MASERS AS TRACERS OF ANGULAR MOMENTUM IN MOLECULAR OUTFLOWS

TECNOCIENCIA

MÁSERES COMO TRAZADORES DE MOMENTO ANGULAR EN FLUJOS MOLECULARES

López N., Diana V.; Araya, Esteban D

Diana V. López N.
dianavlopezn@gmail.com
Universidad de Panamá, Panamá

Esteban D Araya
ed-araya@wiu.edu
Western Illinois University, Estados Unidos

Tecnociencia
Universidad de Panamá, Panamá
ISSN: 1609-8102
ISSN-e: 2415-0940
Periodicity: Semestral
vol. 25, no. 1, 2023
Luis.rodriguez@up.ac.pa

Received: 22 September 2022
Accepted: 08 November 2022

URL: http://portal.amelica.org/ameli/journal/224/2243827009/

Abstract: The dissipation of angular momentum of collapsing molecular cores is a key component in the formation of stars. Previous observations have reported that highly collimated protostellar jets can remove angular momentum from low-mass protostars. In contrast, there is no clear evidence that this occurs for high-mass protostars. Here we report the results of developing a data analysis platform to investigate whether molecular masers in the outflows of two high-mass star forming regions, DR21(OH) and W75N(B), trace net angular momentum. No statistically significant evidence was found for masers to trace net angular momentum transfer in these regions. However, our results show that high-angular resolution observations of masers near high-mass protostars have the potential of revealing this phenomenon at scales similar to the specific angular momentum carried by planets in our Solar System.

Keywords: Astrophysics, radio astronomy, high-mass stars, formation of stars, masers.

Resumen: La disipación del momento angular en los núcleos pre-estelares es un componente clave en la formación de las estrellas. Observaciones previas han detectado chorros proto-estelares altamente colimados como los responsables de parte de la remoción del momento angular en protoestrellas de baja masa. En cambio, no se ha encontrado evidencia significativa de que esto ocurra para las protoestrellas de alta masa. En este estudio reportamos los resultados de desarrollar una plataforma de análisis de datos dedicada a investigar si máseres en los flujos moleculares de dos regiones de formación de estrellas masivas, DR21(OH) y W75N(B), son capaces de trazar momento angular neto. Estadísticamente no se detectó evidencia significativa de transferencia de momento angular en las regiones estudiadas. Sin embargo, los resultados muestran que observaciones de alta resolución de máseres cercanos a las protoestrellas de alta masa tienen el potencial de revelar la naturaleza de este fenómeno a escalas similares a las del momento angular específico que portan los planetas de nuestro Sistema Solar.

Palabras clave: Astrofísica, radioastronomía, estrellas masivas, formación estelar, máseres.

INTRODUCTION

Recent evolutionary models of high-mass star formation, i.e., stars with 8 or more times the mass of the Sun, describe how these objects form in molecular clouds of gas and dust (e.g., see review by Motte et al., 2018). Inside molecular clouds complexes at parsec scales, there are sites called ridges and hubs, in which massive dense cores start to form. Kinematic studies of molecular gas tracers suggest that global collapse conditions can be present in the ridges through flow streams, which increase the mass of the dense cores, leading to the formation of high-mass protostars. The inflowing gas streams lead to high accretion rates, which in turn result in the development hot molecular cores and molecular outflows. To form a star, of the material must collapse, which is possible only if angular momentum is somehow dissipated.

According to theoretical models and recent observations of low mass protostellar jets (e.g., Lee et al., 2017), molecular outflows can remove angular momentum from circumstellar disks, allowing material to fall onto the central young stellar object. In contrast, there is no clear evidence that this occurs for high-mass protostars. Massive stars play a significant role in galactic dynamics; from birth to death, massive stars contribute to the energetics of galaxies via stellar winds, radiation, supernovae, etc. Hence, it is important to understand the mechanisms involved in their formation.

