LSR}}$ of the YSO: $V_{\text{LSR}} = -6.4 \text{ km s}^{-1}$) to northeast and southwest, respectively. These structures are the opposite lobes of a collimated outflow from the YSO, located in between the two lobes.

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the disk axis (the black dashed line in Fig. 2a) is the intercept of the jet axis at the YSO position. From previous VLBA observations, we know that the jet axis has to lay close to the plane of the sky, with an inclination of ≤30°. According to the maser $V_{\text{LSR}}$, the jet is inclined towards us to the northeast, and away from us to the southwest.

The jet and disk axes provide a convenient coordinate system to refer the maser positions to. In the following, we present the interpretation of the maser kinematics, which is based on the analysis of the three independent observables: $z$, the elevation above the disk plane (or offset along the jet), $R$, the radial distance from the jet axis (or transversal offset), and the maser $V_{\text{LSR}}$. As discussed in ‘Observations’ in Methods, the accuracy of the maser positions is ~0.05 au, and that of the maser $V_{\text{LSR}} \approx 0.5 \text{ km s}^{-1}$. Without loss of generality, we can express the maser velocities as the sum of two terms, one associated with the toroidal component or rotation around the jet axis, $V_{\text{rot}}$, and the other associated with the poloidal component including all the contributions owing to non-rotation, $V_{\text{off}}$. As the jet axis is close to the plane of the sky and we observe the rotation close to edge-on (Fig. 3), we can write:

$$V_{\text{LSR}} = V_{\text{off}} + V_{\text{rot}} = V_{\text{off}} + \omega R \sin(\phi)$$

$$R = R \sin(\phi)$$

$$\phi = \omega t$$

where $\phi$ is the angle between the rotation radius $R$ and the line of sight, and $\omega$ and $t$ are the angular velocity and the time, respectively.
The observation of a well-defined sinusoidal pattern requires that \( \omega \) and \( V_z \) are directly proportional, or constant. The constancy of \( V_z \) implies that \( V_{\text{mas}} \) is also constant, because, if the rotation radius does not change, \( V_{\text{mas}} \) is the projection along the line of sight of \( V_z \). Following equations (1) and (2), the constancy of \( \omega \) and \( V_{\text{mas}} \) would result into a tight linear correlation between \( V_{\text{mas}} \) and transversal offsets \( R \). While a good linear correlation between \( V_{\text{mas}} \) and \( R \) is observed for the southwest and NE-1 spiral motions (Figs. 4b and 5b, black symbols), the scatter in velocity is considerable for the NE-2 spiral motion (Fig. 5b, red symbols). In ‘Velocity scatter’ in Methods, we investigate the physical reason for the observation of well-defined sinusoidal patterns despite the presence of a significant velocity scatter. Applying the equations of motions for an axisymmetric MHD flow, we find that the magnetic-field configuration has to be helical over the maser emission region, and the motion along such an helical field line, in the reference frame co-rotating with the launch point, leads to the sinusoidal pattern of maser positions.

We consider now the north region (Fig. 2a) and show that, in this region as well, the maser kinematics is consistent with the predictions for an MHD disk wind. The north masers have a larger separation from the jet axis than the northeast and southwest masers. A few nearby masers show quite different \( V_{\text{mas}} \), which could hint at distinct streams, as observed (Fig. 5a) and discussed (see ‘Resolving the northeast emission into three distinct streams’ in Supplementary Information) for the northeast flow. In this case, however, only a single stream is reasonably well sampled in position and \( V_{\text{mas}} \) with the masers, and we focus our kinematical analysis on that. The spatial distribution of this stream presents an arc-like shape: a subset of maser features draws a line at small angle with the disk axis and another group extends at higher elevations about the disk axis. Then, the good linear correlation between \( V_{\text{mas}} \) and \( R \) is observed close to the plane of the sky. In this case, the maser \( V_{\text{mas}} \) should mainly trace rotation, which is also expected to be the dominant velocity component at low elevations above the disk. A disk in Keplerian rotation around an YSO of about 5.6\( M_\odot \) attains an angular velocity equal to \( \omega_{\text{K}} \) at \( R \approx 40 \) au. The line drawn by the masers at the lowest elevations intercepts the disk axis close to \( -40 \) au (Fig. 6a), as expected if the gas, launched from the disk, first streams approximately along a straight line and then progressively bends up along the jet axis. It is noted that, based on equations (1) and (2), the derivation of \( \omega_{\text{K}} \) does not depend on the maser geometry. Therefore, the finding that the masers lay along a line intercepting the disk at about \(-40 \) au provides an ‘a posteriori’ test of the assumption that the north emission is observed close to the plane of the sky.

