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Luca Moscadelli (✉ luca.moscadelli@inaf.it)

INAF

Alberto Sanna

INAF-Osservatorio Astronomico di Cagliari

Henrik Beuther

Max-Planck-Institute for Astronomy <https://orcid.org/0000-0002-1700-090X>

Rolf Kuiper

Zentrum für Astronomie der Universität

Andre' Oliva

Institut für Astronomie und Astrophysik, Universität

Physical Sciences - Article

Keywords: ISM: jets and outflows, ISM: kinematics and dynamics, Stars: formation 13, Masers, Techniques: interferometric

Posted Date: February 23rd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1384761/v1>

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Version of Record: A version of this preprint was published at Nature Astronomy on August 11th, 2022.
See the published version at <https://doi.org/10.1038/s41550-022-01754-4>.

1 Snapshot of a magnetohydrodynamic disk wind

2 L. Moscadelli^{*1}, A. Sanna², H. Beuther³, R. Kuiper⁴, and G.A. Oliva⁵

3 ¹ INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy

4 e-mail: luca.moscadelli@inaf.it

5 ² INAF-Osservatorio Astronomico di Cagliari, Via della Scienza 5, 09047, Selargius,
6 CA, Italy

7 ³ Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany

8 ⁴ Zentrum für Astronomie der Universität Heidelberg, Institut für Theoretische As-
9 trophysik, Albert-Ueberle-Straße 2, 69120 Heidelberg, Germany

10 ⁵ Institut für Astronomie und Astrophysik, Universität Tübingen, Auf der Morgen-
11 stelle 10, D-72076 Tübingen, Germany

12 **Key words.** ISM: jets and outflows – ISM: kinematics and dynamics – Stars: formation
13 – Masers – Techniques: interferometric

14 The formation of astrophysical objects of different nature and size, from
15 black holes to gaseous giant planets, involves a disk-jet system, where the
16 disk drives the mass accretion onto a central compact object and the jet is
17 a fast collimated ejection along the disk rotation axis. Magnetohydrodynamic
18 disk winds can provide the link between mass accretion and ejection, which
19 is essential to ensure that the excess angular momentum is removed from the
20 system and accretion onto the central object can proceed. However, up to now,
21 we have been lacking a direct observational proof of disk winds. This work
22 presents a direct view of the velocity field of a disk wind around a high-mass
23 forming star. Achieving a very high spatial resolution of ≈ 0.05 au, our water
24 maser observations trace the velocities of individual streamlines emerging from
25 the disk orbiting the forming star. We find that, at low elevation above the disk
26 midplane, the flow co-rotates with its launch point in the disk, in agreement
27 with magneto-centrifugal acceleration where the gas is flung away along the
28 magnetic field line anchored to the disk. Beyond the co-rotation point, the
29 flow rises spiraling around the disk rotation axis along a helical magnetic field.
30 Our results are, presently, the clearest evidence for a magnetohydrodynamic

Fig. 1. Previous NOEMA, JVLBA and VLBA observations^{12,13} towards IRAS 21078+5211. (a) The gray-scale (from 10 to 35 mJy beam⁻¹) map reproduces the NOEMA 1.37 mm continuum emission. The colored dots represent the channel emission peaks of the CH₃CN $J_K = 12_K - 11_K$ ($K = 3-6$) and HC₃N $J = 24-23$ lines, with colors denoting the channel V_{LSR} : blue for $[-13.6, -10]$ and red $[-2.5, 0.5]$ km s⁻¹. The green (70%, 80%, and 90% of 0.50 mJy beam⁻¹) and white (from 30% to 90%, in steps of 10% of 0.096 mJy beam⁻¹) contours show the JVLBA A-Array continuum at 1.3 cm and 5 cm, respectively. (b) Colored dots and arrows give absolute positions and proper motions of the 22 GHz water masers determined with multi-epoch (2010–2011) VLBA observations, with colors denoting the maser V_{LSR} . The black contours (from 10% to 90%, in steps of 10% of 0.50 mJy beam⁻¹) indicate the JVLBA A-Array continuum at 1.3 cm. The dashed rectangle delimits the field of view plotted in Fig. 2a.

31 disk wind, and show that water masers and high-mass forming stars provide
 32 a suitable combination of tracer and environment to allow us studying the
 33 disk-wind physics.

34 Magnetohydrodynamic (MHD) disk winds have been proposed to be the engines of the
 35 powerful jets observed at varying length scales in many diverse sources, from young stellar
 36 objects¹⁸ (YSO) to black holes³. According to the classical model of an ideal MHD disk
 37 wind³, in the reference frame co-rotating with the launch point, the flow streams along
 38 the magnetic field line anchored to the accretion disk. An observer at rest sees magneto-
 39 centrifugal acceleration: the magnetic field keeps the flow in co-rotation with its launch
 40 point while its radial distance increases, till reaching the Alfvén point where the poloidal
 41 kinetic and magnetic energies are equal. Beyond the Alfvén point, the flow spirals outward
 42 along the rotation axis with a stably increasing ratio of the streaming onto the rotational
 43 velocity, until it gets eventually collimated into a fast jet^{15,10}. So far, the best observational
 44 evidence for a MHD disk wind has been the finding of line of sight velocity gradients
 45 transversal to the jet axis, which are interpreted in terms of jet rotation and the imprint
 46 of the magneto-centrifugal acceleration^{2,6,11,1}. However, that is an indirect evidence and
 47 the derivation of key parameters, as the launch radius and the magnetic lever arm, can be
 48 seriously affected by systematic biases²⁴.

49 IRAS 21078+5211 is a star forming region of high bolometric luminosity, $5 \times 10^3 L_{\odot}$ ¹²
 50 at a distance of 1.63 ± 0.05 kpc²⁵, and harbors a YSO significantly more massive than
 51 the Sun. On scales of a few 100 au, a disk¹³ is observed in high-density molecular tracers
 52 (CH₃CN and HC₃N, see Fig. 1a) rotating around a YSO of mass of $5.6 \pm 2 M_{\odot}$. Inter-

ferometric observations at radio wavelengths (5 cm) using the Jansky Very Large Array (JVLA) have revealed a jet¹² directed NE-SW (PA = 44°) emerging from the YSO, whose position at the center 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 (the laser equivalent at radio wavelengths) of the water molecule at 22 GHz. These observations have discovered a cluster of masers placed ≈ 100 au NE from the YSO, whose proper motions are collimated NE-SW (PA = 49°) and trace the base of the jet from the YSO¹² (see Fig.1b). The analysis of the three-dimensional (3D) maser motions, specifically the local standard of rest (LSR) velocity (V_{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 a MHD disk wind.

In October 2020, we performed novel observations (see Fig.2a) of the water maser emission in IRAS 21078+5211 by including all telescopes available in the Very Long Baseline Interferometry (VLBI) network, with the aim to simulate next-generation radio interferometers which will improve current sensitivities by more than an order of magnitude (see Appendix A). In the following, we will show that these new observations prove that the water masers trace magnetized streams of gas emerging from the YSO's disk (see Fig.2b). The maser emission concentrates in three regions to NE, N, and SW, inside the three dashed rectangles of Fig.2a. Along the jet axis (the dashed red line in Fig.2a), whose sky-projection is known from previous observations, we observe two elongated structures, blue- and red-shifted (with respect to the systemic V_{LSR} of the YSO: $V_{\text{sys}} = -6.4 \text{ km s}^{-1}$) to NE and SW, respectively. These structures are the opposite lobes of a collimated outflow from the YSO, located in between the two lobes; 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 $\leq 30^\circ$. According to the maser V_{LSR} , the jet is inclined towards us to NE, and away from us to SW.