Masers (Microwave Amplification by Stimulated Emission of Radiation) from different molecular species and transitions have been a very useful tool to study molecular outflows. Some maser species, such as transitions from methanol (CH_3OH), water (H_2O) and other molecules, are known tracers (indicators) of regions of massive star formation (e.g., Paulson & Pandian 2020; Torrelles et al. 1997; Araya et al. 2015). Radiation and shocks in jets and outflows from young high-mass stellar objects can excite molecules resulting in population inversion, whose stimulated de-excitation (in a cascade) produce narrow bandwidth (monochromatic) and high brightness-temperature spectral lines, which can be used to trace gas kinematics in star forming regions at sub- arcsecond resolutions. The maser phenomenon is like that of lasers, but for long wavelength radiation (radio/microwaves) instead of visible light (e.g., Saldaño, 2016).

In this project we developed a data analysis platform to investigate whether masers in molecular outflows of massive protostars can trace dissipation of angular momentum. We focused on the analysis of two regions of high-mass star formation, DR21(OH) and W75N(B), which belong to the Cygnus X complex. DR21(OH) is in an early phase of evolution, in which massive protostars have not yet substantially ionized the surrounding molecular gas (e.g., Araya et al. 2009). Observations by Kogan & Slysh (1998), which were confirmed by Kurtz et al. (2004) and Araya et al. (2009), reveal a bipolar structure of CH_3OH masers consistent with a molecular outflow. Similarly, W75N(B) harbors stellar objects in very early phases of high-mass star formation, as revealed by an ionized jet and molecular masers (e.g., Carrasco-González et al. 2015). Haschick et al. (1981) proposed that W75N(B) is excited by a binary system of massive stars (B1 type) in formation. Observations of

OH masers by Baart et al. (1986) using the Multi-Element Radio Linked Interferometer Network (MERLIN) supported a scenario in which the OH and H_2O masers are tracing an outflow in this region.

MATERIALS AND METHODS

A Jupyter notebook was developed in the Python programming language, the code was designed to read ASCII files of Right Ascension (RA) and Declination (Dec) positions, as well as observed velocities of masers in molecular outflows in two high-mass star forming regions. Our approach uses the offset positions of the masers with respect to the approximate geometrical center of the outflow (the expected location of the high mass protostellar object), the approximate direction of the molecular outflow, and the velocity field of the masers to estimate the projected specific angular momentum.

1. Star Forming Regions Studied

The distribution of thirty-seven 44 GHz CH_3OH masers in the DR21(OH) region was analyzed. The data were extracted from Araya et al. (2009). The masers reported in DR21(OH) appear to trace a sequence of bow shocks in four arc-like structures, as it is shown in Figure 1. The morphology of the CH_3OH masers shows two arcs oriented to the east (blueshifted) and two apparent arcs oriented to the west (redshifted). Araya et al. (2009) suggested that the distribution is like a jet bow-shock outflow produced by a protostar. This hypothesis is supported by the detection of a continuum source located close to the center of the CH_3OH maser outflow. The angular resolution of these observations is approximately 0.92 arcsec.

High-resolution data reported in Torrelles et al. (1997) of the region W75N(B) was also analyzed. In this region, we focused on two sources with 22 GHz H_2O masers: VLA 1 with 11 H_2O masers shown in Figure 2, and VLA 2 with 9 H_2O masers shown in Figure 3.