Figure 4c shows the remarkable finding that the spatial coordinates \( z \) and \( R \) of the maser emission in the southwest flow satisfy the relation:

\[
R = C \sin(f_z(z - z_0))
\]

(4)

where \( C \), the amplitude of the sinusoid, \( f_z \), the spatial frequency, and \( z_0 \), the position of zero phase, are fitted constants (Table 1). In ‘Resolving the northeast emission into three distinct streams’ in Supplementary Information, we demonstrate that the masers in the northeast flow can be separated in three different streams (NE-1, NE-2 and NE-3), each of them satisfying the relation (4) (Fig. 5c and Table 1). The comparison of equations (2) and (4) leads to a straightforward interpretation of the sinusoidal relation between the coordinates by taking: (1) \( \mathfrak{R} = C \), and (2) \( \phi = f_z \|z - z_0\| \). The first equation indicates that the rotation radius is the same for all the masers, and the second equation shows that the motions of rotation around and streaming along the jet axis are locked together, which is the condition for a spiral motion. Denoting with \( V_z \) the streaming velocity along the jet axis, we can write \( \|z - z_0\| = V_z t \) and, by comparing with equation (3), we derive the relation between the rotation and streaming velocities:

\[
f_z = \omega/V_z
\]

(5)
The southwest spiral motion. a, Expanding view of the maser positions and $V_{\text{LSR}}$ in the southwest region. Coloured dots have the same meaning as in Fig. 2a. The distances along the jet (red) and disk (black) axes are indicated. b, Plot of the maser $V_{\text{LSR}}$ (and corresponding $2\sigma$ errors, denoted with error bars) versus $R$. The black dashed and dotted lines show the best linear fit and the associated uncertainty, respectively. c, Plot of the maser coordinates $R$ versus $z$. The positional error is smaller than the cross size. The black dashed curve is the fitted sinusoid, whose parameters are reported in Table 1.

Table 1 | Parameters of the linear and sinusoidal fits

| Stream | $\omega$ (km s$^{-1}$ au$^{-1}$) | $V_{\text{LSR}}$ (km s$^{-1}$) | $R_{1}$ (au) | $f_{z}$ (rad au$^{-1}$) | $z_{5}$ (au) |
|--------|-------------------------|------------------|------------|----------------|------------|
| SW     | 1.15 ± 0.12             | 17.5 ± 1.3       | 21.6 ± 1.0 | 0.0366 ± 0.0012 | −16.5 ± 1.9 |
| NE-1   | 1.15 ± 0.09             | −29.2 ± 0.6      | 36 ± 5     | 0.0307 ± 0.0008 | 16.3 ± 2.0  |
| NE-2   | 0.64 ± 0.27             | −10.9 ± 3.0      | 22.9 ± 0.5 | 0.0386 ± 0.0008 | 47.8 ± 1.2  |
| NE-3   | 2.0 ± 0.5              | −49 ± 27         | 17.2 ± 0.3 | 0.0405 ± 0.0023 | 7.3 ± 2.3   |

Column 1 denotes the maser stream. Columns 2 and 3 provide the values of $\omega$ and $V_{\text{LSR}}$ from the linear fit of maser $V_{\text{LSR}}$ versus $R$. Columns 4, 5 and 6 report the amplitude, the spatial frequency and the position of zero phase, respectively, of the sinusoidal fit of the maser coordinates $R$ versus $z$. The determination of this error, smaller than the value, 17 km s$^{-1}$ au$^{-1}$, from the linear fit, is discussed in ‘The angular velocity of the NE-3 stream’ in Supplementary Information.

