REPORT

STAR FORMATION

Gas flow and accretion via spiral streamers and circumstellar disks in a young binary protostar

F. O. Alves[1]*, P. Caselli[1], J. M. Girart[2,3], D. Segura-Cox[1], G. A. P. Franco[4], A. Schmiedeke[1], B. Zhao[1]

The majority of stars are part of gravitationally bound stellar systems, such as binaries. Observations of protobinary systems constrain the conditions that lead to stellar multiplicity and subsequent orbital evolution. We report high–angular resolution observations of the circumbinary disk around [BHB2007] 11, a young binary protostar system. The two protostars are embedded in circumstellar disks that have radii of 2 to 3 astronomical units and probably contain a few Jupiter masses. These systems are surrounded by a complex structure of filaments connecting to the larger circumbinary disk. We also observe accretion and radio jets associated with the protobinary system. The accretion is preferentially onto the lower-mass protostar, consistent with theoretical predictions.

About half of the stars in the solar neighborhood are in gravitationally bound stellar systems, such as binaries (*1*). The mean separation between components, a few tens of astronomical units (AU; 1 AU = 149,597,870.7 km), is a consequence of their formation process, thought to be fragmentation of the protostellar disk due to gravitational instabilities (*2*, *3*). Observations of young binary systems rarely probe such small scales. We seek to investigate the dynamical evolution of a binary system still embedded in its natal cloud, where gas from a circumbinary disk is expected to accrete onto each binary component. In the protobinary accretion phase, theoretical models indicate that high–angular momentum material accretes preferentially onto the less massive companion, which has a higher orbital angular momentum than the primary, causing ultimately an equal share of mass among the individual components (*4*–*6*).

[BHB2007] 11 (right ascension $17^h11^m23.18^s$, declination $-27°24'31.5''$, J2000 equinox) is the youngest member [age 0.1 to 0.2 million years (*7*)] of the small cluster of young stellar objects in the Barnard 59 (B59) core (part of the Pipe Nebula molecular cloud), which is still growing mass through dust and gas accretion (a class 0/I young stellar object). Previous observations of this object show an envelope surrounding a circumbinary disk of radius 90 AU, with prominent bipolar outflows launched near the disk edge (*8*).

[1]Center for Astrochemical Studies, Max Planck Institute for Extraterrestrial Physics, Garching, 85748, Germany. [2]Institut de Ciències de l'Espai, Consejo Superior de Investigaciones Científicas, Cerdanyola del Vallès, E-08193, Catalunya, Spain. [3]Institut d'Estudis Espacials de Catalunya, Barcelona, E-08034, Spain. [4]Departamento de Física, Instituto de Ciências Exatas, Universidade Federal de Minas Gerais, Belo Horizonte, 30.123-970, Brazil.
*Corresponding author. Email: falves@mpe.mpg.de

We observed [BHB2007] 11 at 225.3 GHz (wavelength ~1.3 mm) with the Atacama Large Millimeter/submillimeter Array (ALMA) (*9*). The observations were centered on the circumbinary disk of [BHB2007] 11 and reveal its internal structure. Figure 1 shows a multiscale view of the dust distribution, extending from the B59 core scale (~20,600 AU) to the subdisk scale (~6 AU); the latter is the maximum spatial resolution of our map, given the B59 distance of 163 pc (1 pc = 206,264.8 AU) (*10*). The dust map reveals two compact sources that we interpret as circumstellar disks around both components of a protobinary system, which has a projected separation of ~28 AU. The components were also seen in previous observations (*11*, *12*) with the Karl G. Jansky Very Large Array (VLA). We designate the individual components as [BHB2007] 11A (northern source) and [BHB2007] 11B (southern source). The dust emission seen in the ALMA data arises from circumstellar disks with radii 3.1 ± 0.6 AU ([BHB2007] 11A) and 2.1 ± 0.5 AU ([BHB2007] 11B), similar to the radius of the asteroid belt in the Solar System. Their inclinations are ~40° between the disk normals and the line of sight. From the continuum emission, the masses of the circumstellar disks are estimated to be within an order of magnitude of a Jupiter mass (M_{Jup}), with the [BHB2007] 11A disk slightly more massive than the [BHB2007] 11B disk (*9*). The dust content in the disks is a few Earth masses (M_{Earth}) (*9*). The larger circumbinary disk has a total mass of 0.08 ± 0.03 solar masses ($M_{\odot}$, where $1M_{\odot} \sim 1000\ M_{\mathrm{Jup}} \sim 330{,}000\ M_{\mathrm{Earth}}$). Because this represents ~260 M_{Earth} in dust, we speculate that the circumstellar disks may later form rocky terrestrial planets (*13*).