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_{LSR} . As discussed in Appendix A, 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_{rot} , and the other associated with the poloidal component including all the contributions owing to non-rotation, V_{off} . Since the jet axis is close to the plane of the sky and we observe the rotation close to edge-on (see Fig 3), we

can write:

$$V_{\text{LSR}} = V_{\text{off}} + V_{\text{rot}} = V_{\text{off}} + \omega \Re \sin(\phi) \quad (1)$$

$$R = \Re \sin(\phi) \quad (2)$$

$$\phi = \omega t \quad (3)$$

where ϕ is the angle between the rotation radius $\Re$ and the line of sight, and ω and t are the angular velocity and the time, respectively.

Fig. 4c shows the remarkable finding that the spatial coordinates z and R of the maser emission in the SW flow satisfy the relation:

$$R = C \sin(f_z(z - z_0)) \quad (4)$$

where C , the amplitude of the sinusoid, f_z , the spatial frequency, and z_0 , the position of zero phase, are fitted constants (see Table 1). In Appendix B we demonstrate that the masers in the NE flow can be separated in three different streams, each of them satisfying the relation 4 (see Fig. 5c and Table 1). The comparison of Eqs. 2 and 4 leads to a straightforward interpretation of the sinusoidal relation between the coordinates by taking: 1) $\Re = C$, and 2) $\phi = f_z |z - z_0|$. The former equation indicates that the rotation radius is the same for all the masers, the latter 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, comparing with Eq. 3, we derive the relation between the rotation and streaming velocities:

$$f_z = \omega/V_z \quad (5)$$

According to Eq. 5, the observation of a well defined sinusoidal pattern requires that ω and V_z are directly proportional, or constant. The constancy of V_z implies that V_{off} is also constant, because, if the rotation radius does not change, V_{off} is the projection along the line of sight of V_z . Following Eqs. 1 and 2, the constancy of ω and V_{off} would result into a tight linear correlation between V_{LSR} and transversal offsets R . While a good linear correlation between V_{LSR} and R is observed for the SW and NE-1 spiral motions (see Figs. 4b and 5b, black symbols), the scatter in velocity is considerable for the NE-2 spiral motion (see Fig. 5b, red symbols). In Appendix D 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

124 motion along such an helical field line, in the reference frame co-rotating with the launch
 125 point, leads to the sinusoidal pattern of maser positions.

126 We consider now the N region (see Fig.2a) and show that, in this region as well, the
 127 maser kinematics is consistent with the predictions for a MHD disk wind. The N masers
 128 have a larger separation from the jet axis than the NE and SW masers. Their spatial
 129 distribution presents an arc-like shape: a subset of maser features draws a line at small
 130 angle with the disk axis and another group extends at higher elevations about parallel to
 131 the jet axis (see Fig.6a). Fig.6c shows that the maser V_{LSR} increases linearly with R in the
 132 range $70 \text{ au} \lesssim R \lesssim 95 \text{ au}$ up to an elevation $z \approx 60 \text{ au}$. The relatively large separation
 133 from the jet axis and radial extent, and the arc-like shape of the maser distribution lead
 134 us to think that the N emission is observed close to the plane of the sky. In this case,
 135 the maser V_{LSR} should mainly trace rotation, which is also expected to be the dominant
 136 velocity component at low elevations above the disk. Then, the good linear correlation
 137 between V_{LSR} and R indicates that the masers co-rotate at the same angular velocity,
 138 $\omega_{\text{N}} = 0.274 \pm 0.005 \text{ km s}^{-1} \text{ au}^{-1}$, up to $R \approx 95 \text{ au}$ and $z \approx 60 \text{ au}$. A simple interpretation
 139 is in terms of a magneto-centrifugally accelerated stream of gas emerging from a point of
 140 the disk. A disk in Keplerian rotation around an YSO of about $5.6 M_{\odot}$ attains an angular
 141 velocity equal to ω_{N} at $R \approx 40 \text{ au}$. The line drawn by the masers at the lowest elevations
 142 intercepts the disk axis close to 40 au (see Fig.6a), as expected if the gas, launched from
 143 the disk, first streams approximately along a straight line and then progressively bends up
 144 along the jet axis. Note that, basing on Eqs. 1 and 2, the derivation of ω_{N} does not depend
 145 on the maser geometry. Therefore, the finding that the masers lay along a line intercepting
 146 the disk at $\approx 40 \text{ au}$ provides an "a posteriori" test of the assumption that the N emission
 147 is observed close to the plane of the sky.

148 The masers found at elevation $> 60 \text{ au}$ appear to set aside of the arc-like distribution
 149 (see Fig.6a) and their V_{LSR} are significantly more negative and do not follow the linear
 150 correlation with the radius (see Fig.6c). A natural interpretation is that the location at
 151 $R \approx 95 \text{ au}$ and $z \approx 60 \text{ au}$ is the Alfvén point of the stream, and beyond that the
 152 gas is not any longer co-rotating. The lever arm of the stream is $\approx (95 \text{ au})/(40 \text{ au}) =$
 153 2.4 , in agreement with the values of $2\text{--}3$ predicted by theory^{20,19}. The more negative
 154 V_{LSR} are explained if V_z (and the absolute value of V_{off}) increases with the elevation, as a
 155 consequence of the magneto-centrifugal launching. The linear correlation between V_{LSR} and
 156 z ($dV_{\text{LSR}}/dz = -0.195 \pm 0.002 \text{ km s}^{-1} \text{ au}^{-1}$) shown in Fig.6b results from the combination
 157 of the two regimes: 1) sub-Alfvénic, where $V_{\text{LSR}} \propto R$ and the gas streams approximately
 158 along a straight line, that is $R \propto z$; 2) trans-Alfvénic, where V_z increases fast with z
 159 and V_{off} starts to be significant.

160 From the previous analysis, a MHD disk wind seems to be a natural frame to explain
 161 both the spiral motions traced by the masers close to the jet axis in the NE and SW

162 regions and the gas co-rotation along the N stream. If some locations of the YSO's disk are
 163 perturbed, the flow emerging from those perturbed launch points should harbor internal
 164 shocks, which travel outward along spiraling trajectories. These internal shocks provide
 165 physical conditions suitable for the excitation of the water masers^{5,7,9}. The spiral motions
 166 traced with the masers would correspond to portions of the trajectories beyond the Alfvén
 167 point where the rotation radius keeps about constant. An essential feature of the proposed
 168 model is that, as the launch point rotates, the maser emissions have to travel along spatially
 169 distinct, spiraling trajectories. These trajectories are invariant under rotation and nearby
 170 masers share the same orbital parameters. However, since the masers sample different
 171 trajectories, we need to make a distinction between the angular velocity of the trajectory,
 172 ω , derived through the linear fit of the maser V_{LSR} versus R (see Eqs. 1 and 2, and
 173 Figs. 4b and 5b), and the effective angular velocity of rotation, ω_e , the one to be used in
 174 Eqs. 3 and 5. Since the different trajectories are rigidly anchored to the launch point and
 175 water masers at higher (absolute) elevations have been launched earlier in time, the simple
 176 relation holds:

