Super-rotating protostellar jets

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Protostellar jets are most striking phenomena in star-forming regions and considered to be an essential ingredient in the star formation process. Stars form in gravitationally collapsing clouds. The mass of protostar at its birth is equivalent to Jovian mass or 0.1 percent of the solar mass\textsuperscript{22}. After the birth, the protostar acquires its mass by accreting material from a surrounding rotation disk embedded in an infalling envelope that is a remnant of the natal cloud of the star. Protostellar jets are believed to expel the excess angular momentum from the circumstellar region that allows accretion onto the star. Here, we report the detection of super-rotating jets driven from a protostar FIR 6b (HOPS 60) in Orion Molecular Cloud-2 \textsuperscript{34}. The jet rotation velocity exceeds \textit{20 km s\textsuperscript{-1}} and the specific angular momentum of the jet is as large as \textit{\sim 10^{-4} cm^2 s^{-1}}, which hitherto are the largest that have been observed in protostellar jets. The extraordinary large rotation velocity and specific angular momentum can be explained by a magnetohydrodynamic disk wind.\textsuperscript{35} This is clear evidence that magnetic fields play a crucial role for protostellar evolution and that angular momentum is removed by protostellar jets.

The target FIR 6b (HOPS 60) is located in Orion Molecular Cloud-2 (hereafter we call this object FIR 6b) and identified as a Class 0 intermediate mass protostar\textsuperscript{23}. The distance to FIR 6b is \textit{d \sim 392 pc} and the systemic velocity is \textit{v_{sys} \sim 11 km s^{-1}} in the Local Standard of Rest (LSR)\textsuperscript{36}. FIR 6b has a bolometric luminosity of \textit{L_{bol} \sim 21.9 L_{\odot}}.\textsuperscript{37} A low-velocity (\textit{\sim 5 km s^{-1}}) bipolar outflow was already observed in the northeast to southwest direction toward the protostar FIR 6b\textsuperscript{38}.\textsuperscript{39} A small amount of gas remains in the envelope around FIR 6b\textsuperscript{40}.\textsuperscript{41}. In addition, the disk-like structure with a size of \textit{\sim 120 au} and \textit{\sim 56 au} were also inferred from continuum observations at 0.87 mm by the Atacama Large Millimeter/submillimetre Array (ALMA) and 9 mm by the Very Large Array (VLA), respectively\textsuperscript{42}. Thus, FIR 6b is expected to be in the later main accretion phase and considered to be a Class 0 protostar.

We observed the region around FIR 6b using ALMA. For the first time, we confirm the high-velocity jets (or high-velocity jets) driven from FIR 6b. The high-velocity jets have a well-collimated structure within which several knots or blobs are embedded (Fig. 1). The length of the jets is \textit{\sim 4800 au} as a whole, while the jet width is \textit{\sim 2400 – 5000 au} depending on the distance from the central protostar. Although the CO emission in the southwest direction is slightly distorted near FIR 6b, the jets have a roughly point symmetric structure toward the central protostar FIR 6b (Fig. 1). The asymmetrical velocity structure in the upper- and lower-side of jets is sometimes seen in other observations.\textsuperscript{43} Recent simulation also indicates that the asymmetric jet (velocity) can be realized by the temporal asymmetric mass accretion from the infalling envelope onto the circumstellar disk\textsuperscript{44}. The northeast side of the jet moves away from us with a velocity range of \textit{22.5 km s\textsuperscript{-1}} to \textit{87.5 km s\textsuperscript{-1}} with respect to the systemic velocity, while the southwest side is coming toward us with a velocity of \textit{10 km s\textsuperscript{-1}} to \textit{27.5 km s\textsuperscript{-1}} with respect to the systemic velocity. Thus, the northeast part corresponds to the red-shifted component (or the red-shifted jet), while the southwest part is the blue-shifted component (or the blue-shifted jet). The propagation direction of the high-velocity components is the same as that of the low-velocity components reported in previous studies\textsuperscript{40}. Since the jets have a velocity range of \textit{10 km s\textsuperscript{-1}} to \textit{87.5 km s\textsuperscript{-1}} with respect to the systemic velocity in the redshifted components, the intrinsic jet peak velocity exceeds \textit{100 km s\textsuperscript{-1}} after correcting for jet inclination angle of \(i = 80^\circ\) with respect to the line of sight. However, the blue-shifted jet has slower velocity than the red-shifted one, and no high velocity component has been observed in the southeast direction. In this paper, we mainly discuss the red-shifted component to focus on the jet rotation in the high velocity component.