The protobinary is in the center of a complex network of dust structures distributed in spiral shapes. Spirals in protostellar systems such as LDN 1448NB have been interpreted as the outcome of disk fragmentation (*14*). The Toomre parameter, which quantifies the dynamical state of the disk (*15*), shows that the [BHB2007] 11 circumbinary disk is stable against gravitational collapse (*9*), so the observed spirals are unlikely to be the result of disk fragmentation. The total length of the filaments is ~392 AU, their mean width is ~12 AU, and the mean brightness temperature is 14 K, from which we estimate a mean total mass of ~19 M_{Jup} (*9*). This corresponds to a mean mass per unit length of $\sim 10\ M_{\odot}\ \mathrm{pc}^{-1}$, which is below the critical value required to produce fragmentation in the filaments. The spiral shape centered on the protobinary system indicates dynamical interaction with the protostars. Figure 1B shows that the geometrical center of the circumbinary disk is located near [BHB2007] 11A, within the angular resolution, suggesting that this source is the primary, higher-mass object of the system. We suggest that the filaments are inflow streamers from the extended circumbinary disk onto the circumstellar disks of the protobinary system. We estimate a mass accretion rate from the circumbinary disk into the circumstellar disk of $\sim 1.1 \times 10^{-5}\ M_{\odot}\ \mathrm{year}^{-1}$ (*9*), which is consistent with other protostellar sources (*16*). The rotationally supported disk may be redistributing its angular momentum (through processes such as viscosity, magnetic braking, or gravitational torques), causing material to fall into the gravitational potential wells of the individual protostars. Although other factors such as envelope accretion into the circumbinary disk, misaligned disks, or eccentric binary orbit could also produce substructure such as filaments in the circumbinary disk (*6*, *17*, *18*), accretion streamers feeding the circumstellar disks can still occur in those scenarios (*6*, *17*).

We measured kinematics by reanalyzing (*9*) previous observations (*8*) of the CO (angular momentum quantum number J = 2→1) molecular emission line in [BHB2007] 11. The relative positions of the molecular gas in each velocity channel of the emission spectra were determined with positional accuracies better than 0.05″ (*9*). The systemic velocity of [BHB2007] 11 with respect to the local standard of rest is $v_{\mathrm{lsr}} \sim 3.6\ \mathrm{km\ s^{-1}}$. The CO line traces primarily outflow emission, but velocity components faster than the outflows are detected within the circumbinary disk (*8*). These high-velocity components reach up to 15 km s^{-1}. The blue- and redshifted velocities ($v_{\mathrm{lsr}} < -1.5\ \mathrm{km\ s^{-1}}$ and $v_{\mathrm{lsr}} > 9\ \mathrm{km\ s^{-1}}$, respectively) are centered on [BHB2007] 11B, with the higher velocities closest to the position of the protostar (Fig. 2A). No high-velocity components are detected near [BHB2007] 11A. The increasing velocity toward [BHB2007] 11B indicates acceleration of infalling gas from the circumbinary disk onto [BHB2007] 11B.