$$177 \quad \omega_e = \omega - \omega_K \quad (6)$$

178 where ω_K is the Keplerian angular velocity of the launch point. Eq. 6 shows that ω_e
 179 is the angular velocity of the spiraling trajectory as observed in the reference frame co-
 180 rotating with the launch point. Based on axisymmetric MHD models^{17,24}, the ratio ω_K/ω
 181 increases stably from 1 up to a value ≈ 4 while the gas climbs from z_A to $10 \Re_K$, where
 182 z_A is the elevation of the Alfvén point and $\Re_K$ is the launch radius. Being $\omega \leq \omega_K$, the
 183 negative value of ω_e indicates that the rotation angle of the maser positions decreases
 184 with z . Following the previous discussion, Eq. 5 has to be corrected by replacing ω with
 185 ω_e :

$$186 \quad f_z = |\omega_e|/V_z \quad (7)$$

187 A good test of the above considerations comes directly from our data. Assuming that
 188 all the masers move along a single trajectory and using the fitted values of ω and f_z in
 189 Eq. 5, we obtain implausibly small values for V_z : 31, 37, 17 and 49 km s⁻¹, for the SW,
 190 NE-1, NE-2, and NE-3 spiral motions, respectively. There are two strong observational
 191 evidences that the derived streaming velocities are too small. First, comparing them with
 192 the values of V_{off} (see Table 1), the two velocities have similar amplitudes, and that is
 193 inconsistent with the expectation that V_{off} be the line of sight component of V_z and the
 194 jet axis being close to the plane of the sky. Second, taking the ratio between the highest
 195 elevations reached by the masers, that is 100–130 au (see Figs. 4 and 5), and the above
 196 values of V_z , the derived traveling 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.

Since V_{off} corresponds to the line of sight projection of V_z , we can write:

$$V_z = |V_{\text{off}} - V_{\text{sys}}| / \sin(i_{\text{axi}}) \quad (8)$$

where V_{off} is corrected for the systemic V_{LSR} of the YSO, and i_{axi} is the inclination angle of the jet axis with the plane of the sky. As we know that $i_{\text{axi}} \leq 30^\circ$, Eq. 8 allows us to derive a lower limit for V_z , reported in Table 2. Using the derived lower limit of V_z and the corresponding value of f_z (see Table 1), by means of Eq. 7 we can calculate a lower limit for ω_e . Finally, we use Eq. 6 and the fitted value of ω (see Table 1) to infer a lower limit for $\omega_K = \omega + |\omega_e|$ and, knowing the mass of the YSO, a corresponding upper limit for the launch radius $\mathfrak{R}_K$ (see Table 2). The NE-1 stream, which extends the most in elevation (from 20 to 130 au, see Fig.5a), includes a group of maser features at elevation of ≈ 20 au, which should be located closer to the Alfvén point. In Appendix E, we study the change of V_{LSR} versus R internal to this cluster and obtain a lower limit for $\omega_K \geq 2.4 \text{ km s}^{-1} \text{ au}^{-1}$ that agrees well with the corresponding value reported in Table 2 for the NE-1 stream. The results shown in Table 2 are in general agreement with the theoretical predictions from MHD disk winds^{20,19}: the inferred lower limits on the streaming velocity V_z increase steeply with decreasing launch radius; for the SW and NE-3 streams, which are those with relatively lower uncertainty in the measurement of both ω and $\mathfrak{R}$ (see Table 1), the ratio between V_z and the rotation velocity $\omega \mathfrak{R}$ is $\geq 2-3$.

In conclusion, our observations resolve, for the first time, the kinematics of a 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 spiraling outward 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. These results provide the best evidence for a MHD disk wind to date. Since 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.

Acknowledgments

We thank Christian Fendt and Daniele Galli for very useful discussion. GAO acknowledges financial support from the Deutscher Akademischer Austauschdienst (DAAD), under the program Research Grants - Doctoral Projects in Germany, and complementary financial support for the completion of the Doctoral degree by the University of Costa Rica, as part of their scholarship program for postgraduate studies in foreign institutions. HB acknowl-

edges support from the European Research Council under the Horizon 2020 Framework Programme via the ERC Consolidator Grant CSF-648505. HB also acknowledges support from the Deutsche Forschungsgemeinschaft in the Collaborative Research Center (SFB 881) “The Milky Way System” (subproject B1). RK acknowledges financial support via the Emmy Noether and Heisenberg Research Grants funded by the German Research Foundation (DFG) under grant no. KU 2849/3 and 2849/9. The European VLBI Network is a joint facility of independent European, African, Asian, and North American radio astronomy institutes. Scientific results from data presented in this publication are derived from the following EVN project code: GM077.

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Table 1. Parameters of the linear and sinusoidal fits

Stream	Linear fit		Sinusoidal fit		
	ω (km s ⁻¹ au ⁻¹)	V_{off} (km s ⁻¹)	$\Re$ (au)	f_z (rad au ⁻¹)	z_0 (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^a	-49 ± 27	17.2 ± 0.3	0.0405 ± 0.0023	7.3 ± 2.3

Notes.

Column 1 denotes the maser stream; Cols. 2 and 3 provide the values of ω and V_{off} from the linear fit of maser V_{LSR} versus R ; Cols. 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 .

^a The determination of this error, smaller than the value, $1.7 \text{ km s}^{-1} \text{ au}^{-1}$, from the linear fit, is discussed in Appendix C.

Fig. 2. October 2020, global VLBI observations of the 22 GHz water masers and 3D view of the proposed interpretation for the maser kinematics. (a) Colored dots give absolute positions of the 22 GHz water masers, with colors denoting the maser V_{LSR} . The black dotted rectangles encompass the three regions, to the N, NE and SW, where maser emission concentrate. The red and black dashed lines mark the sky-projected jet and disk axis, respectively. (b) Illustration of the spiral motion of the masers (small balls) along the helical magnetic field lines (blue) emerging from the rotating YSO's disk. The disk rotation axis is oriented accordingly to our observations. Different colors (red and yellow) distinguish the masers spiraling at smaller and larger radii along the SW-NE, and N streams, respectively. This plot is based on the data from (resistive-radiative-gravito-) MHD simulations of a jet around a forming massive star. The plot size is not to scale with the observations.

Table 2.

Stream	V_z (km s ⁻¹)	ω_K (km s ⁻¹ au ⁻¹)	$\Re_K$ (au)
SW	≥ 48	≥ 2.9	≤ 9
NE-1	≥ 46	≥ 2.6	≤ 10
NE-2	≥ 9	≥ 1.0	≤ 17
NE-3	≥ 85	≥ 5.4	≤ 6

Notes.

Column 1 indicates the maser stream; Col. 2 reports the estimated streaming velocity along the jet axis; Cols. 3 and 4 give the estimate of the angular velocity and the radius, respectively, at the launch point.

Fig. 3. Illustration of the spiral motion of the masers (small red balls) along a magnetic field line (blue) emerging from the YSO's disk. The rotation angle, ϕ , and radius, R , are labeled. The field line is anchored to a point of the disk rotating at an angular velocity ω_K . This plot is based on the data from (resistive-radiative-gravito-) MHD simulations of a jet around a forming massive star.

Fig. 4. The SW spiral motion. (a) Expanding view of the maser positions and V_{LSR} in the SW region. Colored dots have the same meaning as in Fig.2a. The distance along the jet axis (in red) is indicated. (b) Plot of the maser V_{LSR} (and corresponding errors, denoted with errorbars) 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.