2–3 predicted by theory$^{16,19}$. The more negative $V_{\text{LSR}}$ are explained if $V_{z}$ (and the absolute value of $V_{\text{LSR}}$) increases with the elevation, as a consequence of the magneto-centrifugal launching. The linear correlation between $V_{\text{LSR}}$ and $z$ (d$V_{\text{LSR}}$/dz = −0.195 ± 0.002 km s$^{-1}$ au$^{-1}$) shown in Fig. 6b results from the combination of the two regimes: (1) sub-Alfvénic, where $V_{\text{LSR}} \propto R$ and the gas streams approximately along a straight line, that is, $R \propto z$, and (2) trans-Alfvénic, where $V_{z}$ increases quickly with $z$ and $V_{\text{LSR}}$ starts to be significant.

From the previous analysis, an MHD disk wind seems to be a natural frame to explain both the spiral motions traced by the masers close to the jet axis in the northeast and southwest regions and the gas co-rotation along the north stream. If some locations of the YSO’s disk are perturbed, the flow emerging from those perturbed launch points should harbour internal shocks (see ‘Shock type and corresponding flow kinematics of water masers’ in Methods), which travel outwards along spiralling trajectories. These internal shocks provide physical conditions suitable for the excitation of the water masers$^{20–22}$. The spiral motions traced with the masers would correspond to portions of the trajectories beyond the Alfvén point where the rotation radius keeps about constant. An essential feature of the proposed model is that, as the launch point rotates, the maser emissions have to travel along spatially distinct, spiralling trajectories. These trajectories are invariant under rotation and nearby masers share the same orbital parameters. However, as the masers sample different trajectories, we need to make a distinction between the angular velocity of the trajectory, $\omega$, derived through the linear fit of the maser $V_{\text{LSR}}$ versus $R$ (see equations (1) and (2), and Figs. 4b and 5b), and the effective angular velocity of rotation, $\omega_{t}$, the one to be used in equations (3) and (5). As the different trajectories are rigidly anchored to the launch point and water masers at higher (absolute) elevations have been launched earlier in time, the simple relation holds:

$$\omega_{t} = \omega - \omega_{K}$$

(6)

where $\omega_{K}$ is the Keplerian angular velocity of the launch point. Equation (6) shows that $\omega_{t}$ is the angular velocity of the spiralling trajectory as observed in the reference frame co-rotating with the launch point. On the basis of axisymmetric MHD models$^{23,24}$, the ratio $\omega_{t}/\omega$ increases stably from 1 up to a value ~4 while the gas climbs from $z_{1}$ to 10 $\mathcal{R}_{K}$, where $z_{1}$ is the elevation of the Alfvén point and $\mathcal{R}_{K}$ is the launch radius. Being $\omega \leq \omega_{K}$, the negative value of $\omega_{t}$ indicates that the rotation angle of the maser positions decreases with $z$. Following the previous discussion, equation (5) has to be corrected by replacing $\omega$ with $\omega_{t}$:

$$f_{z} = \parallel \omega_{t} \parallel /V_{z}$$

(7)

