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# Magnetocentrifugal Origin for Protostellar Jets Validated through Detection of Radial Flow at the Jet Base

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### Abstract

Jets can facilitate the mass accretion onto the protostars in star formation. They are believed to be launched from accretion disks around the protostars by magnetocentrifugal force, as supported by the detections of rotation and magnetic fields in some of them. Here we report a radial flow of the textbook-case protostellar jet HH 212 at the base to further support this jet-launching scenario. This radial flow validates a central prediction of the magnetocentrifugal theory of jet formation and collimation, namely, the jet is the densest part of a wide-angle wind that flows radially outward at distances far from the (small, sub-au) launching region. Additional evidence for the radially flowing wide-angle component comes from its ability to reproduce the structure and kinematics of the shells detected around the HH 212 jet. This component, which can transport material from the inner to outer disk, could account for the chondrules and Ca–Al-rich inclusions detected in the solar system at large distances.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Star formation (1569); Jets (870)

## 1. Introduction

Protostellar jets are seen associated with young stellar objects (Bally 2016; Anglada et al. 2018; Lee 2020). They are ejected from the innermost parts of accretion disks (Ray et al. 2007) and linked to the process of mass accretion onto the central protostars (Cabrit et al. 1990; Hartigan et al. 1990). However, how they are launched is still under debate. Recently, they were found to be spinning (Bacciotti et al. 2002; Lee et al. 2017a) and magnetized (Lee et al. 2018a), as expected from magnetocentrifugal launching models, carrying angular momentum away from the disks. However, more observations of protostellar jets are still needed to confirm and constrain the launching models.

Because of its well-defined structure with high collimation and symmetry, HH 212 is a textbook-case protostellar jet (Zinnecker et al. 1998). The jet is ejected from a rotating accretion disk around a low-mass protostar (Codella et al. 2014; Lee et al. 2017b) at a distance of  $\sim$ 400 pc in Orion. It lies almost in the plane of the sky (Claussen et al. 1998). It was recently found to be rotating, carrying angular momentum away from the innermost part of the disk (Lee et al. 2017a), consistent with the magnetocentrifugal launching models. Here we search for another telltale sign to support the models: a radial flow at the base of the jet. This radial flow is required because, in the classic magnetocentrifugal picture (Blandford & Payne 1982), the initially rigid magnetic field lines must be inclined away from the disk normal (i.e., the jet axis) direction by more than  $30^{\circ}$  in order to centrifugally launch the outflow from the disk surface and accelerate it to a high speed. This requirement means that the magnetocentrifugally driven outflow must start out as a wide-angle wind with a range of flow directions (Shu et al. 1994; Ferreira 1997; Krasnopolsky et al. 2003). As the wind propagates to large distances, inner

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. streamlines are gradually collimated by the "hoop stresses" associated with the toroidal magnetic field into a high-density jet along the axis, while the remaining part remains wide-angled (Shu et al. 1995, Krasnopolsky et al. 2003). The slow collimation leads to two generic predictions for the magneto-centrifugally driven jets: (1) the jet material near the base moves in a wider range of radial directions (hereafter referred to as "radial flow") than farther out, and (2) the jet is always surrounded by a (more tenuous) wide-angle wind. Here we report new observations of HH 212 to test these predictions.

## 2. Observations

Observations of the HH 212 protostellar system were obtained with Atacama Large Millimeter/submillimeter Array (ALMA) in Band 7 centered at a frequency of  $\sim$ 341.5 GHz on 2017 November 27 in Cycle 5 (2017.1.00044.S). The target was observed with a total time of  $\sim$ 98 minutes and projected baselines of  $\sim 60-8500$  m. Four spectral windows were used, with three in continuum mode having a bandwidth of 2 GHz and one in spectral mode having a bandwidth of 1.875 GHz. The SiO line was included in the spectral mode with a velocity resolution of  $\sim 1.69$  km s<sup>-1</sup> channel<sup>-1</sup>. CASA version 5.1 was used to calibrate the visibility data and generate the SiO line data with the continuum subtracted. We used a robust factor of 0.5 for the visibility weighting to generate SiO channel maps with a synthesized beam of  $0.036 \times 0.032$  (or 14.4 au  $\times 12.8$ au) at a position angle of  $\sim -78^{\circ}$  and a noise level of  $\sim 0.75$ mJy beam<sup>-1</sup> (or  $\sim 7$  K) in each channel. These channel maps are then used to generate the total intensity map and positionvelocity (PV) diagrams.