Fig. 5. The NE spiral motions. (a) Expanding view of the maser positions and V_{LSR} in the NE 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. Colors denote the maser V_{LSR} . The distance along the jet axis (in red) is indicated. The black dashed rectangle encompasses the maser cluster closest to the YSO. (b) In this and following panel, black, red, and blue colors refer to masers belonging to the NE-1, NE-2, and NE-3 streams, respectively. Errorbars, dashed and dotted lines have the same meaning as in Fig.4b. Masers in the NE-2 stream with similar radii, $10 \text{ au} \leq R \leq 22 \text{ au}$, but different elevations, $60 \text{ au} \leq z < 90 \text{ au}$ and $z \geq 90 \text{ au}$, have V_{LSR} different by $\approx 10 \text{ km s}^{-1}$ (see Appendix D). For the NE-2 stream, the linear fit of the V_{LSR} has been performed considering only the masers with $z \geq 90 \text{ au}$. (c) Plot of the maser V_{LSR} calculated from the linear fits of panel b versus z . Being the plotted velocities a linear transformation of the radii, these plots are equivalent to the R versus z plots, with the advantage to overlap less and improve the visibility of each of the three streams. The dashed curves are the fitted sinusoids. In Table 1, we report the parameters of the sinusoidal fits of the radii.

Fig. 6. The co-rotating N stream. (a) Expanding view of the maser positions and V_{LSR} in the N region. Colored dots and triangles give absolute positions of the 22 GHz water masers, with colors denoting the maser V_{LSR} . The triangles mark a few masers with detached V_{LSR} excluded from 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 $z < 20 \text{ au}$. Plot of maser V_{LSR} versus z (b) and R (c). In both panels, errorbars give the maser V_{LSR} and corresponding errors, and the black dashed and dotted lines show the best linear fit and the associated uncertainty, respectively. The linear fit of V_{LSR} versus R has been performed considering only the masers with $V_{\text{LSR}} \geq -27 \text{ km s}^{-1}$.

306 Appendix A: Observations

307 We observed the $6_{16} - 5_{23}$ H_2O maser transition (rest frequency 22.235079 GHz) to-
 308 wards IRAS 21078+5211 (tracking center: RA(J2000) = $21^{\text{h}}9^{\text{m}}21^{\text{s}}.720$ and Dec(J2000)
 309 = $+52^{\circ}22'37''.08$) with global VLBI for 24 hr, starting on 2020 October 27, 13:30 UT.
 310 The antennae involved were 16 antennae of the European VLBI network (EVN): Yebes,
 311 Sardinia, Medicina, Jodrell_Bank, Effelsberg, Onsala, Metsahovi, Torun, Svetloe, Badary,
 312 Zelenchukskaya, KVN_Tamna, KVN_Ulsan, KVN_Yonsei, Urumqi, Tianma; plus the 10
 313 antennae of the VLBA: Brewster, Fort Davis, Hancock, Kitt Peak, Los Alamos, Mauna Kea,
 314 North Liberty, Owens Valley, Pie Town, and Saint Croix. The observations were designed to
 315 achieve a relative and absolute position accuracy of ~ 0.01 mas and ~ 1 mas, respectively,
 316 and to reach a sensitivity in the maser line ≤ 1 mJy beam $^{-1}$. While the EVN antennae
 317 observed continuously the target, interleaving calibration scans ≈ 8 min long every hour,
 318 the VLBA performed also phase-referencing observations (over 10 hr), alternating scans
 319 on the target and the phase-reference calibrator every 45 s. During the phase-reference
 320 session, the target and the calibrators were always observed by the VLBA simultaneously
 321 with the EVN to ensure global VLBI baselines. The fringe-finder and bandpass calibra-
 322 tors were: J2202+4216, 2007+777, 3C84 and 3C48; the phase-reference calibrators were
 323 2116+543 and 2051+528, both within 2.5° from the target and with a correlated flux of
 324 ~ 0.1 Jy beam $^{-1}$ at 22 GHz.

325 We recorded dual circular polarization through four adjacent bandwidths of 16 MHz,
 326 one of them centered at the maser V_{LSR} of -6.4 km s $^{-1}$. The four 16 MHz bandwidths were
 327 used to increase the signal to noise ratio (SNR) of the weak continuum (phase-reference)
 328 calibrators. The data were processed with the SFXC correlator at the Joint Institute for
 329 VLBI in Europe (JIVE, at Dwingeloo, the Netherlands) in two correlation passes, using
 330 1024 and 128 spectral channels to correlate the maser 16 MHz bandwidth and the whole
 331 set of four 16 MHz bandwidths, respectively. The spectral resolution attained across the
 332 maser 16 MHz band was 0.21 km s $^{-1}$. The correlator averaging time was 1 s.

333 Data were reduced with the Astronomical Image Processing System (AIPS) package
 334 following the VLBI spectral line procedures²². The emission of an intense and compact
 335 maser channel was self-calibrated, and the derived (amplitude & phase) corrections were
 336 applied to all the maser channels before imaging. To cover the whole maser emission, we
 337 produced images extending $0''.65$ in both RA cos δ and DEC, and 84 km s $^{-1}$ in V_{LSR} .
 338 Using natural weighting, the FWHM major and minor sizes of the beam are 0.7 mas and
 339 0.3 mas, respectively, and the beam PA is -49° . In channel maps with (relatively) weak
 340 signal, the 1σ rms noise is 0.7 mJy beam $^{-1}$, close to the expected thermal noise.

341 Inverse phase-referencing²² produced good SNR (≥ 10) images of the two phase-reference
 342 calibrators. Taking into account that the calibrators are relatively compact with size

343 $\lesssim 1$ mas, and that the absolute position of the calibrators is known within a few 0.1 mas,
 344 we estimate that the error on the absolute position of the masers is $\lesssim 0.5$ mas.

345 Table A.3 reports the parameters (intensity, V_{LSR} , position) of the 22 GHz water masers
 346 in IRAS 21078+5211. Individual maser features are a collection of quasi-compact spots
 347 observed on contiguous channel maps and spatially overlapping (within their FWHM size).
 348 The spot positions are determined by fitting a two-dimensional elliptical Gaussian to their
 349 spatial emissions. The uncertainty of the spot position relative to the reference maser
 350 channel is the contribution of two terms: $\Delta\theta_{\text{spot}} = \sqrt{\Delta\theta_{\text{fit}}^2 + \Delta\theta_{\text{bandpass}}^2}$. The first term
 351 depends on the SNR of the data, following²¹: $\Delta\theta_{\text{fit}} = \theta_{\text{beam}} / (2 \text{ SNR})$, where θ_{beam}
 352 is the resolution beam size, conservatively taken equal to the FWHM major beam size of
 353 0.7 mas. The second term depends on the accuracy of the bandpass calibration through the
 354 expression²⁶: $\Delta\theta_{\text{bandpass}} = \theta_{\text{beam}} (\Delta\Psi/360^\circ)$, where $\Delta\Psi$ in degrees is the phase stability
 355 across the observing band. In our case $\Delta\Psi \lesssim 10^\circ$ and $\Delta\theta_{\text{bandpass}} \lesssim 0.02$ mas becomes
 356 the dominant error term for spot intensity ≥ 100 mJy beam⁻¹. The maser feature position
 357 (and corresponding error) is estimated from the error-weighted mean of the spot positions
 358 (and corresponding errors), and the feature V_{LSR} from the intensity-weighted mean of the
 359 spots' V_{LSR} . To be conservative, the uncertainty on the feature V_{LSR} is taken equal to
 360 0.5 km s⁻¹, corresponding to half of the typical maser FWHM line width.