A good test of the above considerations comes directly from our data. Assuming that all the masers move along a single trajectory and using the fitted values of $\omega$ and $f_{z}$ in equation (5), we obtain implausibly small values for $V_{z}$: 31 km s$^{-1}$, 37 km s$^{-1}$, 17 km s$^{-1}$ and 49 km s$^{-1}$, for the southwest, NE-1, NE-2 and NE-3 spiral motions, respectively. There are two strong observational evidences that
**Fig. 5** | The northeast spiral motions. **a,** Expanding view of the maser positions and $V_{\text{LSR}}$ in the northeast region. Different symbols are employed to identify the three spiral motions: dots for the NE-1, triangles for the NE-2 and squares for the NE-3 spiral motion. Colours denote the maser $V_{\text{LSR}}$. The distances along the jet (red) and disk (black) axes are indicated. The black dashed rectangle encompasses the maser cluster closest to the YSO. **b,** In this and the following panel, black, red and blue colours refer to masers belonging to the NE-1, NE-2 and NE-3 streams, respectively. Error bars, dashed lines and dotted lines have the same meaning as in Fig. 4b. Masers in the NE-2 stream with similar radii, 10 au $\leq R < 22$ au, but different elevations, 60 au $\leq z < 90$ au and $z \geq 90$ au, have $V_{\text{LSR}}$ different by $\pm 10$ km s$^{-1}$ (see ‘Velocity scatter’ in Methods). For the NE-2 stream, the linear fit of the $V_{\text{LSR}}$ has been performed considering only the masers with $z \geq 90$ au. **c,** Plot of the linear transformation (using the coefficients A and B) of $V_{\text{LSR}}$ versus $z$. For each of the three streams, the coefficients A and B are taken equal to the corresponding values of $\omega$ and $\rho_{\text{LSR}}$, respectively. In Table 1, we report the parameters of the sinusoidal fits of the radii.

**Fig. 6** | The co-rotating north stream. **a,** Expanding view of the maser positions and $V_{\text{LSR}}$ in the north region. Coloured dots and triangles give absolute positions of the 22GHz water masers, with colours denoting the maser $V_{\text{LSR}}$. The triangles mark a few masers with detached $V_{\text{LSR}}$, respectively, in Table 1. We plot the linear transformation of the radii to $V_{\text{LSR}}$ in the northeast region. Different symbols are employed to identify the kinematical analysis. The distances along the jet (red) and disk (black) axes are indicated. The black dashed line shows the linear fit of the positions of the masers at elevation $z < 20$ au. **b, c,** Plot of maser $V_{\text{LSR}}$ versus $z$ (b) and $R$ (c). In both panels, error bars denote the maser $V_{\text{LSR}}$ and corresponding $2\sigma$ errors, and the black dashed and dotted lines show the best linear fit and the associated uncertainty, respectively. The linear fit of $V_{\text{LSR}}$ versus $R$ has been performed considering only the masers with $V_{\text{LSR}} \geq -27$ km s$^{-1}$.

The derived streaming velocities are too small. First, comparing them with the values of $V_{\text{off}}$ (Table 1), the two velocities have similar amplitudes, and this is inconsistent with the expectation that $V_{\text{off}}$ is the line-of-sight component of $V_z$ and that the jet axis is close to the plane of the sky. Second, taking the ratio between the highest elevations reached by the masers, that is 100–130 au (Figs. 4 and 5), and the above values of $V_z$, the derived travelling times of 15–40 yr exceed the separation of 10 yr since the previous VLBA
observations, when no maser emission was detected at corresponding positions.

As $V_{\text{eff}}$ corresponds to the line-of-sight projection of $V_{\nu}$, we can write:

$$V_{\nu} = \parallel V_{\text{eff}} - V_{\text{sys}} \parallel \sin(i_{\text{mas}})$$  

where $V_{\text{eff}}$ is corrected for the systemic $V_{\text{LISG}}$ of the YSO, and $i_{\text{mas}}$ is the inclination angle of the jet axis with the plane of the sky. As we know that $i_{\text{mas}} \leq 30^\circ$, equation (8) allows us to derive a lower limit for $V_{\text{eff}}$ reported in Table 2. Using the derived lower limit of $V_{\nu}$ and the corresponding value of $f_{\nu}$ (Table 1), by means of equation (7) we can calculate a lower limit for $\omega_{\nu}$. Finally, we use equation (6) and the fitted value of $\omega$ (Table 1) to infer a lower limit for $\omega_{\nu} = \omega + [\omega_0]$, and, knowing the mass of the YSO, a corresponding upper limit for the launch radius $R_{\text{LISG}}$ (Table 2). The NE-1 stream, which extends the most in elevation (from 20 au to 130 au; Fig. 5a), includes a group of maser features at elevation of ~20 au, which should be located closer to the Alfvén point. In Constraining the Alfvén point of the MHD disk wind on length scales of 1–100 au, allowing us to study the velocity pattern of individual streamlines launched from the disk. As represented in Fig. 2b, close to the disk rotation axis, we observe flows spiralling outwards along a helical magnetic field, launched from locations of the disk at radii $\leq 6$–17 au. At larger separation from the rotation axis, we observe a stream of gas co-rotating with its launch point from the disk at radius of ~40 au, in agreement with the predictions for magneto-centrifugal acceleration.