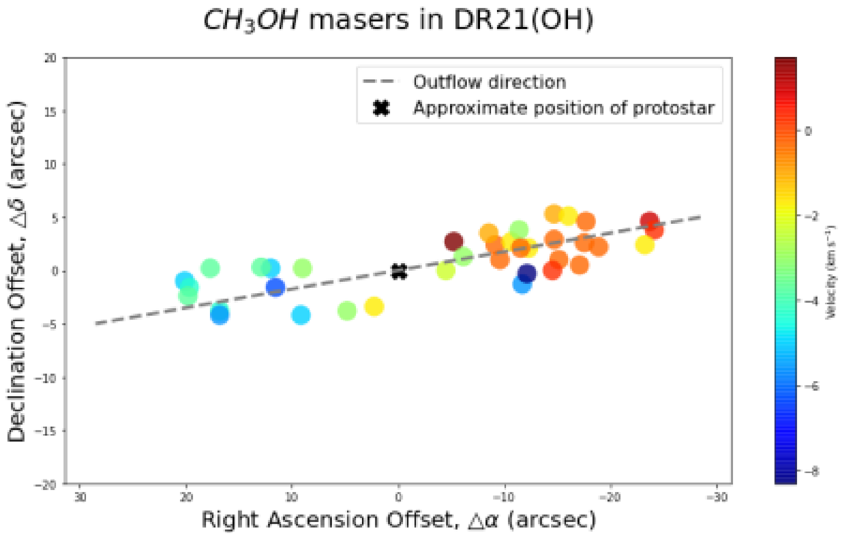

FIG 1.
LSR velocity field of 44 GHz CH_3OH masers in the DR21(OH) region. The dashed line corresponds to the approximate outflow direction. The cross shows the assumed position of the outflow's origin based on the spatial and kinematic distribution of the masers.

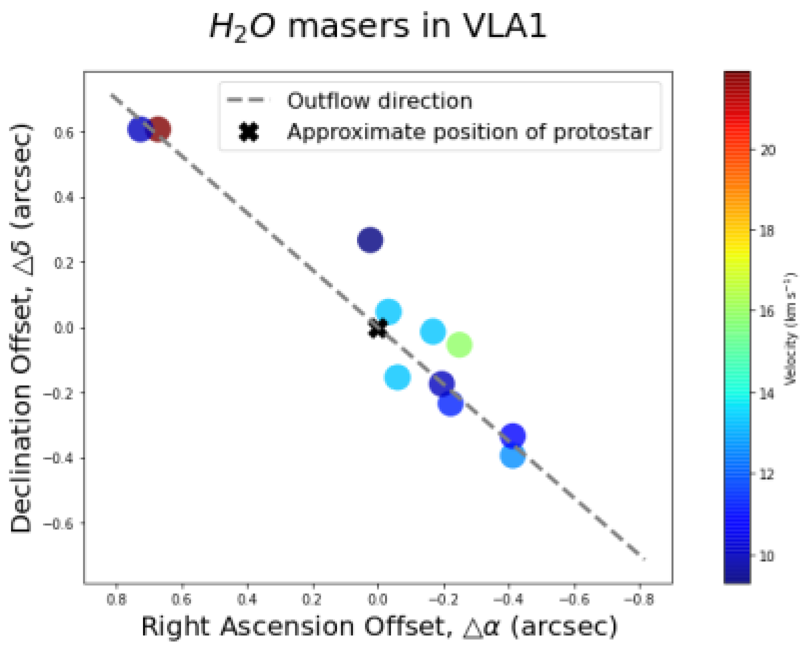

FIG. 2
As Figure 1 but for H2O masers in WN75(B) VLA 1.

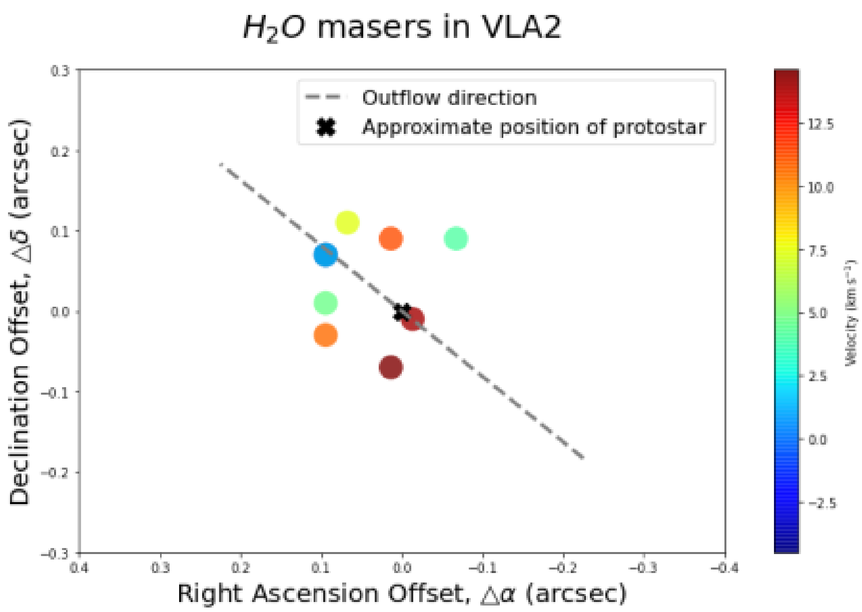

FIG. 3
As Figure 1 but for H2O masers in WN75(B) VLA 2.