Figure 1 | CO (\textit{J}=2–1) high velocity integrated intensity map (color and black contour). High velocity components of the CO (\textit{J}=2–1) emission are integrated over the LSR velocity ranges of \textit{32.5 to 97.5 km s\textsuperscript{-1}} (red-shifted component, northeast side) and \textit{17.5 to 0 km s\textsuperscript{-1}} (blue-shifted component, southwest side). The 1.3 mm continuum emission is overlaid with gray contours, which shows the peak toward OMC-2/FIR 6b at (R.A., Dec.) = (05h35m23.34s, -05\degree12\arcmin03\arcsec.970). The integrated CO emission shows a well-collimated structure that is distributed from the northeast to the southwest direction centered around FIR 6b. Several knots corresponding to the local emission peaks indicated by arrows are found within the jets. The synthesized beams are denoted in the left bottom with a black open ellipse for the CO emission and filled gray ellipse for the 1.3 mm continuum emission, respectively. The contour levels of the CO emission are \textit{5\sigma}, \textit{10\sigma}, \textit{15\sigma}, and \textit{20\sigma}, (\textit{1\sigma} = 1.0 Jy beam\textsuperscript{-1} \cdot km s\textsuperscript{-1}), and those of the 1.3 mm continuum emission are \textit{8\sigma}, \textit{40\sigma}, \textit{80\sigma}, \textit{120\sigma}, \textit{160\sigma}, \textit{240\sigma}, and \textit{320\sigma} (\textit{1\sigma} = 0.2 mJy beam\textsuperscript{-1}).

Fig. 2 shows maps of the mean velocity obtained from the CO (\textit{J}=2–1) emission. A clear velocity gradient is found along the jet short-axis in the red-shifted jet (Fig. 2a). The northern part of the red-shifted jet is moving towards the front and the southern part is moving...
toward the back. The velocity shifts along the minor axis by 25 km s\(^{-1}\) to 50 km s\(^{-1}\). Thus, the red-shifted jet seems to rotate around its long axis. Several alternative interpretations might be considered to explain the velocity gradient such as jet precession, twin jets and asymmetrical jet structure. Thus, we need to carefully investigate the cause of the velocity gradient.

When the jet precesses, the velocity gradient tends to appear along the jet long-axis or the jet propagation direction. On the other hand, the jet velocity would not be significantly changed along the jet short-axis in the precession model. In addition, the precessing jet should have a strong wave-like structure as a whole, while the observed jet is straight in both the red-shifted and blue-shifted lobes in the integrated intensity map (Fig. 1).

If FIR 6b is a binary system, two protostars can drive two jets. In such a case, the velocity gradient (Fig. 2a) can be potentially explained by twin jets if the direction of jets is slightly different each other. It seems that the red-shifted jet splits along its long-axis in the velocity map (Fig. 2a). However, we cannot see any signature of the twin jets in the integrated intensity map (Fig. 1). In addition, there is no evidence for a protobinary system in the dust continuum within the ALMA at 1.3 mm data at 400 au spatial resolution (Fig. 1) nor in ALMA at 0.87 mm and VLA at 9 mm observations at 40 au resolution. Thus, it is not plausible to consider that the jet are composed of twin flows.

On the other hand, when the jet has an asymmetric or complex velocity distribution, the velocity gradient would appear in the jet short-axis. However, the distribution of CO emission is rather smooth (Fig. 1) and the velocity gradient is systematic. Thus, the velocity gradients within the jets cannot be explained just by the asymmetric nature.

We conclude that rotation is most plausible to interpret the velocity gradient of the jet seen in velocity map (Fig. 2a). It is difficult to explain the velocity gradient with other models except for rotation. In addition, there are similarities between numerical simulations of protostellar jets and the observations. A winding configuration of velocity gradient seen in the velocity map can be confirmed in the simulation of the rotating jets. The knotty structures seen in the integrated intensity map (Fig. 1) are also produced in simulations and can be explained by time-variable mass ejection.