Our interpretation is supported by (resistive-radiative-gravitational) MHD simulations of the formation of a massive star that lead to a magneto-centrifugally launched jet whose properties agree with our maser and thermal (continuum and line) observations of IRAS 21078+5211. These results provide a clear evidence for an MHD disk wind. As water maser emission is widespread in YSOs, sensitive VLBI observations of water masers can be a valuable tool to investigate the physics of disk winds.

**Methods**

**Observations.** We observed the $6_{J_2}$–$5_{J_1}$ H$_2$O maser transition (rest frequency 22.335079 GHz) towards IRAS 21078+5211 (tracking centre: right ascension (J2000) = 21 h 9 min 21.720 s and declination (J2000) = +52° 22′ 37.08′′) with global VLBI for 24 h, starting on 27 October 2020 at 13:30 UT. The antennae involved were 16 antennae of the European VLBI network (EVN): Yebes, Sardinia, Medicina, Jodrell Bank, Eeffelsberg, Onsala, Metsahovi, Torun, Svetloe, Badary, Zelenchukskaya, KVN, Tamna, KVN, Ulsan, KVN, Yonsei, Urumqi and Tamna; plus the 10 antenna of the VLBA: Brewster, Fort Davis, Hancock, Kitt Peak, Los Alamos, Mauna Kea, North Liberty, Owens Valley, Pie Town and Saint Croix. The observations were designed to achieve a relative and absolute position accuracy of ~0.01 mas and ~1 mas, respectively, and to reach a sensitivity in the maser line $\leq 1$ mJy per beam. While the EVN antennae observed continuously the target, interferometer calibration scans ~8 min length every hour, the VLBA performed phase-referencing observations (over 10h), alternating scans on the target and the phase-reference calibrator every 45 s. During the phase-referencing session, the target and the calibrators were always observed by the VLBA simultaneously with the EVN to achieve global VLBI baselines. The fringe-finder and bandpass calibrators were: J2202+4216, 2007+777, 3C84 and 3C48; the phase-reference calibrators were: 2116+543 and 2051+528, both within 2.5° from the target and with a correlated flux of ~0.1 Jy per beam at 22 GHz.

We recorded dual circular polarization through four adjacent bandwidths of 16 MHz, one of them centred at the maser $V_{\text{LISG}}$ of ~6.4 km s$^{-1}$. The four 16 MHz bandwidths were used to increase the signal-to-noise ratio (SNR) of the weak continuum (phase reference) calibrators. The data were correlated with the SFXC correlator at the Joint Institute for VLBI in Europe (JIVE, at Dwingeloo, the Netherlands) in two correlation passes, using 1,024 and 128 spectral channels to correlate the maser 16 MHz bandwidth and the whole set of four 16 MHz bandwidths, respectively. The spectral resolution attained across the maser 16 MHz band was 0.21 km s$^{-1}$.

Data were reduced with the Astronomical Image Processing System (AIPS) package following the VLBI spectral line procedures. The emission of an intense and compact maser channel was self-calibrated, and the derived (amplitude and phase) corrections were applied to all the maser channels before imaging. To cover the whole maser emission, we produced images extending 0.65′′ in both right ascension and declination and 4 km s$^{-1}$ in $V_{\nu}$. Using the full-width at half-maximum (FWHM) major and minor sizes of the beam are 0.7 mas and 0.3 mas, respectively, and the beam PA is ~49°. In channel maps with (relatively) weak signal, the 1σ root-mean-square noise is 0.7 mJy per beam, close to the expected thermal noise.

Inverse phase-referencing produced good SNR (>10) images of the two phase-referencing calibrators. Taking into account that the calibrators are relatively compact with size $\lesssim 1$ mas, and that the absolute position of the calibrators is known within a few 0.1 mas, we estimate that the error on the absolute position of the masers is $\lesssim 0.5$ mas.

