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Multi-line Diagnostics of the Interstellar Medium

Feeding a Protostar with 10 000 au Scale Streamers

Jaime E. Pineda[1,*], *Dominique* Segura-Cox[1,2], *Paola* Caselli[1], *Nichol* Cunningham[3], *Bo* Zhao[1], *Anika* Schmiedeke[1], *Maria José* Maureira[1], and *Roberto* Neri[3]

[1]Max-Planck-Institut für extraterrestrische Physik (MPE), Gießenbachstr. 1, 85748 Garching, Germany
[2]Department of Astronomy, The University of Texas at Austin, 2500 Speedway, Austin, TX 78712, USA
[3]Institut de Radioastronomie Millimétrique (IRAM), 300 rue de la Piscine, 38406 Saint-Martin d'Hères, France

Abstract. Dense cores are the places where stars are formed within the supersonic Molecular Clouds. These dense regions ($n \sim 10^5$ cc) are cold ($T \sim 10$ K) and display subsonic levels of turbulence (Mach ∼ 0.5), and represent the initial conditions for both star and disk formation. However, the influence of the parental core properties on the disk formation process is still not well constrained, and it is therefore crucial to study dense cores with interferometers to better understand the dense core and disk connection. We present NOEMA observations of a Class 0 object, which has been suggested to present a disk under gravitational instability (GI) (asymmetrical features in ALMA high resolution dust continuum emission). Our new data reveal a previously unseen large scale (∼10,000 au, or 33″) streamer of fresh gas from the surrounding dense core down to the disk scales. This streamer is almost perpendicular to the outflow, and it contains material with subsonic levels of turbulence, and therefore unperturbed by the outflow. Based on the total mass in the streamer and the free-fall timescale, we estimate infall rates to the disk scales, which clearly show that accretion via streamer can have an important role in the disk formation. Moreover, these results show that previously observed disk asymmetries could also be driven by large scale asymmetric flows instead of GI. This result shows the power and importance of studying dense cores with interferometers to provide a complete and proper picture of star and disk formation.

1 Introduction

The classical picture of star formation focuses on the material in an isolated parental dense core that undergoes gravitational collapse [1–3]. In addition, all the material used to form stars and planets must pass through the dense core. In this scenario, star- and disk-formation can be studied in numerical simulations of isolated/closed boxes, allowing the implementation of a range of physical processes [e.g., 4–6].

Non-axisymmetric structures around Class 0 objects were observed with *Spitzer*, and they were interpreted as the result of the collapse of non-equilibrium structures [7]. More

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[*] e-mail: jpineda@mpe.mpg.de

recently, ALMA continuum observations on two young Class 0 objects suggested the presence of accretion streamers [8]. These high angular resolution (better than 150 au, or 0.5″) dust continuum polarisation observations at 870 μm revealed the presence of two filamentary features aligned with the polarisation vectors reaching down to the disk scales. It is suggested that accretion streamers could explain at least one of these features. Unfortunately, the lack of complementary molecular line observations does not allow for a confirmation of these structures as accretion streams.

Per-emb-2 is a Class 0 object in the Perseus molecular cloud, which was observed with ALMA in dust continuum emission revealing asymmetrical features at disk scales, which are suggestive of a disk under gravitational instability (GI) [9]. Here we present observations carried out with IRAM NOEMA of Per-emb-2 [see also 10], which reveal the presence of a large scale streamer.

2 Observations

We observed Per-emb-2 with NOEMA in C and D configurations under project S18AG and using the Band 1 (3-mm) receivers. Thanks to the flexibility available with the PolyFix correlator, we are able to place many high-spectral resolution windows (62.5 kHz) targeting several molecular transitions, including HC_3N (10–9) and (8–7), CCS (8_7–7_6), ^{13}CS (2–1), and N_2H^+ (1–0). The observations are calibrated using the standard observatory pipeline in `CLIC`. The imaging is carried out with `MAPPING` using natural weighting, more details can be found in [10]. The typical noise level and beam size are 6 mJy beam^{-1} channel^{-1} and 4″, respectively The integrated intensity maps for HC_3N (10–9), CCS (8_7–7_6), and ^{13}CS (2–1) are shown in Fig. 1.