The position-velocity (PV) diagrams are useful to qualitatively and quantitatively estimate the jet properties. There are two intensity peaks in the PV diagrams cutting along the short-axis each red-shifted component at R1, R3, R7, or R9 (Fig. 3b-3e). The peaks are located in the second and fourth quadrant independent of the cutting position. The tendency seen in the PV diagrams agrees well with typical characteristics of rotating cylinder. It should be noted that the PV diagrams taken in this observation (Fig. 3) do not agree with those seen in the numerical simulations of the precessing jet. The two emission peaks would correspond to the wall or edge of the jet where the integrated intensity along the line of sight should be strong. In addition, the directions of velocity gradient are the same in all the cutting positions. This is natural if the velocity gradient is attributed to the jet rotation.

Using the position-velocity diagram, the jet rotation velocity \(v_\phi\) and the distance from the jet axis (or radius in the cylindrical coordinate) \(r_{\text{rot}}\) are estimated as

\[
v_\phi = \frac{1}{\sin i} \frac{V_{\text{blue}} - V_{\text{red}}}{2},
\]

and

\[
r_{\text{rot}} = \frac{l_{\text{shift}}}{2},
\]

respectively, where \(V_{\text{blue}}\) and \(V_{\text{red}}\) are the velocity at emission peak of red-shifted and blue-shifted components in each PV diagram (Fig. 3). The jet rotation axis was determined using the PV diagrams, in which the half distance of two emission peaks is adopted as the axis (Fig. 3). In the position velocity diagrams, the jet width \(l_{\text{shift}}\) was calculated from the distance between two peaks (Fig. 3). The disk inclination angle is estimated to \(i = 80^\circ\) with respect to the line of sight in past observation. We also estimated the jet inclination angle using the 1.3 mm continuum emission which presumably traces the disk around FIR 6b. The disk inclination angle was estimated to be \(i = 42^\circ\) with \(i \equiv \arccos(L_{\text{min}}/L_{\text{maj}})\) where the deconvolved size along the major \(L_{\text{maj}}\) and minor \(L_{\text{min}}\) axes are \(1.1 \times 0.82\) arcsec \((416 \times 312\) au) which is calculated from the two-dimensional Gaussian fitting. A disk inclination angle of \(i = 55^\circ\) was inferred from recent higher angular resolution. Therefore, the jet inclination angles were estimated to 40°, 60°, and 80° in this and other observations. Recent theoretical study showed that the inclination angle of the disk (or normal direction of the disk) changes depending on the spatial scale. Thus, it is difficult to accurately determine the inclination angle of the disk and jet from observations. Here, we adopt the jet inclination angle \(i = 80^\circ\) which gives the minimum rotation velocity and specific angular momentum.

The measured rotation velocities are in the range of \(v_\phi = 11.2 - 28.4\) km s\(^{-1}\), while the jet radius (or the distance from the jet axis) is in the range of \(r_{\text{rot}} \sim 220 - 800\) au (Table 1). The rotation velocities estimated for FIR 6b are the highest among those reported in other sources even after correcting for the jet inclination angle: \(v_\phi \sim 6 - 15\) km s\(^{-1}\) for DG Tau, \(v_\phi \sim 2\) km s\(^{-1}\) for CB 24, \(v_\phi \sim 5 - 14\) km s\(^{-1}\) for SVS 13A, and \(v_\phi \sim 10\) km s\(^{-1}\) for Orion Source. With the jet velocity and radius, the specific angular momentum of the jet at each position is also estimated as \(j = v_\phi r_{\text{rot}}\). The specific angular momentum is

![Figure 2](image-url)

**Figure 2** | CO mean velocity maps. (a) Northeast-side (or red-shifted) jet. The velocity map with the LSR velocity range of 32.5 km s\(^{-1}\) to 97.5 km s\(^{-1}\) excluding the component at the systemic velocity between \(v_{\text{LSR}} = 7.5\) and 12.5 km s\(^{-1}\). (b) Southwest-side (or blue-shifted) jet. The velocity map with the velocity range of \(-17.5\) km s\(^{-1}\) to 0 km s\(^{-1}\) excluding the component at the systemic velocity. The 1.3 mm continuum emission is also plotted in each panel with gray contours as same as in Fig. 1. The ellipses in the bottom left corner are the synthesized beams sized for the CO \(J=2\rightarrow 1\) emission (black) and the 1.3 mm continuum emission (gray).
in the range of $9.2 \times 10^{21}$ cm$^2$ s$^{-1} \leq j \leq 1.9 \times 10^{22}$ cm$^2$ s$^{-1}$ (Table 1). The maximum specific angular momentum estimated in this study is one or two orders of magnitude larger than those reported in other sources. The specific angular momenta calculated in previous studies are $j \approx 3.5 \times 10^{20}$ cm$^2$ s$^{-1}$ for DG Tau [32] and $j \approx 1.5 \times 10^{20}$ cm$^2$ s$^{-1}$ for CB 24 [33] and $j \approx 7.5 \times 10^{20}$ cm$^2$ s$^{-1}$ for Orion Source [33]. Among the jets where the rotation speed was measured, only the rotating jet bullet SVS 13A has a comparable but slightly smaller value of the specific angular momentum ($\sim 9.8 \times 10^{21}$ cm$^2$ s$^{-1}$) [32].