### 3. Results

## 3.1. SiO Observations of the HH 212 Jet

Figure 1 shows the inner part of this jet within 1400 au of the protostar in the SiO J = 8-7 line. The jet is well detected in SiO within  $\sim 200$  au of the protostar, surrounded by the SO shells

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**Figure 1.** The HH 212 jet and model. Panel (a) shows the SiO total intensity map (orange) of the jet within 1400 au of the protostar at  $0.036 \times 0.032$  resolution integrated from -16.1 to 17.6 km s<sup>-1</sup>, with the 350 GHz continuum map (gray; adopted from Lee et al. 2021b) of the dusty disk. They are rotated by 22.5 clockwise to align the jet axis vertically. The dotted blue curves show the shells previously detected in SO (Lee et al. 2021b). Panel (b) shows the innermost jet within ~200 au of the protostar, with the nomenclature of the knots from Lee et al. (2017a). Panel (c) shows the PV diagram along the jet axis for the innermost jet, made with a transverse width of 8 au. The contours start at  $3\sigma$  with a step of  $4.5\sigma$ , where  $\sigma = 5.8$  K. The green lines show the FWHM line widths obtained from a Gaussian fit. Panel (d) shows the number density and velocity in our X-wind model, with the dusty disk (dark gray) and shells (light gray), illustrating the increase of the SiO line width of the jet toward the protostar. Here the jet is the densest core of the wind outlined by the gray curves.

(blue dotted curves) detected before (Lee et al. 2021b). It is highly collimated and appears cylindrical (though knotty), extending out from the disk. No SiO jet emission can be seen down to the protostar because it is blocked by the optically thick disk (Lee et al. 2017c). Further away in the south, some faint clumpy emission is also seen along the jet axis, tracing the jet itself. Further away in the north, a chain of roughly equally spaced wide and flat structures is seen along the jet axis, each one oriented almost perpendicular to the jet axis, probably tracing the internal shocks. The PV diagram of the SiO emission along the jet axis shows that the radial velocity range (i.e., line width) of the collimated jet along the line of sight increases toward the protostar, with its Gaussian FWHM line width increasing from 5–7 km s<sup>-1</sup> at 160 au to 16-20 km s<sup>-1</sup> at 20 au. It indicates that, despite the cylindrical appearance of the observed jet, the outflowing material in the jet at the base is moving more radially outward from the innermost part of the disk, consistent with magnetocentrifugal models (see, e.g., Figure 1(d)).

A similar increase of line width toward the source has been detected toward more evolved T Tauri jets, e.g., DG Tau and

RW Aur (Pyo et al. 2003, 2006). In those cases, the line profiles become more complex toward the sources, showing prominent low-velocity emission referred to as the low-velocity component (LVC). This LVC also shows a decrease in radial velocity toward the source, e.g., in DG Tau (Pyo et al. 2003; Maurri et al. 2014). The observed line width of the RW Aur jet near the source was first found to be too large to be fully explained by a divergent constant velocity flow of  $4^{\circ}$  in opening angle (Hartigan & Hillenbrand 2009) but later reproduced with an X-wind (Liu & Shang 2012). It is thus not yet clear whether part or all of the LVC traces the wide-angle base of the collimated jet or different flow components, e.g., an outer disk wind (Simon et al. 2016; Nisini et al. 2018) or entrained matter.

In the case of HH 212, no clear LVC can be identified in the PV structure. Although the peak emission of knots N1 and N2 shows a decrease of radial velocity toward the source, the line wing emission of these knots extends to higher and lower radial velocities, producing broader line profiles toward the source. The jet interaction with the SO shell at the base could contribute to the widening of the line profiles close to the



Figure 2. Jet velocity of HH 212 measured at a distance from  $\sim 40$  to 160,000 au. It is derived from the proper motion of the SiO jet measured here from  $\sim 100$  to 1000 au (see the Appendix) and those previously reported at other distances along the jet axis (Claussen et al. 1998; Lee et al. 2015; Reipurth et al. 2019). Red and blue data points are for the redshifted and blueshifted jet components, respectively. Since the jet is almost in the plane of the sky, the jet velocity is the same as the proper motion. In panel (b), the data points are shifted to their expected positions at the mean date (2016 November) of the new ALMA observations, assuming ballistic motion.

source on the low-velocity side, since the SO shell has a low velocity near the base (see Section 3.4).