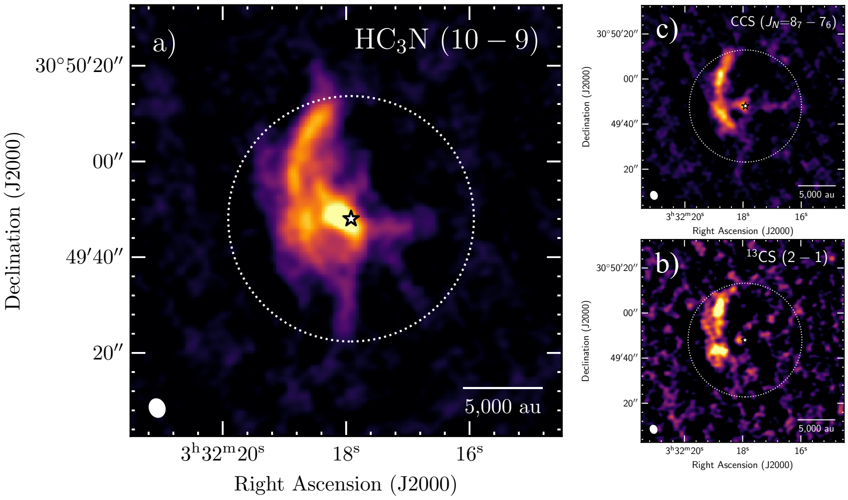

Figure 1. A large scale streamer seen in the integrated intensity maps of carbon-bearing species observed towards Per-emb-2. The emission form HC_3N (10–9), ^{13}CS (2–1), and CCS (8_7–7_6) are shown in panels a, b, and c; respectively. The centroid velocity from HC_3N (10–9) is in the background, original data from [10]. The dotted circle shows the Primary Beam at the line frequency. Beam size and scale bar are shown in bottom left and right corner, respectively.

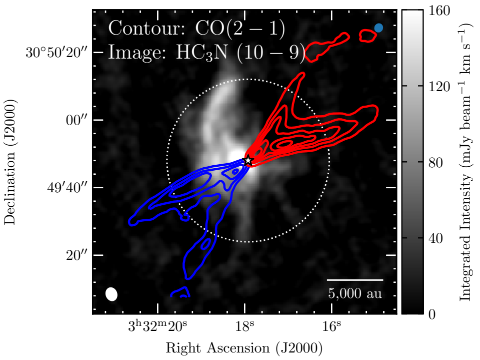

Figure 2. The outflow emission as traced by CO (2–1) in red and blue contours, while the background emission is the HC_3N integrated intensity. This shows that the streamer approaches disk-forming scales at an almost perpendicular angle to the outflow direction, and it is unrelated to a possible outflow interaction. The primary beam response for the CO (2–1) observation is shown by the white dotted circle. The CO contours levels are drawn at 5, 15, 25, 35 and 45× rms, where rms is 0.2 Jy beam^{-1} km s^{-1}.

3 Results

The emission traced by the carbon bearing species reveals a clear narrow and elongated structure, connecting the edge of the primary beam and the disk forming scales, see Fig. 1. These observations detected the streamer in molecular line emission, but not in the (less sensitive) dust continuum emission. The derived velocity map in the streamer is smooth and shows a streamer that begins at ≈10 000 au (or 33″) from the central YSO (beyond the classical dense core seen in NH_3 and N_2H^+).

The streamer emission approaching disk-forming scales is at an almost perpendicular angle to the outflow direction, as traced with the CO (2–1) from the MASSES survey [11], and therefore unrelated to the outflow (see Fig. 2). Moreover, the derived velocity dispersion of the HC_3N emission is subsonic, and therefore the gas is unperturbed by the outflow.

We model the on-sky trajectory and velocity along the line of sight with a streamline model [12], which includes rotation on a free-falling parcel of gas. This model matches well the trajectory and velocity of the observations, as seen in Fig. 3. Thanks to the detection of HC_3N (10–9) and (8–7) along the streamer, we estimate an average density of $(4 \pm 2)10^4$ cm^{-3} by comparing the line ratio with LTE models using RADEX [13]. Combing the streamer model and the estimated density, we estimate an average infall rate from the streamer onto the disk forming scales is 10^{-6} $M_\odot$ yr^{-1}, which is comparable to the current protostellar accretion rate of 7×10^{-7} $M_\odot$ yr^{-1} [14, 15]. This suggests that the streamer could modify protostellar accretion by funnelling extra material to the central region.

These results shows how the improved sensitivity and flexibility achieved with NOEMA can play a crucial role in bridging the gap between the large scale molecular cloud studies and the high-angular resolution disk studies. These type of studies are already modifying our picture of star-formation [16], however, it is important to further determine if these streamers are frequent enough and provide sufficient mass to have a decisive role on the disk evolution and planet formation process [e.g., 17, 18].