It is crucial to explore the launching radius $r_0$ of the jet in order to clarify the jet driving mechanism. Based on the Bernoulli’s theorem and the angular momentum conservation law, we can estimate the jet launching radius [23]. Using the same method, recent ALMA observations estimated the launching radius $r_0$ of both low-velocity outflow and high-velocity jet for different objects; $r_0 \approx 10 - 100$ au for the low-velocity outflow and $r_0 \approx 0.05 - 7$ au for the high-velocity jet [23]. For FIR 6b, the launching radii are estimated using the toroidal $v_\phi$ and poloidal $v_{pol}$ velocities and jet radius of each position with the analytical solution [23] 

$$r_0 = \frac{0.7 \text{ au} \left( \frac{v_{rot}}{10 \text{ au}} \right)^{2/3} \left( \frac{v_\phi}{100 \text{ km s}^{-1}} \right)^{2/3} \left( \frac{v_{pol}}{100 \text{ km s}^{-1}} \right)^{-4/3} \left( \frac{M_{\text{star}}}{1 M_\odot} \right)^{1/3}}{2},$$  \tag{3}$$

where the poloidal velocity components of the jet are derived with 

$$v_{pol} = \frac{1}{\cos i} \left( v_{blue} + v_{red} \right),$$  \tag{4}$$

where $v_\phi$, $v_{rot}$, and $v_{pol}$ are the poloidal and toroidal velocity components, respectively, and $r_0$ is the launching radius of the jet [23].

The mass of the central protostar is simply assumed to be $M_{\text{star}} = 0.1 M_\odot$. Note that the dependence of the estimated launching radius on the protostellar mass is weak (eq. 3). The rotation velocity and radius estimated in the PV diagrams give the jet launching radius in the range of $r_0 = 0.97 - 1.37$ au (Table 1). Thus, the jet is expected to be driven by the intermediate region of the circumstellar disk where magnetic field is expected to be coupled with neutral gas, not by the region very close to the protostar. Therefore, these observations are most consistent with the disk wind mechanism [23], but do not support the X-wind and entrainment mechanism [23].

The jet is directly driven from the wide range of circumstellar disk in the disk wind mechanism, while it is driven only from the region very close to the protostar ($\lesssim 0.01$ au) in the others. It should be noted that high-velocity jets with a small amount of angular momentum are expected in the X-wind and entrainment scenarios, because the jets appear in the region near the protostar where the angular momentum is not large.

The very large specific angular momentum of the jet cannot be simply explained. For example, the centrifugal radius is estimated as 

$$r_{\text{cent}} = j^2 / (GM_{\text{star}}),$$

in which the Keplerian rotation is assumed. With $j = 10^{22}$ cm$^2$ s$^{-1}$ and $M_{\text{star}} = 0.1 M_\odot$, the centrifugal radius becomes $r_{\text{cent}} = 4.9 \times 10^5$ au. The centrifugal radius estimated here is much larger than the disk-like structure observed around FIR 6b, and not realistic. Thus, the jet needs to receive the very large angular momentum in some way. Only the magnetic effect provides a solution to the large specific angular momentum and the origin of the super-rotation of the jet.

To investigate the effect of magnetic field on the angular momentum transfer, the Alfvén radius $r_A$ at each position is estimated using 

$$r_A = \sqrt{\frac{r_{\text{cent}} V_A}{\Omega_0}},$$  \tag{5}$$

where $\Omega_0 = \sqrt{GM_{\text{star}}/r_0^3}$ is the Keplerian angular velocity at the jet launching radius. The Alfvén radius is in the range of $r_A = 25.0 - 46.4$ au (Table 1). The ratio of the Alfvén radius to the jet launching radius $\lambda$ is as large as $\lambda \equiv r_A/r_0 = 25.8 - 33.9$. Thus, the long magnetic lever arm efficiently transports the angular momentum from the circumstellar region for the super-rotating jet case [35].