#### 3.2. Velocity and Long-range Acceleration of the HH 212 Jet

Measurements of jet velocity can provide an additional constraint to the models. Figure 2 shows the jet velocity at a distance from  $\sim 40$  to 160,000 au, derived from the proper motion of the SiO jet measured here from  $\sim 100$  to 1000 au (see the Appendix) and those previously reported at other distances along the jet axis (Claussen et al. 1998; Lee et al. 2015; Reipurth et al. 2019). Panel (a) shows the velocities at the measured positions, while panel (b) shows the velocities at the expected positions at the date of current observations assuming ballistic motion. In either case, an apparent acceleration is seen over a large distance, with the velocity increasing from  $\sim$ 50–60 km s<sup>-1</sup> at 40–50 au, to  $\sim$ 90 km s<sup>-1</sup> at 1000 au, and then to  $\sim$ 140 km s<sup>-1</sup> at 3000 au. The velocity further away remains roughly constant. The current MHD ejection model might have difficulty in producing such a long-range acceleration. Most MHD ejection models predict that terminal jet velocities are reached within a distance of  $z = 100r_0$ , where  $r_0$  is the anchoring radius of the streamline in the disk (Jacquemin-Ide et al. 2019; Tabone et al. 2020). Therefore, further work is needed to check if other effects, such as time variability in the ejection velocity and geometrical projection, can produce this apparent acceleration.

# 3.3. Modeling the HH 212 Jet

As discussed earlier, radial flow is a generic feature of the magnetocentrifugal wind at large distances from the (small) launching region. This asymptotic behavior is not only valid for an X-wind (Shu et al. 1995) but also for an inner disk wind (Cabrit et al. 1999; Pudritz et al. 2007), especially if mass loading is concentrated toward the inner disk edge (Krasnopolsky et al. 2003). In the X-wind, the gas speed along all streamlines is roughly similar, while in the disk wind, the flow speed decreases as the anchoring radius of the streamline increases. The dense core of these winds appears as a collimated jet. For a jet almost in the plane of the sky, the line profile is expected to widen toward the source to both lower and higher velocities in both the X-wind and disk wind.

We will focus our comparison on the asymptotic X-wind (Shu et al. 1995), for which analytic solutions exist. The wind solution is governed by the magnetic field–to–mass flux ratio  $\beta$  and the amount of specific angular momentum *J* carried by the gas and field along the streamlines. It is an asymptotically radial wind but with the central part collimated by the tension force of the toroidal magnetic field into a dense jet. To be specific, we adopt the X-wind parameters reported in Shu et al. (1995), with the mean values averaged over the streamlines  $\overline{J} \sim 3.7053$  and  $\overline{\beta} \sim 1.1675$ . This  $\overline{J}$  value is similar to the mean value previously found in young protostellar jets (Lee 2020). It determines the terminal velocity and specific angular momentum of the jet to be  $\sim v_{k,x} \sqrt{2\overline{J} - 3}$  and  $\sim \overline{J} l_{k,x}$ , respectively, where  $v_{k,x}$  and  $l_{k,x}$  are the Keplerian rotation



Figure 3. Comparison of the X-wind model and the observations of the HH 212 jet. Panel (a) shows the SiO map of the jet and the 350 GHz continuum map of the disk derived from the model. Panel (b) shows the map of the jet and disk convolved to the observed resolution. Panel (c) shows the observed SiO jet and dusty disk. Panel (d) shows the comparison of the PV structures between the model (red contours) and observations (gray image with black contours). Contour levels are the same as those in Figure 1(c).

velocity and specific angular momentum at the launching point called "the X-point."