In contrast to DR21(OH), the distribution of masers in VLA 1 did not trace arc-like structures. However, as Torrelles et al. (1997) pointed out, the elongated emission of VLA 1 resembles that of the radio jets found in young stellar objects. For VLA 2, the masers trace a more compact shell distribution. The relative astrometry of the masers is 0.01 arcsec for the Torrelles et al. (1997) data.

2. Projected Specific Angular Momentum

The distribution of masers in the sky traces a two-dimensional projection of a three-dimensional structure. Our model was developed using Euclidean geometry to estimate the relative distances of the masers and direction of the outflows with respect to the geometric and kinematic center of the flows. Figure 4 shows a diagram of the vectors used in the analysis of the sources. The vector ## represents the position of each maser with respect to the assumed position of the protostar:

$$\vec{r} = \vec{r}_{maser} - \vec{r}_{protostar} \quad (1)$$

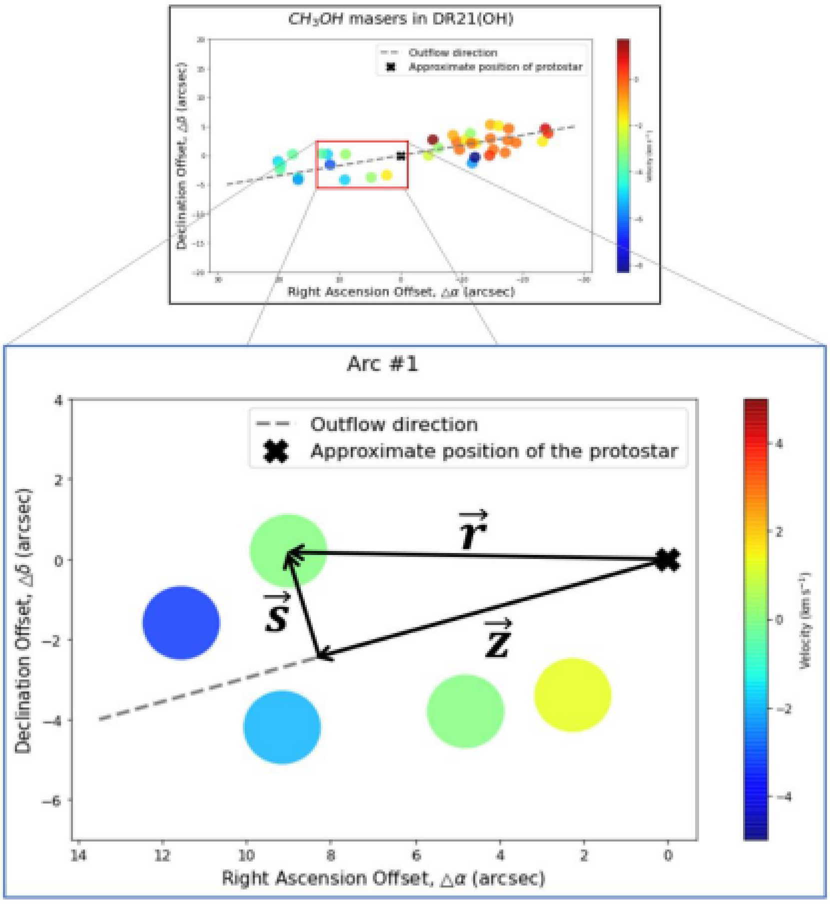

FIG. 4
Vectors used in the analysis of DR21(OH). A similar approach was used for the region W75N(B). The zoom-in view (blue rectangle) includes only the masers that were assigned to the first bow shock (Arc #1). Based on the symmetry of the arc structures, some of the masers toward the North-East of the inset box (red rectangle) appear to be associated with a different maser arc, and therefore, were not included in the blue zoom-in view.