361 Appendix B: Resolving the NE emission into three distinct streams

362 The masers in the NE emission are separated into three distinct streams identified with
 363 different symbols: dots, triangles and squares (see Fig.5a). Each stream traces a sinusoid in
 364 the plane of the sky (see Fig.5c), which is the signature for a spiral motion. The identifica-
 365 tion of the maser features belonging to each of the three sinusoids can be done with good
 366 confidence. First, we note that the masers at elevation $z \geq 90$ au can be unambiguously
 367 divided into two streams, dots and triangles, on the basis of the very different V_{LSR} of
 368 nearby emissions. Both dots and triangles at $z \geq 90$ au have R decreasing with z ,
 369 suggesting that they could trace the descending portion of a sinusoid, and one can argue
 370 that the corresponding ascending portion would be traced by masers with $z < 90$ au.
 371 Next, we note that the group of masers with $30 \text{ au} \leq z \leq 60 \text{ au}$ draw an arc, and, since
 372 they cannot be part of a sinusoid together with other masers at larger R , they have to
 373 trace a third sinusoid with maximum radius close to the radius, $R_{\text{apex}} = 17.2$ au, of the
 374 apex of the arc. We have also verified that the blue-shifted cluster of masers located at
 375 elevation $z \approx 20$ au (inside the dashed rectangle of Fig.5a) cannot be adjusted within this
 376 third sinusoid. We have fitted the expression:

$$377 \quad R = (R_{\text{apex}} - C) + C \sin(f_z(z - z_0)) \quad (B.1)$$

379 with the maximum radius fixed to R_{apex} and the zero level given by $R_{\text{apex}} - C$, with C
 380 free parameter. When the masers at elevation $z \approx 20$ au and those drawing the arc at
 381 $30 \text{ au} \leq z \leq 60 \text{ au}$ are considered together, the fit of Eq. B.1 results into an implausible,
 382 very negative zero level at ≈ -60 au. Thus, after putting all the masers with 30 au
 383 $\leq z \leq 60 \text{ au}$ (and only them) into a third spiral motion, it remains to deal only with the
 384 masers in the two separated ranges $20 \text{ au} \leq z < 30 \text{ au}$ and $60 \text{ au} \leq z < 90 \text{ au}$. The
 385 sinusoidal fit of R versus z of the triangles at $z \geq 90 \text{ au}$ indicates that the ascending
 386 portion of the sinusoid has to extend from $\approx 50 \text{ au}$ to $\approx 90 \text{ au}$, and, over that range
 387 of elevations, intercepts all the observed masers. Finally, the remaining masers at 20 au
 388 $\leq z < 30 \text{ au}$ trace the ascending portion of the sinusoid identified with dots in Fig.5a.

389 **Appendix C: The angular velocity of the NE-3 stream**

390 The NE-3 stream is sampled by the masers only close to the positions where it attains the
 391 maximum radius. Because of the small radial range, $15 \text{ au} \lesssim R \lesssim 17 \text{ au}$, the linear fit of
 392 V_{LSR} versus R constrains very little the angular velocity, $\omega = 2.04 \pm 1.72 \text{ km s}^{-1} \text{ au}^{-1}$.
 393 However, since R , and the rotational velocity ωR , are sinusoidal functions of the elevation
 394 z , we can use the results of the sinusoidal fits to reduce the error in ω . For plausible values
 395 of ω in the range 0–4, we have performed the sinusoidal fit of the rotational velocity, and
 396 estimated the radius from the ratio of the fitted amplitude, $\mathfrak{C}$, and ω . For a given value of
 397 ω , we have fitted the expression:

$$\omega R = (\omega R_{\text{apex}} - \mathfrak{C}) + \mathfrak{C} \sin(f_z(z - z_0)) \quad (\text{C.1})$$

400 fixing the maximum velocity to ωR_{apex} and fitting the zero level $\omega R_{\text{apex}} - \mathfrak{C}$, with the
 401 amplitude $\mathfrak{C}$ as a free parameter. Fig.C.1 shows that, apart a minor fraction of scattered
 402 results, the radius estimated from the sinusoidal fit decreases regularly with ω , and attains
 403 a value consistent with the observations, $17.5 \pm 2.5 \text{ au}$, for $\omega = 2.0 \pm 0.5 \text{ km s}^{-1} \text{ au}^{-1}$,
 404 thus effectively reducing the uncertainty to $0.5 \text{ km s}^{-1} \text{ au}^{-1}$.

405 **Appendix D: Velocity scatter**

406 Figs. 4b and 5b show that the maser V_{LSR} are linearly correlated with R in the SW and
 407 NE-1 streams. For the masers belonging to the NE-2 stream, the measurement scatter from
 408 the linear fit of V_{LSR} versus R is considerable (with large fit errors, see Table 1), while,
 409 in the case of the NE-3 stream, the range in R is too small (2 au only) to constrain the
 410 parameters of the linear fit. The noticeable deviation of V_{LSR} from the linear fits seems
 411 difficult to conciliate with the accuracy with which the maser positions reproduce the
 412 sinusoidal patterns (see Figs. 4c and 5c). The average scatters of maser V_{LSR} and positions
 413 (along the jet axis from the fitted sinusoid) are 2.4 km s^{-1} and 1.9 au , 3.1 km s^{-1} and

Fig. C.1. Constraining ω for the NE-3 stream. Plot of the rotation radius estimated from the ratio $\mathfrak{C}/\omega$ versus ω , where $\mathfrak{C}$ is the amplitude of the sinusoidal fit of the rotational velocity, ωR , versus z (see Appendix C). The blue continuous and dashed lines mark the observed value of the rotation radius and the corresponding range of uncertainty, respectively; the red dashed lines delimit the range of ω for which the fitted radius is consistent with the observations.

3.8 au, 6.9 km s⁻¹ and 2.1 au, and 2.7 km s⁻¹ and 1.7 au, for the SW, NE-1, NE-2 and NE-3 streams, respectively. Assuming that the V_{LSR} scatter reflects mainly the variation of the streaming velocity V_z , since the jet axis is within 30° from the plane of the sky, the change in V_z has to be at least twice that observed in V_{LSR} . Then, using the above values, the ratios of the corresponding scatters in position and V_z give upper limits for the maser traveling times of $\leq 1\text{--}3$ yr. These traveling times, for maximum (absolute) elevations of the maser streams of 100–130 au (see Figs. 4 and 5), imply $V_z \geq 200\text{--}500$ km s⁻¹, which appears to be too large with respect to the observed maser V_{LSR} . In the following, we investigate the physical reason for the observation of well defined sinusoidal patterns despite the co-occurrence of significant velocity scatters.

In a stationary, axisymmetric MHD flow, the two fundamental equations of motions^{16,20,19} linking velocity and magnetic field along a field line are:

$$\rho V_p = k B_p \quad (\text{D.1})$$

$$B_\phi = \frac{\rho}{k} (V_\phi - \omega_K \mathfrak{R}) \quad (\text{D.2})$$

where V_p and V_ϕ , and B_p and B_ϕ are the poloidal and toroidal components of the velocity and magnetic field, respectively, ρ is the gas mass volume density, ω_K is the Keplerian angular velocity at the launch point, $\mathfrak{R}$ is the rotation radius, and k is the "mass load" of the wind, expressing the fixed ratio of mass and magnetic fluxes along a given magnetic field line. Since $V_\phi - \omega_K \mathfrak{R}$ is the toroidal velocity in the reference frame co-rotating with the launch point, Eqs. D.1 and D.2 lead to the well-known result that the velocity and magnetic field vectors are always parallel in the co-rotating reference frame. Writing $V_\phi = \omega \mathfrak{R}$, where ω is the angular velocity of the trajectory at radius $\mathfrak{R}$, the

two equations above can be combined into:

$$\frac{B_\phi}{B_p} = \frac{(\omega - \omega_K)}{V_p} \mathfrak{R} = \frac{\omega_e}{V_p} \mathfrak{R} \quad (\text{D.3})$$

where we have used the definition of ω_e in Eq. 6. We can define the magnetic field helix angle $\alpha_B = \arctan(B_\phi/B_p)$, which is the angle with which a helical field line winds around the jet axis.