This asymptotic X-wind model is self-similar and scaled with the mass of the protostar  $M_*$ , the radius of the launching point  $R_x$ , and the mass-loss rate of the wind  $\dot{M}_w$ . Since the total mass of the protostar and disk was estimated to be  $\sim 0.25 \pm 0.05 \ M_{\odot}$  (Lee et al. 2017b), and the disk itself was estimated to have a mean mass of  $0.10 \pm 0.05 M_{\odot}$  (Lee et al. 2017c, 2021a), we have  $M_* \sim 0.15 \pm 0.07 \ M_{\odot}$ . Then, with the adopted  $\bar{J}$  and the observed specific angular momentum of  $\sim 10 \pm 3$  au km s<sup>-1</sup> (Lee et al. 2017a), we have  $l_{k,x} \sim 2.7 \pm 0.8$  au km s<sup>-1</sup>, and thus  $R_x \sim 0.05 \pm 0.02$  au and  $v_{k,x} \sim 51.7 \pm 15.9$  km s<sup>-1</sup>. This model produces a terminal jet velocity of  $\sim 109 \pm 33$  km s<sup>-1</sup>, similar to the mean velocity of the jet and consistent with the jet velocity measured at large distances within the error bars (see Figure 2). The mass-loss rate in the jet was previously estimated to be  $\sim (1.0 \pm 0.5) \times 10^{-6} \ M_{\odot} \ yr^{-1}$  at a large distance of  $\sim$ 4000–8000 au (Lee et al. 2015). Considering that the massloss rate in the wide-angle component of the X-wind can still be comparable to that in the jet at that large distance (Shu et al. 1995), we assume  $\dot{M}_w \sim (1.5 \pm 0.7) \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ . The resulting wind velocity, rotation velocity, and density have been given in Shu et al. (1995). The jet is the densest core of the wind, with  $\beta \sim 1$  and  $J \sim 3.2$  within 1000 au of the protostar (see Figure 1 in Shu et al. 1995). Using Equation 4(b) in Shu et al. (1995) with these  $\beta$  and J values, we find that the jet velocity in the model increases slowly from  $91 \pm 28$  to  $93 \pm 29$  km s<sup>-1</sup> at a distance from 40 and 1000 au. Although the jet velocity at 1000 au in the model is consistent with our

measurement, the jet velocity at 40–300 au is about twice the observed values there (see Figure 2). The actual X-wind could have a slightly different acceleration efficiency, and detailed numerical calculations (Najita & Shu 1994) are needed to fit the observations more closely.

We can compare the model quantitatively to the observed SiO jet up to a distance of  $\sim$ 160 au, where no clear internal shocks are seen affecting the structure and kinematics. Since we do not intend to reproduce the observed knotty structure in the jet, which could be due to episodic ejections, the X-wind is assumed to be steady. For this comparison, we adopt  $M_* \sim 0.15 \ M_{\odot}$ ,  $R_x \sim 0.05$  au, and  $\dot{M}_w \sim 1.5 \times 10^{-6} \ M_{\odot}$ yr<sup>-1</sup>, with the resulting number density and velocity shown in Figure 1(d). To mimic the observations, we also include a dusty disk (dark gray) to block the innermost jet and shells (light gray) to set the outer boundary of the X-wind in the model. The SiO molecules are assumed to have a temperature of 400 K, as in another young SiO jet, HH 211 (Hirano et al. 2006). A radiative transfer code (Lee et al. 2021b) adding the SiO line with an assumption of LTE is used to calculate the model SiO maps and then the model PV diagrams. The inclination angles of the jet are required to be 3° and 1°.8 to the plane of the sky for the northern and southern components, respectively, to match the observed mean jet velocity there. This difference in the inclination angles is acceptable because the jet seems to have a bending of  $2^{\circ} \pm 1^{\circ}$  (Lee et al. 2007). Also, as discussed earlier, since the observed jet velocity appears to be half of that in the current model, the inclination angles could be twice as high and become roughly the same as those found for the shells later. Without understanding the long-range acceleration, we



Figure 4. Comparison of the velocity gradients in the PV structures across the knots in the innermost jet due to jet rotation. The observed PV structures (black contours with gray image) were adopted from Lee et al. (2017a) at 8 au spatial resolution and 1.7 km s<sup>-1</sup> velocity resolution. The model PV structures (red contours) are derived from the X-wind model at the same resolutions. The contour levels start at  $4\sigma$  with a step of  $1\sigma$ , where  $\sigma = 21.3$  K.

postpone the modeling of the jet with such inclination angles to a future investigation.