The outflow direction is considered as the axis of rotation. The vector ## represents the perpendicular distance between each maser and the outflow direction. The vector ## represents the position of each maser projected onto the outflow axis:

$$\vec{z} = \vec{r} - \vec{s} \quad (2)$$

The mass of the maser clouds is unknown and hence we calculated the projected specific angular momentum as a function of ##. In our approach, the projected specific angular momentum is defined as:

$$\vec{l} = \frac{\vec{L}}{m} = \vec{s} \times \vec{v} \quad (3)$$

In which the vector ## refers to the velocity of the maser in the protostar's reference frame corrected for the outflow's expansion. However, the observed maser velocities correspond to the Local Standard of Rest (LSR) projections in our line-of-sight. Consequently, we had to correct for 1) the systemic velocity shift of the maser velocities due to the relative motion of the Solar System and each star forming region, and

2) the velocity gradient of the masers caused by the projected outflow motion (which does not trace angular momentum but the expansion of the molecular gas along the outflow's axis). To correct for both effects, we calculated a reference velocity function based on a linear regression (Least Square method) of the observed maser velocities along the outflow's axis, such that both the systemic velocity and the velocity gradient due to the outflow motion could be corrected. In our model, the reference velocity is a function of the vector ##; the reference velocity for each maser was subtracted from the observed LSR velocities to estimate the value of ## that was used in the specific angular momentum calculation.

RESULTS AND DISCUSSION

A non-zero average of the projected specific angular momentum of the maser distribution would indicate the detection of net angular momentum in the outflows (the sign of the non-zero average would indicate the direction of the angular momentum with respect to ##). Figure 5 shows the results for DR21(OH). For this source, we obtained an averaged projected specific angular momentum of 1.8×10^3 AU km/s, that is greater than the projected specific angular momentum of the planets in the Solar System (between 20 and 1.7×10^2 AU km/s, star symbol in Figure 5), but smaller than the standard deviation (σ) of the data (7.8×10^3 AU km/s). Therefore, no significant net angular momentum is traced by the 44 GHz CH_3OH masers in DR21(OH).

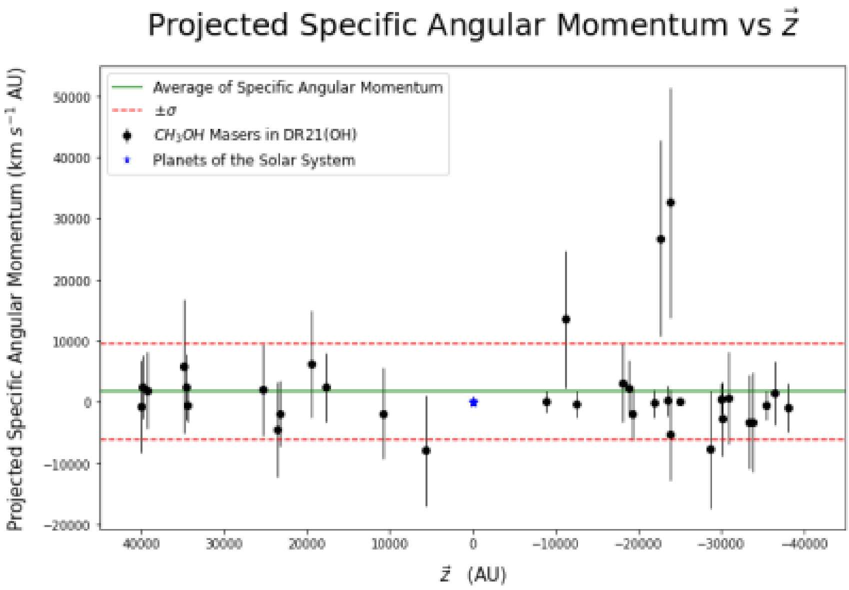

FIG. 5
Projected specific angular momentum vs ## in DR21(OH). The green line represents the average specific angular momentum of all masers in the sample, and the dashed red lines show one standard deviation dispersion with respect to the mean. For comparison, blue stars are included to show the specific angular momentum of the planets of the Solar System (all stars are blended in this graph).