We have seen that the observation of well defined sinusoids in the plane of the sky requires that the rotation radius $\mathfrak{R}$, and the ratio of the effective angular velocity ω_e on the streaming velocity V_z keep constant (see Eq. 7). Since the polar velocity V_p is equal to V_z if $\mathfrak{R}$ is constant, Eq. D.3 implies that α_B does not vary along each of the observed maser streams. However, the reverse argument holds too. If the magnetic field is sufficiently stable and has a constant helix angle (that is, a helical configuration), the motion along the field line (in the co-rotating reference frame) requires a constant value of the ratio ω_e/V_z . That preserves the maser sinusoidal pattern despite the concomitant presence of a relatively large velocity scatter. From Eqs. D.3 and 7, with $V_p = V_z$, we have:

$$\frac{|B_\phi|}{B_p} = f_z \mathfrak{R} \quad (\text{D.4})$$

Using the values reported in Table 1, we derive: $f_z \mathfrak{R} = 0.79 \pm 0.06$, 1.1 ± 0.2 , 0.88 ± 0.04 , and 0.70 ± 0.05 for the SW, NE-1, NE-2 and NE-3 streams, respectively. From Eq. D.2, $B_\phi \approx 0$ within the Alfvén point when the flow co-rotates with the disk and $V_\phi \approx \omega_K \mathfrak{R}$. Beyond the Alfvén point, the inertia of the matter in the flow forces the magnetic field to fall behind the rotation of the disk, which causes $|B_\phi|$ to increase. The derived values of the ratio $|B_\phi|/B_p$ in the range 0.7–1.1 agree with the water masers tracing a region of the spiraling trajectory in between the Alfvén point and the fast magneto-sonic point, beyond which the toroidal magnetic field component should become the predominant component^{20,23}.

Finally, we discuss briefly possible causes for the observed velocity scatter. For the SW, NE-1, and NE-2 spiral motions, the residual of the linear fit of V_{LSR} versus R is plotted versus z in Fig.D.1. These plots indicate that the residual velocity is not correlated with position, contrarily to what it would be expected if the velocity scatter from the linear fit was caused by the smooth change with z of the characteristic velocities, ω and V_z (and consequently V_{off}), of the spiraling trajectory. The irregular change of the velocities can be naturally linked to our flow tracers, the water masers, which are excited in internal shocks of the flow emerging from perturbed locations of the disk. Eq. D.1 and D.2 show that the flow velocity depends critically on the mass load k , which, on its turn, depends on the physical conditions, including dissipative processes, near the disk surface. If the physical conditions of the perturbed launch points varied erratically on time scales so short as months, that would qualitatively explain the observed scatter of maser velocities. Emission variability

Fig. D.1. Maser velocity scatter. The residual velocity from the linear fit of maser V_{LSR} versus R (see Figs. 4b and 5b) is plotted versus $|z|$ for the masers in the SW (upper panel), NE-1 (central panel), and NE-2 (lower panel) streams.

over time scales of months is observed and theoretically expected in accretion bursts from high-mass YSOs^{4,8,14}, in such cases where an extended portion of the accretion disk gets perturbed.

Appendix E: Constraining the Alfvén point of the NE-1 stream

Fig.E.1 shows that the V_{LSR} of the five masers at the base ($z \approx 20$ au) of the NE-1 stream (inside the dashed rectangle of Fig.5a) changes linearly with R . The derived value of $\omega = 1.82 \pm 0.09 \text{ km s}^{-1} \text{ au}^{-1}$ is significantly higher than the value, $1.15 \pm 0.09 \text{ km s}^{-1} \text{ au}^{-1}$ (see Table 1), determined at larger elevations. That can be interpreted as evidence that the gas closer to the Alfvén point rotates faster than that at higher elevations, in agreement with the MHD disk-wind theory. As described in Appendix A, each maser feature is a collection of many compact spots for which we have accurately measured position and V_{LSR} . For the maser feature (out of the five) nearest to the jet axis, Fig.E.2a shows that the spatial distribution of the spots is linear and elongated close to (7° away from) the disk axis, and Fig.E.2b shows that the spot V_{LSR} changes linearly with the position, ΔR , along the major axis of the spatial distribution. Given its orientation, it is natural to interpret the V_{LSR} gradient internal to the maser feature in terms of rotation, and from the linear fit of V_{LSR} versus ΔR we derive a value of $\omega = 2.3 \pm 0.1 \text{ km s}^{-1} \text{ au}^{-1}$. This should still be considered a lower limit for ω_K , the angular velocity at the Alfvén point. Beside the one just considered, other two maser features present a well defined, internal V_{LSR} gradient. In these two features, the linear distribution of the spots is directed at larger angles, $20\text{--}30^\circ$, from the disk axis, and the amplitudes of the V_{LSR} gradients are 1.8 ± 0.1 and $3.1 \pm 0.1 \text{ km s}^{-1} \text{ au}^{-1}$. These two features have larger separation from the jet axis

Fig. E.1. Estimate of ω at the base of the NE-1 stream. Plot of V_{LSR} versus R for the maser cluster at the base of the NE-1 stream, inside the dashed rectangle in Fig.5a. Vertical black and horizontal red errorbars indicate velocities and radii (with corresponding errors), respectively. The black dashed and dotted lines show the best linear fit and the associated uncertainty, respectively.

Fig. E.2. Rotation inside individual maser features. (a) Colored errorbars give positions (and corresponding errors) of the individual spots collected into the maser feature, with colors denoting the maser V_{LSR} . The black continuous and dashed lines give the best linear fit of the spot positions and the associated uncertainty, respectively. (b) Plot of the spot V_{LSR} versus positions projected along the major axis of the spot distribution. The black continuous and dashed lines show the best linear fit of the plotted values and the associated uncertainty, respectively.

496 and the corresponding larger inclination of the spot distribution with the plane of rotation
 497 could indicate that the internal V_{LSR} gradient is influenced by non-rotation terms, as, for
 498 instance, the increase of the streaming velocity with the elevation. In any case, assuming
 499 that also for these two features the internal V_{LSR} gradient is dominated by rotation, we
 500 obtain a consistent average value for the in-feature angular velocity of $\omega = 2.4 \text{ km s}^{-1} \text{ au}^{-1}$.

501 **Correspondence and Request for Material:**

502 Any request should be addressed to Luca Moscadelli

503 **Data Availability:**

504 This letter makes use of the following EVN data: GM077 (EVN project code).

505 The datasets generated during and/or analyzed during the current study are available
506 from the corresponding author on reasonable request.