References

[1] R.B. Larson, MNRAS **145**, 271 (1969)
[2] F.H. Shu, ApJ **214**, 488 (1977)
[3] S. Terebey, F.H. Shu, P. Cassen, ApJ **286**, 529 (1984)
[4] B. Zhao, P. Caselli, Z.Y. Li, R. Krasnopolsky, MNRAS **473**, 4868 (2018), `1706.06504`
[5] M.N. Machida, S. Basu, ApJ **876**, 149 (2019), `1904.04424`
[6] P. Marchand, K. Tomida, K.E.I. Tanaka, B. Commerçon, G. Chabrier, ApJ **900**, 180 (2020), `2009.01268`

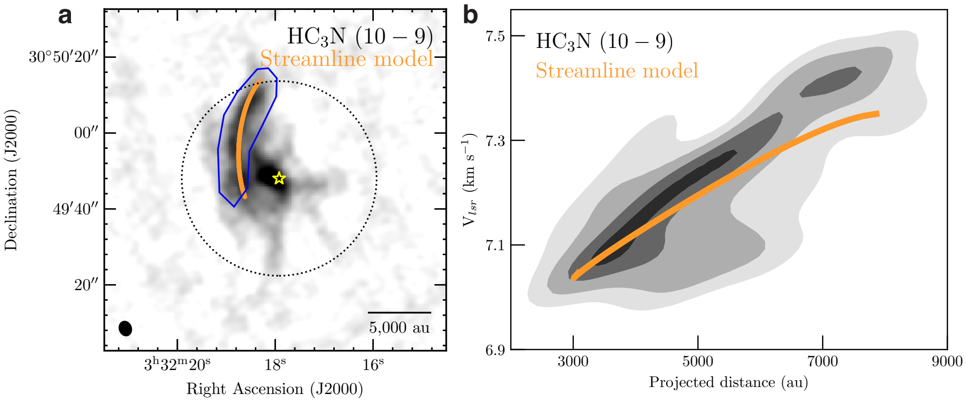

Figure 3. Streamline model (shown in orange) reproduces the trajectory and velocity of the streamer. Left panel show the sky trajectory of a streamer overlaid on the integrated intensity map of the HC$_3$N (10–9) emission, while the blue polygon shows the boundary of the region showing the uncontaminated streamer emission. Right panel shows the kernel density estimate (KDE), for all the points within the blue polygon in the left panel, of the velocity along the line of sight as a function of the projected distance. The dotted circle shows the Primary Beam at the line frequency. Beam size and scale bar are shown in bottom left and right corner, respectively.

[7] J.J. Tobin, L. Hartmann, L.W. Looney, H.F. Chiang, ApJ **712**, 1010 (2010), `1002.2362`

[8] V.J.M. Le Gouellec, C.L.H. Hull, A.J. Maury, J.M. Girart, Ł. Tychoniec, L.E. Kristensen, Z.Y. Li, F. Louvet, P.C. Cortes, R. Rao, ApJ **885**, 106 (2019), `1909.00046`

[9] J.J. Tobin, L.W. Looney, Z.Y. Li, S.I. Sadavoy, M.M. Dunham, D. Segura-Cox, K. Kratter, C.J. Chandler, C. Melis, R.J. Harris et al., ApJ **867**, 43 (2018), `1809.06434`

[10] J.E. Pineda, D. Segura-Cox, P. Caselli, N. Cunningham, B. Zhao, A. Schmiedeke, M.J. Maureira, R. Neri, Nature Astronomy **4**, 1158 (2020), `2007.13430`

[11] I.W. Stephens, T.L. Bourke, M.M. Dunham, P.C. Myers, R. Pokhrel, J.J. Tobin, H.G. Arce, S.I. Sadavoy, E.I. Vorobyov, J.E. Pineda et al., ApJS **245**, 21 (2019), `1911.08496`

[12] S. Mendoza, E. Tejeda, E. Nagel, MNRAS **393**, 579 (2009), `0803.1020`

[13] F.F.S. van der Tak, J.H. Black, F.L. Schöier, D.J. Jansen, E.F. van Dishoeck, A&A **468**, 627 (2007), `0704.0155`

[14] S. Frimann, J.K. Jørgensen, M.M. Dunham, T.L. Bourke, L.E. Kristensen, S.S.R. Offner, I.W. Stephens, J.J. Tobin, E.I. Vorobyov, A&A **602**, A120 (2017), `1703.10225`

[15] T.H. Hsieh, N.M. Murillo, A. Belloche, N. Hirano, C. Walsh, E.F. van Dishoeck, J.K. Jørgensen, S.P. Lai, ApJ **884**, 149 (2019), `1909.02706`

[16] J.E. Pineda, D. Arzoumanian, P. André, R.K. Friesen, A. Zavagno, S.D. Clarke, T. Inoue, C.Y. Chen, Y.N. Lee, J.D. Soler et al., arXiv e-prints arXiv:2205.03935 (2022), `2205.03935`

[17] A. Garufi, L. Podio, C. Codella, D. Segura-Cox, M. Vander Donckt, S. Mercimek, F. Bacciotti, D. Fedele, M. Kasper, J.E. Pineda et al., A&A **658**, A104 (2022), `2110.13820`

[18] C. Ginski, S. Facchini, J. Huang, M. Benisty, D. Vaendel, L. Stapper, C. Dominik, J. Bae, F. Ménard, G. Muro-Arena et al., ApJL **908**, L25 (2021), `2102.08781`