For the sources VLA 1 and VLA 2, we obtained an averaged projected specific angular momentum of -17 AU km/s and -1.1×10^2 AU km/s, respectively. Both results are smaller than the standard deviation of the data. The standard deviation for VLA 1 is 5.6×10^2 AU km/s and 6.3

×10^2 AU km/s for VLA 2. As shown in Figures 6 and 7, we report no significant net angular momentum traced by H_2O masers in W75N(B) VLA 1 and VLA 2 within the standard deviation of the specific angular momentum in the samples. However, due to the high angular resolution of the data (where the masers are tracing the inner regions of the outflows) the dispersion of the specific angular momentum is smaller than the one observed toward DR21(OH) and approaches the values of specific angular momentum of the planets in our Solar System.

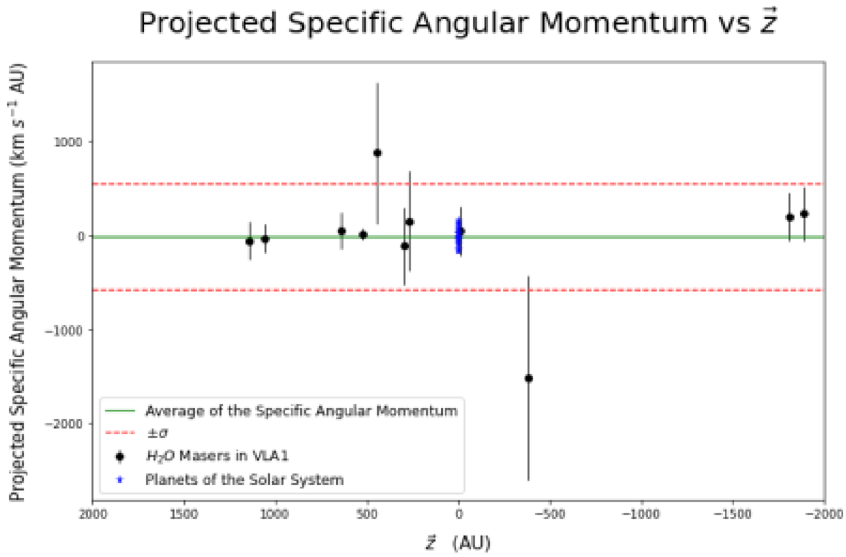

FIG. 6
As Figure 5 but for W75N(B) VLA 1. The blue stars represent the specific angular momentum of the planets of the Solar System, which in Figure 5 appeared as a single star due to the large dispersion of specific angular momentum of the 44 GHz CH_3OH masers.

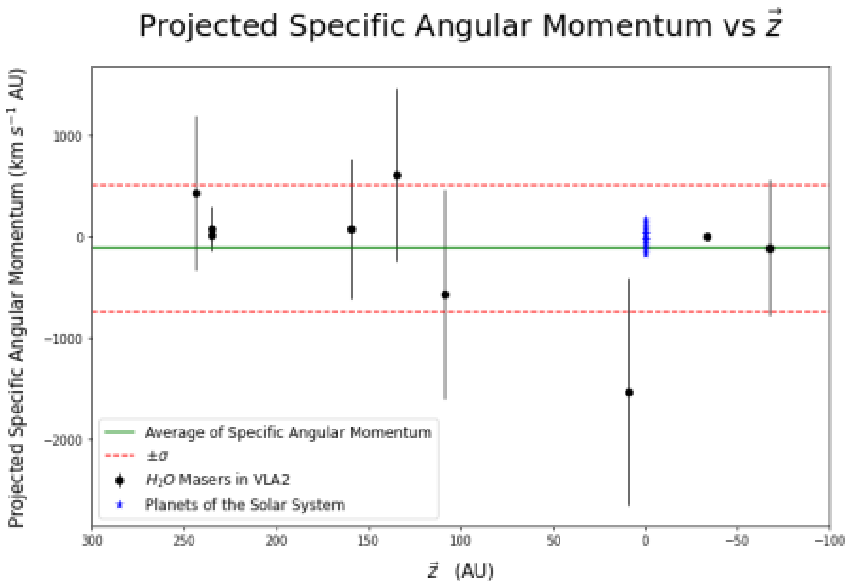

FIG. 7
As Figure 6 but for W75N(B) VLA 2.