The magnetic pressure dominates the ram pressure within the Alfvén radius. Therefore, the large $\lambda$ means that the magnetic field plays a dominant role near the protostar. The large lever arm is expected to be realized in a later main accretion phase during which the density of the infalling envelope should be low. The low density causes a small ram pressure, while the magnetic field should be strong near the protostar. As a result, the magnetic-dominated region expands as the infalling envelope dissipates or the density of the infalling envelope lowers.

Since the jet launching region is distributed in the range of $0.97 - 1.37$ au (Table 1), the foot points of the magnetic field lines connecting
to the jet (Fig. 2) are also distributed in the same range of the circumstellar disk. Thus, wirelike strong (or hard) magnetic field lines originated in the circumstellar disk near the protostar (0.97 – 1.37 au) swing the fluid elements located very far from the foot points of the magnetic field lines (25.0 – 46.4 au). Since the fluid elements are frozen to the magnetic field lines, they are forced to corotate with the Keplerian velocity at foot points of the magnetic field lines (Fig. 4). As a result, the fluid elements receive the angular momentum and are expelled from the circumstellar region by magnetic effect. On the other hand, a parcel of gas in the circumstellar disk near the protostar loses the angular momentum and falls onto the protostar. Therefore, the excess angular momentum is ejected from the circumstellar disk by the rotating jet, and the gas whose angular momentum has been removed by the jet falls onto the protostar and promotes the protostellar growth.

The protostellar jets were observed by CO emission using ALMA. A clear velocity gradient is confirmed along the short axis of the jet and is attributed to the rotation of the jet. Using the PV diagrams and analytical estimate, the properties of the jets are obtained. The rotation velocity and specific angular momentum of the jets are extraordinarily large. The super-rotation of the jet is realized by the angular momentum transfer due to the magnetic effect. In addition, the jet launching points are expected to be located far from the protostellar surface. These findings are well match with the disk wind hypothesis as the jet driving mechanism. The study could unveil the final phase of the protostellar evolution.

**Figure 4** | Schematic view of the super-rotating jet. The magnetic field line inside the Alfvén radius (thick dotted and solid red lines) rotates rigidly with the Keplerian velocity at its foot point and accelerates the gas elements located at the tip. The magnetic field line (red curve) is strongly twisted within the jet. The angular velocity of the jet is the same as that of the foot point and thus the super-rotation (blue arrows) is realized.

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Table 2 Jet parameters with different jet inclination angles with respect to the line of sight

| Position | i = 40° | | i = 60° | |
|----------|---------|---------|---------|---------|
|          | j       | r₀      | v₀      | r₁      | j       | r₀      | v₀      | r₁      |
|          | [cm² s⁻¹] | [au] | [km s⁻¹] | [km s⁻¹] | [au] | [cm² s⁻¹] | [au] | [km s⁻¹] | [km s⁻¹] | [au] |
| R1       | 1.4×10²² | 9.3 | 43.6 | 78.3 | 168 | 1.0×10²² | 4.3 | 32.3 | 120 | 81.5 |
| R2       | 2.2×10²² | 11.6 | 36.6 | 82.9 | 247 | 1.6×10²² | 5.3 | 27.1 | 127 | 120 |
| R3       | 2.9×10²² | 13.1 | 36.6 | 86.8 | 313 | 2.1×10²² | 6.1 | 27.1 | 133 | 152 |
| R4       | 2.1×10²² | 11.2 | 29.6 | 83.5 | 238 | 1.6×10²² | 5.2 | 21.9 | 128 | 115 |
| R5       | 2.6×10²² | 12.4 | 24.9 | 86.1 | 284 | 1.9×10²² | 5.7 | 18.5 | 132 | 138 |
| R6       | 2.4×10²² | 10.4 | 28.8 | 93.3 | 237 | 1.8×10²² | 4.8 | 21.3 | 143 | 115 |
| R7       | 2.7×10²² | 11.6 | 23.3 | 91.4 | 272 | 2.0×10²² | 5.4 | 17.3 | 140 | 132 |
| R8       | 2.2×10²² | 10.3 | 18.7 | 91.4 | 229 | 1.7×10²² | 4.8 | 13.9 | 140 | 111 |
| R9       | 2.1×10²² | 9.6 | 17.1 | 92.7 | 208 | 1.5×10²² | 4.5 | 12.7 | 142 | 101 |