507 **Author Contribution Statement:**

508 L.M. led the project, analysis, discussion, and drafted the manuscript.

509 A.S, H.B., and R.K. commented on the manuscript and participated in the discussion.

510 G.A.O. produced the plots to illustrate the streamlines and magnetic field lines

511 G.A.O. and R.K. performed the numerical jet simulations on which the illustrations are
512 based on.

513 **Competing Interests:**

514 The authors declare no competing (financial and non-financial) interests.

Table A.3. 22.2 GHz H₂O maser parameters for IRAS 21078+5211

Feature Number	I _{peak} (Jy beam ⁻¹)	V _{LSR} (km s ⁻¹)	Δ <i>x</i> (mas)	Δ <i>y</i> (mas)
1	53.066	-21.6	0	0
2	14.326	-3.0	60.42±0.03	27.87±0.03
3	14.017	-24.0	-14.93±0.03	51.87±0.03
4	10.457	-28.5	-1.55±0.03	58.23±0.03
5	7.082	0.4	-42.37±0.03	-36.16±0.03
6	6.565	-1.0	56.89±0.03	18.87±0.03
7	6.502	-15.2	23.06±0.03	-4.24±0.03
8	5.543	-30.2	-1.29±0.03	59.10±0.03
9	4.904	-21.8	0.07±0.03	0.46±0.03
10	4.866	-15.1	33.59±0.03	3.34±0.03
11	4.812	-19.8	58.57±0.03	32.40±0.03
12	4.395	-24.8	-14.78±0.03	52.52±0.03
13	4.273	5.0	-43.75±0.03	-40.90±0.03
14	4.072	-3.2	60.79±0.03	28.54±0.03
15	3.556	-25.2	14.57±0.03	-3.37±0.03
16	3.397	1.5	61.14±0.03	31.34±0.03
17	3.387	-0.1	-41.84±0.03	-34.58±0.03
18	3.206	-15.4	33.76±0.03	3.88±0.03
19	3.177	-22.7	-11.28±0.03	22.53±0.03
20	2.485	-11.7	53.03±0.03	19.32±0.03
21	2.391	-17.3	29.96±0.03	-0.05±0.03
22	2.247	-2.1	59.06±0.03	22.92±0.03
23	2.154	-24.1	-15.03±0.03	51.42±0.03
24	2.072	4.3	-44.37±0.03	-39.19±0.03
25	2.062	-16.2	25.54±0.03	-3.08±0.03
26	1.952	4.5	-45.06±0.03	-41.80±0.03
27	1.926	-6.2	60.50±0.03	38.38±0.03
28	1.740	-27.4	-11.03±0.03	22.50±0.03
29	1.661	-37.8	55.01±0.03	33.58±0.03
30	1.631	-10.8	62.36±0.03	37.98±0.03
31	1.537	5.2	-43.54±0.03	-40.37±0.03
32	1.420	-27.5	121.15±0.03	120.88±0.03
33	1.137	-2.0	57.72±0.03	20.15±0.03
34	1.109	17.1	-11.32±0.03	-16.69±0.03

Table A.3. continued.

Feature Number	I_{peak} (Jy beam ⁻¹)	V_{LSR} (km s ⁻¹)	Δx (mas)	Δy (mas)
35	0.986	-1.6	58.65±0.03	22.43±0.03
36	0.954	-8.1	61.04±0.03	38.18±0.03
37	0.866	-13.6	21.30±0.03	-5.56±0.03
38	0.859	-9.5	44.93±0.03	10.49±0.03
39	0.774	-16.5	23.77±0.03	-3.55±0.03
40	0.756	0.4	59.72±0.03	27.76±0.03
41	0.745	-10.7	44.31±0.03	10.40±0.03
42	0.678	-22.7	14.29±0.03	-4.41±0.03
43	0.649	-8.9	120.25±0.03	100.23±0.03
44	0.554	-0.0	-42.04±0.03	-35.56±0.03
45	0.539	-30.3	-1.21±0.03	59.56±0.03
46	0.512	6.7	-57.34±0.03	-138.41±0.03
47	0.428	-8.9	44.04±0.03	9.57±0.03
48	0.375	-25.2	14.07±0.03	-3.40±0.03
49	0.374	-15.8	34.29±0.03	4.60±0.03
50	0.367	-23.3	14.55±0.03	-3.95±0.03
51	0.364	-4.3	60.56±0.03	30.64±0.03
52	0.358	-9.1	61.21±0.03	37.42±0.03
53	0.352	-18.1	118.48±0.03	99.46±0.03
54	0.339	-31.6	55.84±0.03	40.17±0.03
55	0.290	-8.5	121.39±0.03	100.59±0.03
56	0.270	-1.7	58.08±0.03	21.15±0.03
57	0.268	-3.5	138.43±0.03	90.24±0.03
58	0.266	-17.4	29.50±0.03	-0.42±0.03
59	0.259	-10.0	43.61±0.03	9.66±0.03
60	0.228	-25.8	-8.48±0.03	57.46±0.03
61	0.213	-30.6	55.99±0.03	39.54±0.03
62	0.200	-16.9	33.88±0.03	4.64±0.03
63	0.200	-12.2	21.80±0.03	-5.36±0.03
64	0.199	-10.1	62.03±0.03	38.42±0.03
65	0.195	-15.6	33.15±0.03	2.76±0.03
66	0.191	4.4	-45.46±0.03	-42.22±0.03
67	0.185	-16.5	24.85±0.03	-3.22±0.03
68	0.181	-8.5	124.31±0.03	100.94±0.03

Table A.3. continued.

Feature Number	I_{peak} (Jy beam $^{-1}$)	V_{LSR} (km s $^{-1}$)	Δx (mas)	Δy (mas)
69	0.178	0.5	-40.76 $\pm$ 0.03	-32.20 $\pm$ 0.03
70	0.170	-12.1	34.87 $\pm$ 0.03	5.95 $\pm$ 0.03
71	0.164	-1.2	60.11 $\pm$ 0.03	34.24 $\pm$ 0.03
72	0.161	-13.0	59.54 $\pm$ 0.03	29.23 $\pm$ 0.03
73	0.161	-1.9	61.56 $\pm$ 0.03	32.23 $\pm$ 0.03
74	0.161	-8.4	122.16 $\pm$ 0.03	100.72 $\pm$ 0.03
75	0.155	-19.9	58.58 $\pm$ 0.03	31.90 $\pm$ 0.03
76	0.155	-33.7	55.96 $\pm$ 0.03	37.71 $\pm$ 0.03
77	0.152	1.0	58.10 $\pm$ 0.03	23.42 $\pm$ 0.04
78	0.145	2.0	-42.80 $\pm$ 0.03	-37.01 $\pm$ 0.03
79	0.138	-27.5	-10.99 $\pm$ 0.03	22.85 $\pm$ 0.03
80	0.132	-26.0	30.09 $\pm$ 0.03	0.66 $\pm$ 0.03
81	0.127	-13.4	62.41 $\pm$ 0.03	36.36 $\pm$ 0.03
82	0.121	6.8	38.38 $\pm$ 0.03	-105.32 $\pm$ 0.03
83	0.107	-20.4	14.92 $\pm$ 0.05	-5.16 $\pm$ 0.05
84	0.105	-12.1	58.11 $\pm$ 0.03	25.16 $\pm$ 0.03
85	0.102	-1.0	61.01 $\pm$ 0.03	30.58 $\pm$ 0.04
86	0.101	-18.0	65.66 $\pm$ 0.03	36.02 $\pm$ 0.03
87	0.099	-18.6	-4.44 $\pm$ 0.03	57.01 $\pm$ 0.03
88	0.097	-23.5	-15.53 $\pm$ 0.03	49.39 $\pm$ 0.03
89	0.096	1.6	57.02 $\pm$ 0.03	21.67 $\pm$ 0.03
90	0.094	-1.2	-44.13 $\pm$ 0.03	-38.22 $\pm$ 0.03
91	0.094	2.9	60.86 $\pm$ 0.03	30.86 $\pm$ 0.03
92	0.093	5.7	-42.83 $\pm$ 0.03	-39.80 $\pm$ 0.03
93	0.091	-34.2	-12.84 $\pm$ 0.03	51.09 $\pm$ 0.03
94	0.074	-26.3	-11.14 $\pm$ 0.03	22.22 $\pm$ 0.03
95	0.069	-18.4	30.26 $\pm$ 0.03	0.51 $\pm$ 0.03
96	0.069	-8.3	127.68 $\pm$ 0.03	100.86 $\pm$ 0.03
97	0.067	-0.2	-40.55 $\pm$ 0.05	-31.83 $\pm$ 0.04
98	0.065	0.0	58.01 $\pm$ 0.04	21.83 $\pm$ 0.05
99	0.065	-18.2	-12.24 $\pm$ 0.03	22.63 $\pm$ 0.03
100	0.064	-17.9	-20.70 $\pm$ 0.03	26.63 $\pm$ 0.03
101	0.064	-19.8	-22.59 $\pm$ 0.03	32.39 $\pm$ 0.03
102	0.063	-10.9	62.10 $\pm$ 0.03	37.24 $\pm$ 0.03

Table A.3. continued.