In order to match the observed SiO emission intensity in the jet, the SiO abundance is required to be  $[SiO/H] \sim 3.3 \times 10^{-6}$ roughly consistent with the molecular synthesis model (Glassgold et al. 1991) for a collimated fast wind similar to the X-wind. In addition, in order to match the observed width and velocity range at the base of the jet, the SiO abundance is set to zero when the number density (in H) drops below  $6 \times 10^6$  cm<sup>-3</sup>, as marked by the gray curves in Figure 1(d). This density could be considered either as the minimum value required to excite the SiO J = 8-7 emission (which has a critical density of  $\sim 2.5 \times 10^7$  cm<sup>-3</sup>; Lee et al. 2021b) or as the minimum value where the SiO molecules have formed. As seen in Figure 3, the model produces a hollow SiO jet and can roughly reproduce the observed width of the SiO jet after convolution to the observed resolution. This model can also reproduce the PV structure along the jet axis (see Figure 3(d)), with the Gaussian FWHM line width increasing from  $\sim 6$  km s<sup>-1</sup> at 160 au toward the protostar to  $\sim 18$  km s<sup>-1</sup> at 20 au, similar to the observations. Moreover, as shown in Figure 4, this model can also roughly reproduce the transverse velocity gradients of the knots in the jet due to jet rotation previously obtained at higher resolution (Lee et al. 2017a). This match further supports the jet to be launched by magnetocentrifugal force, and the jet indeed carries away roughly the same amount of specific angular momentum as in the model.

#### 3.4. Modeling the Shells around the HH 212 Jet

Faint hollow shells are also seen in SiO in the north and south surrounding the jet axis extending out from 200–300 au to more than 1000 au, as shown in Figure 5. They connect to those previously seen in SO at the base back to the disk (blue dotted curves), forming lobe structures around the jet axis. The PV diagram of the SiO emission along the jet axis shows a tilted V-shaped PV structure arising from the shell in the south and an inverted V-shaped PV structures and the previously detected parabolic PV structures of the SO shells near the base (Lee et al. 2018b) form tilted lobe-shaped PV structures.

Previously, the shells were thought to be produced by a pure collimated jet through jet-driven bow shocks at the tips of the shells (Lee et al. 2021b). However, the spur PV structures, which are the signatures of the jet-driven bow shocks and have a large velocity range at the bow tips due to sideways ejection (Lee et al. 2001; Tabone et al. 2018), are not seen here in the PV diagram at the tips of the shells. Instead, the shells could be driven by X-winds that have wide-angle radial components, because tilted lobe-shaped PV structures have been modeled before with such winds to account for the large-scale molecular outflows around the jets (Shu et al. 1991; Lee et al. 2001; Shang et al. 2020).

Here we construct a momentum-driven shell model to account for the structure and kinematics of the shells. In this



**Figure 5.** Comparison of the shell and PV structure along the jet axis between the model and observations. The model structure (red dotted curves) and model PV structure (red solid curves) of the shells are derived from an interaction of the X-wind with an extended disk wind. The dotted blue curves outline the shells previously detected in SO (Lee et al. 2021b). The contours start at  $3\sigma$ with a step of  $4.5\sigma$ , where  $\sigma = 5.8$  K.

model, the shells are produced as the X-wind expands into the extended disk wind coming out from the outer disk detected before in SO (Tabone et al. 2020; Lee et al. 2021b). This extended disk wind is a hollow wind launched from the outer

disk with a radius from  $\sim 4$  to 40 au. It is magnetic and vanishes inside 4 au, probably because of a decrease of disk magnetization (Lee et al. 2021b). It has a mass-loss rate of  $\sim 10^{-6} M_{\odot}$ yr<sup>-1</sup>, with the number density decreasing with the increasing height from the disk midplane approximately as (in spherical coordinates)

$$n_d \sim 6 \times 10^6 \left( \frac{\sin \theta}{\sin 45^\circ} \right) \left( \frac{100 \text{ au}}{r \cos \theta} \right)^p \text{ cm}^{-3},$$
 (1)