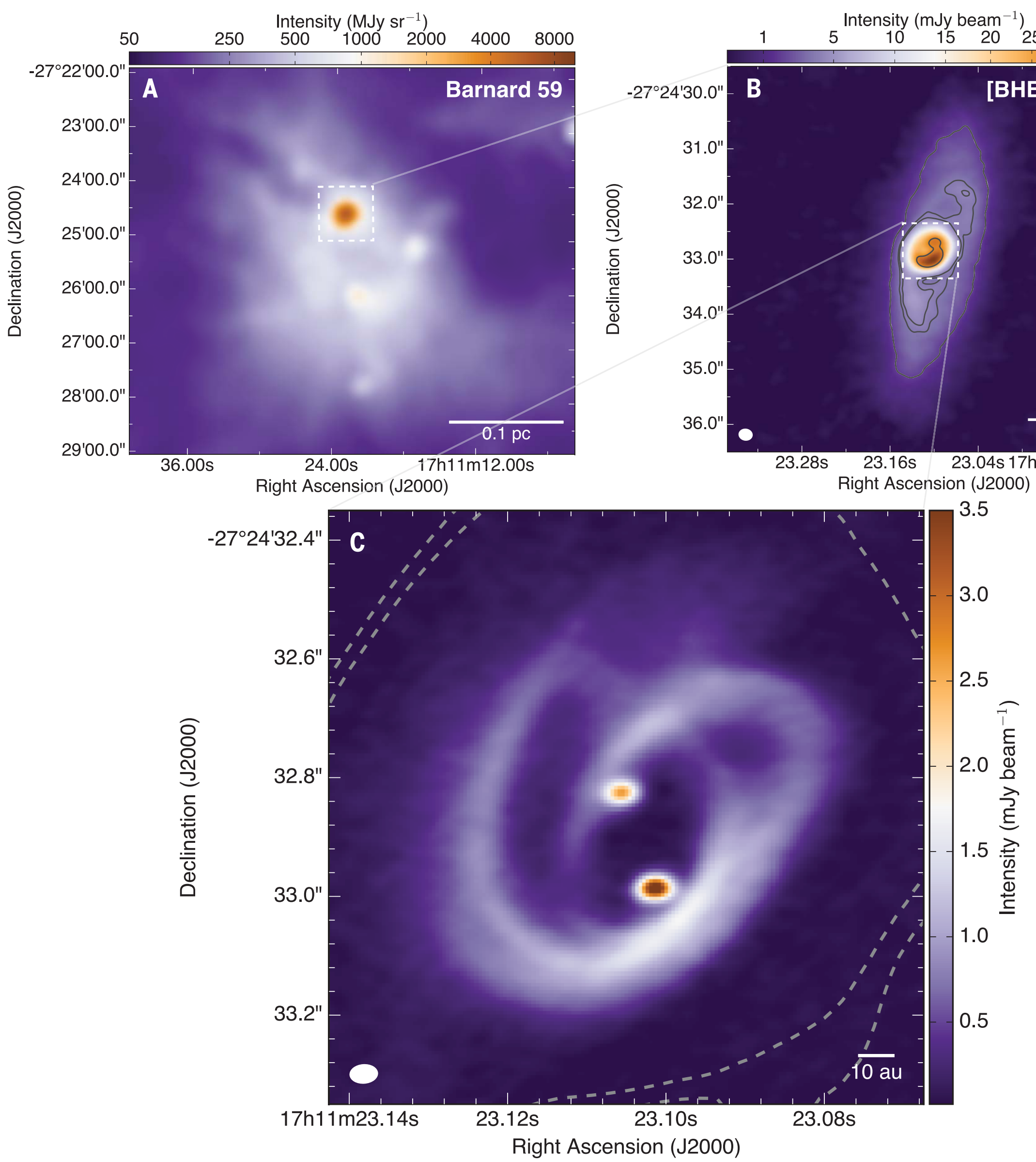

Fig. 1. Dust distribution in [BHB2007] 11 on scales from the core to the circumstellar disks. (**A**) The core of Barnard 59 observed at 250 μm with the Herschel space telescope (*20*). (**B**) The [BHB2007] 11 disk and envelope observed at 1.3 mm with ALMA (*8*). The contours indicate intensity levels of 30, 60, 70, and 450 times the map noise of 62 μJy per beam (1 Jy = 10^{-26} W m^{-2} Hz^{-1}). Intensity levels are scaled logarithmically in (A) and (B). (**C**) Zoomed-in view of the circumbinary disk, revealing the dust filaments surrounding the protobinary system, where [BHB2007] 11A is the northern component and [BHB2007] 11B is the southern and brighter component. The dashed lines are the intensity contours from (B). In (B) and (C), the ALMA synthesized beam is shown in the bottom left corner.

The observed velocities are consistent with the filament accretion rate estimated above. Figure 2B shows the CO spectrum with the high-velocity channels used to compute the CO emission peaks.