Feature Number	I_{peak} (Jy beam $^{-1}$)	V_{LSR} (km s $^{-1}$)	Δx (mas)	Δy (mas)
103	0.062	-10.6	35.68 $\pm$ 0.03	8.84 $\pm$ 0.03
104	0.061	17.0	-11.54 $\pm$ 0.03	-16.91 $\pm$ 0.03
105	0.060	-14.3	41.60 $\pm$ 0.03	10.24 $\pm$ 0.03
106	0.056	9.1	-45.72 $\pm$ 0.03	-44.04 $\pm$ 0.03
107	0.051	-0.9	-21.86 $\pm$ 0.05	-17.36 $\pm$ 0.04
108	0.049	-9.9	37.06 $\pm$ 0.03	7.68 $\pm$ 0.03
109	0.048	-14.7	59.47 $\pm$ 0.03	28.61 $\pm$ 0.03
110	0.048	2.7	58.82 $\pm$ 0.03	25.55 $\pm$ 0.03
111	0.047	-12.2	59.77 $\pm$ 0.03	29.64 $\pm$ 0.03
112	0.046	-12.5	43.30 $\pm$ 0.03	11.05 $\pm$ 0.03
113	0.046	-8.3	-41.69 $\pm$ 0.03	-23.95 $\pm$ 0.03
114	0.044	-12.5	62.24 $\pm$ 0.03	35.91 $\pm$ 0.03
115	0.044	-1.1	-23.09 $\pm$ 0.06	-18.46 $\pm$ 0.05
116	0.043	-16.0	59.12 $\pm$ 0.04	27.70 $\pm$ 0.04
117	0.043	-33.2	-13.02 $\pm$ 0.03	50.88 $\pm$ 0.03
118	0.041	11.6	12.77 $\pm$ 0.03	-29.04 $\pm$ 0.03
119	0.040	10.5	12.91 $\pm$ 0.03	-27.04 $\pm$ 0.03
120	0.039	-11.5	44.63 $\pm$ 0.03	10.64 $\pm$ 0.03
121	0.039	-7.7	36.05 $\pm$ 0.03	7.54 $\pm$ 0.03
122	0.036	-5.9	60.39 $\pm$ 0.03	37.90 $\pm$ 0.03
123	0.036	11.0	-50.13 $\pm$ 0.03	-135.02 $\pm$ 0.03
124	0.033	-27.4	121.11 $\pm$ 0.04	120.44 $\pm$ 0.03
125	0.032	-18.4	-21.05 $\pm$ 0.03	27.82 $\pm$ 0.03
126	0.032	3.6	-43.27 $\pm$ 0.03	-38.14 $\pm$ 0.04
127	0.032	-31.6	56.14 $\pm$ 0.03	40.39 $\pm$ 0.03
128	0.030	-29.4	54.79 $\pm$ 0.03	35.16 $\pm$ 0.03
129	0.029	-10.8	46.33 $\pm$ 0.04	11.49 $\pm$ 0.03
130	0.029	-20.1	-22.18 $\pm$ 0.04	37.50 $\pm$ 0.04
131	0.027	9.7	-59.68 $\pm$ 0.03	-137.27 $\pm$ 0.03
132	0.025	-5.8	110.29 $\pm$ 0.04	56.94 $\pm$ 0.04
133	0.022	-14.1	34.57 $\pm$ 0.04	5.08 $\pm$ 0.04
134	0.021	5.9	-42.25 $\pm$ 0.03	-39.12 $\pm$ 0.03
135	0.020	-29.4	56.24 $\pm$ 0.04	35.30 $\pm$ 0.04
136	0.019	10.9	13.38 $\pm$ 0.04	-27.78 $\pm$ 0.04

Table A.3. continued.

Feature Number	I_{peak} (Jy beam ⁻¹)	V_{LSR} (km s ⁻¹)	Δx (mas)	Δy (mas)
137	0.019	-18.3	24.24±0.04	-3.28±0.04
138	0.018	10.8	-59.98±0.04	-136.68±0.04
139	0.017	29.3	-59.75±0.03	-120.52±0.03
140	0.017	-5.8	108.81±0.05	57.04±0.05
141	0.017	-18.3	118.43±0.05	98.90±0.04
142	0.016	-31.0	64.36±0.04	45.69±0.05
143	0.015	-7.6	134.19±0.04	91.17±0.04
144	0.015	19.2	-48.27±0.04	-55.22±0.04
145	0.013	7.3	34.56±0.04	-116.70±0.04
146	0.013	-12.7	39.14±0.05	9.70±0.05
147	0.012	-8.8	119.61±0.05	100.15±0.05
148	0.011	13.5	11.24±0.04	-30.82±0.04
149	0.011	-33.5	-13.27±0.04	50.41±0.04
150	0.011	10.4	12.78±0.04	-26.19±0.04
151	0.011	-5.5	111.16±0.05	56.61±0.05
152	0.011	19.0	-60.91±0.04	-124.10±0.04
153	0.010	13.4	12.64±0.04	-32.15±0.04
154	0.010	-5.3	140.28±0.05	33.19±0.05
155	0.010	-31.7	1.13±0.04	61.26±0.04
156	0.009	17.9	-63.61±0.05	-124.63±0.05
157	0.009	-7.6	123.27±0.06	101.80±0.05
158	0.009	-18.7	-21.77±0.06	29.92±0.05
159	0.008	8.6	33.57±0.05	-119.04±0.05
160	0.008	-33.0	-12.72±0.05	51.44±0.05
161	0.008	-5.4	83.67±0.06	45.45±0.07
162	0.008	-9.1	98.09±0.09	68.97±0.08
163	0.007	-39.6	140.57±0.06	213.71±0.06
164	0.007	-37.1	139.82±0.06	214.08±0.06
165	0.006	11.9	13.04±0.06	-29.94±0.05
166	0.006	8.6	40.93±0.06	-85.43±0.07
167	0.006	10.3	-62.68±0.08	-66.21±0.06
168	0.005	12.5	-45.00±0.06	-44.03±0.05

Notes.

Column 1 gives the feature label number; Cols. 2 and 3 provide the intensity of the strongest spot and the intensity-weighted spots' V_{LSR} , respectively; Cols. 4 and 5 give the position offsets (with the associated errors) towards East and North, respectively, relative to feature # 1.

The absolute position of feature # 1 is: R.A. (J2000) = $21^{\text{h}} 9^{\text{m}} 21^{\text{s}}.7099$, Dec (J2000) = $52^{\circ} 22' 37''.001$. The absolute position is evaluated at the observing epoch: October 27, 2020.