Supplementary Table 1 reports the parameters (intensity, $V_{\text{LISG}}$-position) of the 22 GHz water masers in IRAS 21078+5211. Individual maser features are a collection of quasi-compact spots observed on contiguous channel maps and spatially overlapping (within their FWHM size). The spot positions are determined by fitting a 2D elliptical Gaussian to their spatial emissions. The uncertainty of the spot position relative to the reference maser channel is the contribution of two terms: $\Delta \text{offset} = \sqrt{\Delta \text{fit}^2 + \Delta \text{bandpass}^2}$. The first term depends on the SNR of the data, following $\Delta \text{offset} = \text{SNR} / (2 \times \text{SNR})$, where $\text{SNR}$ is the resolution beam FWHM taken equal to $\text{FWHM}$ $\pm 50$% on the FWHM major and minor axis of the beam. The second term depends on the accuracy of the bandpass calibration through the expression $\Delta \text{bandpass} = \text{bandpass} \times (\Delta \text{FWHM} / 50)$, where $\Delta \text{FWHM}$ in degrees is the phase stability across the observing band. In our case $\Delta \text{FWHM} \lesssim 10''$ and $\text{bandpass} = 0.02$ mas becomes the dominant error term for spot intensity $\geq 100$ mJy per beam. The maser feature position (and corresponding error) is estimated from the error-weighted mean of the spot positions (and corresponding errors), and the feature $V_{\text{LISG}}$ from the intensity-weighted mean of the spots’ $V_{\text{LISG}}$. To be conservative, the uncertainty on the feature $V_{\text{LISG}}$ is taken equal to 0.5 km s$^{-1}$, corresponding to the typical maser FWHM line width.

**Velocity scatter.** Figures 4b and 5b show that the maser $V_{\text{LISG}}$ are linearly correlated with $R$ in the southwest and NE-1 streams. For the masers belonging to the NE-2 stream, the measurement scatter from the linear fit of $V_{\text{LISG}}$ versus $R$ is considerable (with large fit errors; Table 1); while, in the case of the NE-3 stream, the range in $R$ is too small (only 2 au) to constrain the parameters of the linear fit. The noticeable deviation of $V_{\text{LISG}}$ from the linear fits seems difficult to conciliate with the accuracy with which the maser positions reproduce the sinusoidal patterns (Figs. 4c and 5c). The average scatters of maser $V_{\text{LISG}}$ and positions (along the jet axis from the jet finessoid) are 2.4 km s$^{-1}$ and 1.9 au, 3.1 km s$^{-1}$ and 3.8 au, 6.9 km s$^{-1}$ and 2.1 au, and 2.7 km s$^{-1}$ and 1.7 au, for the southwest, NE-1, NE-2 and NE-3 streams, respectively. Assuming that the $V_{\text{LISG}}$ scatter reflects mainly the variation of the streaming velocity, since the jet axis is within 30° from the jet plane of the sky, the change in $V_{\text{LISG}}$ has to be at least twice that observed in $V_{\text{LISG}}$. Then, using the above values, the ratios of the corresponding scatters in position and $V_{\text{LISG}}$ give upper limits for the maser travelling times of $\leq 1$–3 yr. These travelling times, for maximum (absolute) elevations of the maser streams of 100–30 au (Figs. 4 and 5), imply $V_{\text{LISG}} \geq 200$–500 km s$^{-1}$. Using large weighting to the observed maser $V_{\text{LISG}}$. In the following, we investigate the physical reason for the observation of well-defined sinusoidal patterns despite the co-occurrence of significant velocity scatters.