where the power-law index p = 4/3. Here the sine factor is to make the wind hollow, with  $\theta$  being the angle measured from the jet axis. Since the SO emission derived from this wind decreases with height slower than that detected in the observations (Lee et al. 2021b), the actual density of the wind could decrease faster with height. Therefore, we increase from p = 4/3 to 2, which also simplifies our calculation of the shells later. The velocity of the extended disk wind is much smaller than that of the X-wind and thus ignored in our calculation. According to Lee et al. (2001), the resulting shell velocity is

$$v_s = \frac{v_w}{1 + \eta^{-1/2}},\tag{2}$$

where  $v_w$  is the velocity of the X-wind and  $\eta = n_w/n_d$ , with  $n_w$  and  $n_d$  being the number density of the X-wind and disk wind, respectively. At the tip of the shell,  $\eta \gg 1$  and thus  $v_s \sim v_w$ . The resulting shell has a lobe-like structure with

$$r_s \approx \frac{L}{1+\eta^{-1/2}},\tag{3}$$

where L is length of the lobe.

Figure 5 shows the model structure with red dotted curves and model PV structure with red solid curves, with  $v_w \sim 90$  km s<sup>-1</sup> and  $L \sim 1050$  au in the north and 1350 au in the south, as measured from the observations. The shells have a dynamical age of  $\sim L/v_w$ , the same as their associated jet component, about  $\sim 60$  yr. The inclination angle of the shell to the plane of sky is  $\sim 6^{\circ}$  in the north and 3° in the south. Like the jet, the small difference of inclination angles between the two sides is acceptable. As can be seen, this model reproduces the shell structure and kinematics reasonably well. Moreover, in this model, the shell velocity increases to  $\sim 20-25$  km s<sup>-1</sup> at a distance of  $\sim 300$  au from the protostar, high enough to sputter Si or SiO from the grains in the dusty disk wind and form the SiO in the gas phase (Schilke et al. 1997), producing the observed SiO emission in the shells.

## 4. Summary and Discussion

Regardless of the uncertainties in the model parameters and measurements, the simple X-wind model can still reproduce the key features (including radial flow, rotation, and structure) of the jet as the densest core of the wind and the key features (including structure and kinematics) of the shells with the interaction between the wide-angle radial component of the wind and an extended dusty disk wind. It is expected that an inner disk wind can also reproduce the key features. Thus, the jet is likely a dense core of either an X-wind or an inner disk wind.

Interestingly, the wide-angle radial component, if does exist, can also solve other existing problems. In particular, since a pure collimated jet has difficulty producing the observed width



Figure A1. Proper-motion measurement of the SiO jet by comparing the SiO total intensity maps in two epochs at  $0^{\prime\prime}_{...}036 \times 0^{\prime\prime}_{...}032$  resolution. The white arrows show the position shifts of the isolated knots and internal shocks (marked with white ellipses) between the two epochs.

and kinematics of large-scale molecular outflows (Lee et al. 2002), the wide-angle radial component can provide a promising solution to the width and kinematic problems of those outflows (Lee et al. 2000; Shang et al. 2006; Arce et al. 2007; Zhang et al. 2019). Moreover, it is still unclear why chondritic materials and Ca–Al-rich inclusions are detected throughout the solar system. It could be that they were originally produced during the star formation in the innermost disk, where the temperature was high enough to form them, but later flung out by the wide-angle wind component to rain down everywhere in the disk (Shang et al. 2000).

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# Appendix Proper Motion

The proper motion of the jet can be measured by comparing the SiO total intensity map of the jet presented in this paper to that obtained about 2 yr earlier on 2015 November 5 and December 3, reported in Lee et al. (2017a). The SiO map taken earlier has been convolved to have the same angular resolution as that here. As shown in Figure A1, the jet shows roughly the same structures in the two epochs. The white arrows show the position shifts of the isolated knots and internal shocks of the jet between the two epochs. The inner knots are not spatially well resolved, and only knots N2, N4, and S3 can be roughly separated to measure the proper motion (see Figure A1(b) for the zoom-in). The position shifts are found to range from 0."05 to 0."11, which is  $\sim 1.5-3$  synthesized beams. Due to cooling, THE ASTROPHYSICAL JOURNAL LETTERS, 927:L27 (8pp), 2022 March 10

expansion, and other factors, the emission features from the same gas could be different between the two epochs. Hence, the uncertainties of the measurements are assumed to be half of the position shifts. The proper motion can then be obtained by dividing the position shifts by the duration of 2 yr.

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