METHODS

ALMA observation and data reduction. Mosaicking observations in the millimeter CO (J = 2–1; 230.538 GHz) molecular line and the 1.3 mm continuum were carried out with the ALMA 12m array on 19 April 2018 and with the ACA 7m array (Morita array) on 7, 10, 11, and 17 January 2018. The data was obtained through the Cycle 5 program 2017.1.01353.3 (PI: S. Takahashi). The OMC-2/FIR 6 region covers 3.8×3.9′ area centered at (R.A., Dec.) = (05h35m21.7s, 70°, −05°12′51.9″) with the Nyquist sampling. In the ALMA 12m array and ACA 7m array observations, the mosaic fields consist of 108 and 42 pointings with the total on-source duration per pointing of 20 and 260 seconds, respectively. The overview of the full survey at OMC-2/FIR 6 region will be presented in a separate paper (Matsushita et al. in prep 2020). In this paper, we presented the result in the area centered on OMC-2/FIR 6b. Two spectral windows with a 1875 MHz width are allocated to the continuum observations centered at 233.100 and 215.200 GHz. Two other spectral windows are placed at the frequency of CO J = 2–1 and SiO J = 5–4 with a 938 MHz width and a 244 kHz frequency resolution (velocity resolution of 0.64 km s⁻¹) in the dual polarization mode. The SiO emission is not detected in FIR 6b. The arrays consisted of 44 and 11 antennas for the ALMA 12m array and the ACA 7m array observations, respectively, with projected baseline coverage from 15.1 to 300.2 m and 8.9 to 48.9 m. The primary beam size was 25.2″ and 43.2″, and the system temperature was from 70 to 180 K and 60 to 210 K for the ALMA 12m array and the ACA 7m array, respectively. The flux, gain, and bandpass calibrators were J0423-0120, J0541-0211, and J0423-0120 for the ALMA 12m array, and J0522-3627 and J0607-0834, J0542-0913, and J0423-0120 for the ACA 7m array. The data were calibrated using the Common Astronomy Software Application (CASA), version 5.1.1 with the ALMA pipeline and imaged with CASA version 5.4.0. The visibility data of the CO line emission was separated from continuum emission using “uvcontsub” task in CASA. Line free free emissions are added to provide a total effective continuum bandwidth of 5.75 GHz. In order to combine the ACA 7m array and ALMA 12m array data for the CO line, we used the CASA task “concat” with the weight of 20:1. Only the ALMA 12m array data were used to image of the 1.3 mm continuum emission. The CO and 1.3 mm continuum data were imaged by the CASA task “tclean” with a robust weight of 0.5. The primary beam correction was applied. The synthesized beam of the final cube of the CO data and image of continuum data are 4.5×2.5 arcsec with the position angle of −87.0° and 1.0×0.78 arcsec with the position angle of −73.6°, respectively. Achieved noise levels are 30 mJy beam⁻¹ for the CO image cube with the velocity resolution of 2.5 km s⁻¹ and 0.5 mJy beam⁻¹ for the 1.3 mm continuum image.

Channel map of red-shifted and blue-shifted components. Figs. 5 and 6 show the channel maps of the red-shifted (northeast side) and blue-shifted (southwest side) jets. In the figures, the jet axis is determined to pass through the emission peaks of three knots on the map of the LSR velocity 70 km s⁻¹ in Fig. 5. In the LSR velocity range of 30 – 70 km s⁻¹, the emission peaks show a deviation from the jet axis in the northeast direction in Fig. 5. On the other hand, in the LSR velocity range of 70 – 95 km s⁻¹, the deviation from the jet axis is confirmed in the southwest direction. Although the velocity gradient depends on the distance from the position of FIR 6b, the emission peak is seen on both side of the jet axis in the channel map. In addition, we can confirm three knots or relatively strong emission peaks in Fig. 5. We cannot confirm the emission peak on both sides of the jet axis in the blue-shifted jet (Fig. 6).