**Table 2 | Estimate of the stream parameters**

| Stream | $V_{\nu}$ (km s$^{-1}$) | $\omega_{\nu}$ (km s$^{-1}$ au$^{-1}$) | $\theta_{\nu}$ (au) |
|--------|-----------------------|-------------------|------------------|
| SW     | $\geq 48$             | $\geq 2.9$        | $< 9$            |
| NE-1   | $\geq 46$             | $\geq 2.6$        | $< 10$           |
| NE-2   | $> 9$                 | $> 1.0$           | $< 17$           |
| NE-3   | $> 85$                | $> 5.4$           | $< 6$            |

Column 1 indicates the maser stream. Column 2 reports the estimated streaming velocity along the jet axis. Columns 3 and 4 give the estimate of the angular velocity and the radius, respectively, at the launch point.
In a stationary, axisymmetric MHD flow, the two fundamental equations of motions\(^\text{13,17}\): linking velocity and magnetic field along a field line are:

\[ \rho \mathbf{V}_p = \mathbf{k} \mathbf{B}_p \]

(9)

\[ B_k \approx \frac{\rho}{k} (V_p - \alpha \omega \mathbf{k}) \]

(10)

where \( V_p \) and \( V_p \) are the poloidal and toroidal components of the velocity and magnetic field, respectively, \( \rho \) is the gas mass volume density, \( \alpha \) is the Keplerian angular velocity at the launch point, \( \mathbf{k} \) is the rotation radius and \( \mathbf{k} \) is the ‘mass load’ of the wind, expressing the fixed ratio of mass and magnetic fluxes along a given magnetic-field line. As \( \mathbf{V}_p \) \( = \alpha \omega \mathbf{k} \) is the toroidal velocity in the reference frame co-rotating with the launch point, equations (9) and (10) lead to the well-known result that the velocity and magnetic field vectors are always parallel along the co-rotating reference frame. As \( \omega \) is the angular velocity of the trajectory around \( \mathbf{k} \), the two equations above can be combined into:

\[ \frac{B_k}{B_p} = \frac{(\alpha \omega - \omega_k)}{V_p} = \frac{\omega_k}{V_p} \]

\[ \omega_k = \frac{\omega_\alpha}{\alpha} \]

(11)

where we have used the definition of \( \omega_\alpha \) in equation (\(\text{s}\)). We can define the magnetic-field helix angle \( \alpha = \arctan(B_p/B_k) \), which is the angle with which a helical field line winds around the jet axis.

We have seen that the observation of well-defined sinuosities in the plane of the sky requires that the rotation radius \( \mathbf{k} \) and the ratio of the effective angular velocity \( \omega_k \) on the streaming velocity \( V_p \), keep constant (equation (7)). As the poloidal velocity \( V_p \) is equal to \( \mathbf{k} \) if \( \mathbf{k} \) is constant, equation (11) implies that \( \alpha \) does not vary along each of the observed maser streams. However, the reverse argument holds if \( \mathbf{k} \) is not constant. In that case the magnetic-field component should become the predominant component of the outflow observed in sulfur monoxide (SO) emission with NOEMA. Clearly, Models of water maser excitation predict them to arise in both strong dissociative J-shocks\(^\text{13}\) and weak non-dissociative C-shocks\(^2\). While J-shocks do not dominate the outflow in the post-shock gas at kinetic temperature \( T_{\text{kin}} \leq 400 \text{K} \), the masers most likely form in the cooling post-shock gas at kinetic temperature \( T_{\text{kin}} = \approx 1000 \text{K} \). The presence of shocks is naturally expected in correspondence with the fast poloidal outflows, whose angular velocities are beyond \( \omega_k = \omega_\alpha \). While the large majority of the 22 GHz water masers arise in strong external streams (Supplementary Fig. 2) over the same region of the sky, the structure of more external streamlines, where the gas is weakly ionized and the velocity is close to the flow speed, especially in direction between the elongated (double lobe) JVLA/ VLBA continuum at 5 cm and the jet axis and the YSO position. This further supports the interpretation that a single YSO is responsible for the excitation and motion of the water masers.

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Simulation snapshot of a forming massive star. As part of a more extensive study we will describe in a forthcoming article, we performed an axisymmetrical simulation of the formation of a massive star starting from the gravitational collapse of a rotating cloud core threaded by a magnetic field (A.O. and R.K., submitted). We used the methods of magnetohydrodynamics to model the weakly ionized gas and dust with the code Pluto\textsuperscript{1}, with an ohmic resistivity model as a non-ideal effect\textsuperscript{2}, and additional modules for self-gravity\textsuperscript{3} and the transport of the thermal radiation emitted by the gas and dust\textsuperscript{4}.