CONCLUSIONS

We developed a Jupyter-notebook platform to search for specific angular momentum traced by masers in the outflows of high-mass star forming regions. We applied the code to 44 GHz CH_3OH masers in DR21(OH) and 22 GHz H_2O masers in W75N(B). While no statistically significant net specific angular momentum was detected in the sample, our results show that high-resolution maser observations (that can trace material closer to the launching site of the outflows) can reveal specific angular momentum values of individual maser spots that are similar to the magnitude of the specific angular momentum of planets in the Solar System.

Therefore, evidence for net angular momentum transfer could be detectable in other sources for which masers are imaged with higher angular resolution, i.e., using very long baseline interferometry (VLBI). In the quest to develop a more complete platform to search for angular momentum in outflows, it will be important to further model the three- dimensional distribution of the masers.

ACKNOWLEDGMENTS

The authors are grateful for comments and suggestions by an anonymous referee that helped us improve this manuscript. This project was developed as a part of the program INDIRA 2021 (Investigación a Distancia en Radioastronomía) organized by NINE HUB Costa Rica and Alpha Cen; NINE is an initiative of the National Radio Astronomy Observatory (NRAO) to enable underrepresented individuals to have access to radio astronomy related resources and networks. We thank these organizations for serving as a communication bridge between the authors. During the writing and development of this project, we were supported by Western Illinois University. EDA acknowledges partial support from the National Science Foundation (NSF) grant AST- 1814063 (in collaboration with grant AST-1814011). DVLN acknowledges the SENACYT for the financial support during the last years of undergraduate studies.

REFERENCES

Araya, E., Kurtz, S., Hofner, P., & Hendrik, L. (2009). Radio continuum and methanol observations of DR21(OH). *Astrophysical Journal, 698*(1), 1321-1329.

Araya, E. D., Olmi, L., Morales Ortiz, J., Brown, J. E., Hofner, P., Kurtz, S., Linz, H., & Creech-Eakman, M. J. (2015). Formaldehyde masers: exclusive tracers of high-mass star formation. *The Astrophysical Journal Supplement Series*, 221(1), 10

Baart, E., Cohen, R., Davies, R., Norris, R., & Rowland, P. (1986). Merlin observations of oh outflow in W75N. *Monthly Notices of the Royal Astronomical Society, 219*, 145-155.

Carrasco-González, C., Torrelles, J.M., Cantó, J., Curiel, S., Surcis, G., Vlemmings, W.H.T., van Langevelde, H.J., Goddi, C., Anglada, G., Kim, S.-W., Kim, J.-S., & Gómez, J.F. (2015). Observing the onset of outflow collimation in a massive protostar. *Science*, 348, 114-117.

Haschick, A., Reid, M., Burke, B., Moran, J., & Miller, G. (1981). VLBI aperture synthesis observations of the oh maser source W75N. *Astrophysical Journal, 244*, 76-87.

Kogan, L., & Slysh, V. (1998). VLA imaging of class I methanol masers at 7 millimeters with angular resolution ~0".2. *The Astrophysical Journal*, 800-806.

Kurtz, S., Hofner, P., & Vargas Álvarez, C. (2004). A catalog of CH3OH 70 −61 A+ maser sources in massive star-forming regions. *The Astrophysical Journal Supplement Series*, 149-165.

Lee, C.-F., Ho, P., Zhi-Yun, L., Hirano, N., Zhang, Q., & Shang, H. (2017). A rotating protostellar jet launched from the innermost disk of HH212. *Nature Astronomy, 1*(1), 0152.

Motte, F., Bontemps, S., & Louvet, F. (2018). High-mass star and massive cluster formation in the milky way. *Annual Review of Astronomy and Astrophysics*, 56, 41-82.

Paulson, S. T., & Pandian, J. D. (2020). Probing the early phases of high- mass star formation with 6.7 GHZ methanol masers. *Monthly Notices of the Royal Astronomical Society*, 492(1), 1335-1347.

Saldaño, H. P. (2016). Propiedades físicas de núcleos pre-estelares masivos. Argentina: Universidad Nacional de Córdoba.

Torrelles, J., Gómez, J., & Rodríguez, L. (1997). A radio maser system in W75N(B) at a 200 Au scale: Exploring the H2O Jet. *The Astrophysical Journal, 489*(1), 744-752.