Low-velocity component. Figs. 7a and 7b show the integrated intensity and mean velocity maps of the low velocity components (5 – 20 km s⁻¹ with respect to the systemic velocity). The cavity-like structures are confirmed in both heads of red-shifted and blue-shifted jets in Fig. 7a. In the moment 1 map (Fig.7b), the velocity gradient along the short axis of the jet cannot be identified. Thus, there is no clear sign of the rotation motion in the low-velocity components. As seen in Fig. 2a, the rotation motion is confirmed in only the high velocity component of 20 – 85 km s⁻¹ with respect to the systemic velocity. The outflow (or jet) velocity should be proportional to the Keplerian velocity at the outflow driving radius. Thus, it is natural that the rapid rotation is observed only in the high-velocity component, because the foot point of the high-velocity outflow (or jet) is located near the protostar where the Keplerian rotation is high. On the other hand, non-detection of the rotation motion in the low-velocity components would be attributed to the driving radius located much far from the central protostar where the Keplerian rotation velocity is small.

Dependence of jet parameters on the jet inclination angle. In the main text, we adopted the jet inclination angle i = 80° with respect to the line of sight. The inclination angle of the disk is inferred to be i = 42° from our observations of the 1.3 mm continuum and i = 55° from published, higher angular resolution continuum observations. Since the jet physical quantities depend on the inclination angle, those for i = 40° and 60° are listed in Table 2. In any case, the specific angular momentum exceeds j = 10²² cm² s⁻¹. The jet launching radii for i = 40° and 60° extend to ~ 4 – 13 au which is considerably far from the central protostar. The maximum rotation velocity exceeds 40 km s⁻¹. Therefore the adopted inclination angle does not significantly affect the conclusions. Thus, we can confidently reject the X-wind and entrainment scenarios both by the distant launching radius and the rapid jet rotation in this observation. It should be noted that although the CO outflow discussed in this study supports the disk wind scenario, we are not denying the X-wind scenario. If we find a faster component with a small amount of angular momentum in other wavelength ranges, it might correspond to the jet in the X-wind model. The disk wind and X-wind can coexist and they should contribute to the angular momentum transfer in different radii of the disk.
Figure 5 | CO ($J$=2–1) channel map of the red-shifted flow. The channel maps presented in the LSR velocity range between 30 km s$^{-1}$ and 95 km s$^{-1}$, which corresponds to the relative velocity range of 19 km/s to 84 km/s with respect to the system velocity ($v_{\text{sys}} = 11$ km s$^{-1}$). The center value of the LSR velocity is described in each panel. The plus symbol at the center corresponds to the position of protostar FIR 6b measured in the 1.3 mm continuum. The broken lines indicate the axes of the red-shifted (northeast side) and blue-shifted (southeast side) jets. The jet axis of the red-shifted components is determined on the map of 70.0 km s$^{-1}$. The contour levels are $3\sigma$, $5\sigma$, $10\sigma$, $15\sigma$, $20\sigma$, $30\sigma$, $40\sigma$, $60\sigma$, $80\sigma$, and $100\sigma$ ($1\sigma = 30$ mJy beam$^{-1}$ · km s$^{-1}$). The black open ellipses in the bottom left corner is the synthesized beam size.

1. McMullin, J. P. et al. CASA Architecture and Applications. *ASPC* 376, 127 (2007).

2. "Your reference here."
Figure 6 | CO (J=2–1) channel map of the blue-shifted flow. Same as Fig. 5. The channel maps presented in the LSR velocity range between −10 km s$^{-1}$ and 0 km s$^{-1}$, which corresponds to the relative velocity range of -22 km/s to -11 km/s with respect to the system velocity ($v_{sys} = 11$ km s$^{-1}$).

Figure 7 | (a) CO (J=2–1) integrated intensity map of the low velocity component. The LSR velocity range of 0 to 30 km s$^{-1}$ are integrated excluding the LSR velocity range around the systemic velocity of 7.5 to 12.5 km s$^{-1}$. The plus symbol at the center corresponds to the position of protostar FIR 6b. The contour levels are 5σ, 10σ, 15σ, and 20σ (1 σ = 2.0 Jy beam$^{-1}$ · km s$^{-1}$). The black open ellipse in the bottom left corner is the synthesized beam size. (b) CO (J=2–1) mean velocity map (color). As same as in Fig. 7a but for the mean velocity of the low velocity components. The contour represents the integrated intensity are shown in Fig. 7a. (c) CO (J=2–1) line profile. The blue-shifted emission is detected in the LSR velocity range of −20 − 10 km s$^{-1}$, while the red shifted emission is detected around 10 − 100 km s$^{-1}$. 