The cloud core has an initial mass of 100 $M_\odot$ and a radius of 0.1 pc. The assumptions for the onset of the gravitational collapse and the magnetic field are uniform. The initial magnitude of the magnetic field correlates with the centrifugal force\textsuperscript{5}, the cloud core rotates like a solid body with a rotational energy equivalent to 4% of its gravitational energy content, and the magnetic field is uniform. The initial magnitude of the magnetic field is determined by the mass-to-flux ratio, which we take as 20 times the critical (collapse preventing) value\textsuperscript{6} and correspondingly a weak initial magnetic field. A constant value of the opacity of 1 cm$^2$ g$^{-1}$ was used to model the gas and dust, as well as an initial dust-to-gas mass ratio of 1%.

We used an axisymmetrical grid of 896 $\times$ 160 cells in spherical coordinates, with the radial coordinate increasing logarithmically with the distance to the centre of the cloud. An inner boundary of 3 au was set up, inside of which the protostar is formed through accretion. No flows are artificially injected from the inner boundary into the collapsing cloud.

The simulation starts with an initial gravitational collapse epoch. After ~5 kyr, enough angular momentum is transported to the centre of the cloud to start forming an accretion disk that grows in size over time. Roughly at the same time, we observe the launch of magnetically driven outflows. Magnetic pressure arising from the dragging of magnetic-field lines by the rotating flow eventually overcomes gravity and seeds the formation of the outflow cavity, thrusting a bow shock in the process (Supplementary Fig. 1d), which propagates outwards as the cavity grows in size. Previous observations of IRAS 21078$+$5211 have uncovered the presence of a bow shock located at distances of ~36,000 au from the forming massive YSO\textsuperscript{7}. The initial launch of the magnetic-field driven outflows helps provide a possible formation mechanism for the observed bow shock and in return, the propagation of the bow shock provides an estimation for the age of the system.

In the simulation, the protostar reaches a mass of 5.24 $M_\odot$, a value in the expected mass interval from observations) after 13.84 kyr of evolution. We estimate that the bow shock has propagated to a distance of ~30,000 au at that time, roughly in line with the observations. At the same time, the accretion disk has grown to about 180 au in radius, in agreement with the observational estimates\textsuperscript{8}, as well. The data reveal a magneto-centrifugally launched jet, in a similar way as reported by the literature\textsuperscript{9}; however, we see that the launching region of the jet is narrower by the centrifugal force\textsuperscript{10}. The conditions of the bow shock is accelerated along the axis of the cloud. As the bow shock propagates away from the protostar, the broader magnetic-field lines present in the outflow cavity could give rise to the kinematic footprint detected in the masers in the north region.

At distances of ~10,000 au, where the outflow material propagates through the cloud (Supplementary Fig. 1c), we notice the existence of re-collimation zones that arise because of magnetic hoop stress and ram pressure from the envelope. The positions of the re-collimation zones are similar to shock waves, which means that a wider and deeper investigation is needed to determine the conditions of the onset of star formation from the observational data.

Data availability

This article makes use of the following EVN data: GM077 (EVN project code). The calibrated datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability

The custom parts of the code for producing the simulations and subsequent data analysis are not ready for public use, but they can be provided upon reasonable request. For the magnetohydrodynamics part of the software, we make use of the open-source code Pluto\textsuperscript{11}. The implementation method of the employed radiation transport module (‘Makemake’) is publicly accessible\textsuperscript{12}.

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Author contributions
L.M. led the project, analysis, discussion and drafted the manuscript. A.S., H.B. and R.K. commented on the manuscript and participated in the discussion. A.O. and R.K. performed the numerical jet simulations described in ‘Simulation snapshot of a forming massive star’ in Methods. A.O. performed the dynamical analysis of the simulations, compared the simulation results to the observations, and produced the illustrations of the magnetic field lines and streamlines.

Competing interests
The authors declare no competing interests.

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