We used the VLA to observe the protobinary in continuum emission at 34.5 GHz (*11*) and at lower frequencies (10, 15, and 22 GHz) (*9*). The centimeter-wavelength data are consistent with thermal free-free emission from partially ionized collimated jets produced by angular momentum redistribution in the disk-star system. This type of emission correlates with the momentum rate, so the radio flux is also correlated with the disk-star accretion rate (*19*). The radio jet–like emission along the east-west direction associated with [BHB2007] 11A (Fig. 3) suggests that this source has a higher (circumstellar) disk-star accretion rate than [BHB2007] 11B. In addition, [BHB2007] 11A has an ionized mass loss rate that is a factor of ~2 higher than that of [BHB2007] 11B [~6.4×10^{-10} $M_\odot$ $year^{-1}$ and ~3.7×10^{-10} $M_\odot$ $year^{-1}$, respectively (*9*)]. The stronger radio jet and higher ionized mass loss rate support the proposition that [BHB2007] 11A is the primary object in the binary system. The infalling gas onto [BHB2007] 11B suggests a hgher accretion from the circumbinary disk onto this object than onto [BHB2007] 11A. This preferential accretion onto the lower-mass stellar object in a binary system matches theoretical predictions (*4*–*6*).

In summary, the small-scale structure seen in our observations includes streamers of gas and dust accreting from a circumbinary disk onto small circumstellar disks around the individual components of a protobinary system. Their disks have a dust mass equivalent to a few

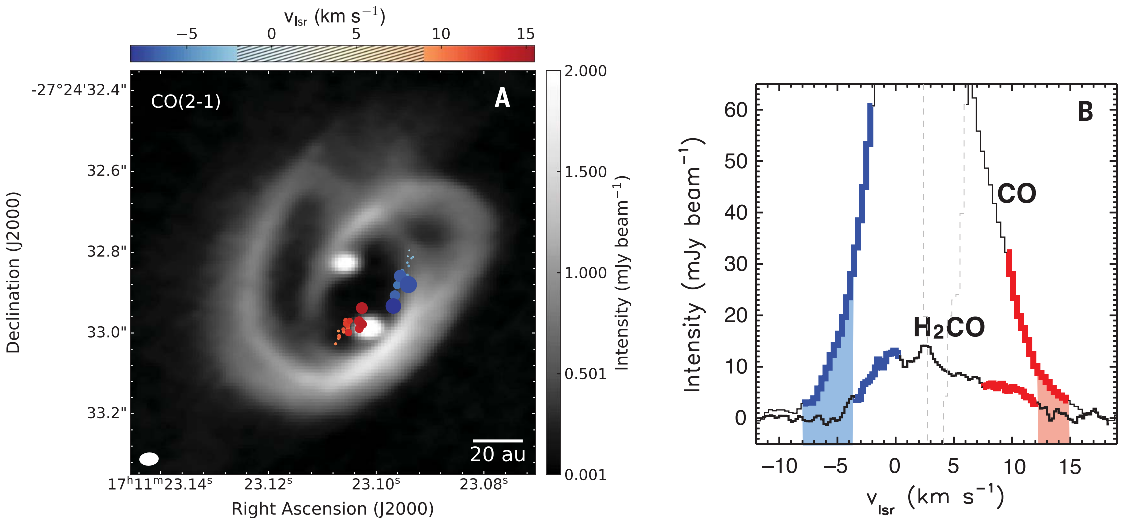

Fig. 2. Small-scale kinematics in [BHB2007] 11 measured from CO molecular line emission. (**A**) High-velocity components of the CO emission (with respect to the ambient local standard of rest velocity of [BHB2007] 11, v_{lsr} ~ 3.6 km s^{-1}) overlaid on the continuum map (gray scale). Circles indicate the position of CO emission peaks in each velocity channel (see the color bar). CO data between −2 and 9 km s^{-1} (indicated as a shaded area in the color bar) are not shown because most gas close to the ambient velocity is filtered out by the interferometer and/or arises from extended emission from outflows or the envelope. Circle sizes denote the uncertainty on the absolute position (*9*). (**B**) CO mean spectrum extracted from the disk area showing the CO velocity channels used in (A). The shaded areas indicate the CO velocity components that exceed the reference H_2CO spectrum associated with the rotation of the circumbinary disk (*9*). The faint dashed lines show the strong filtering of the CO line near the systemic velocity of the source.

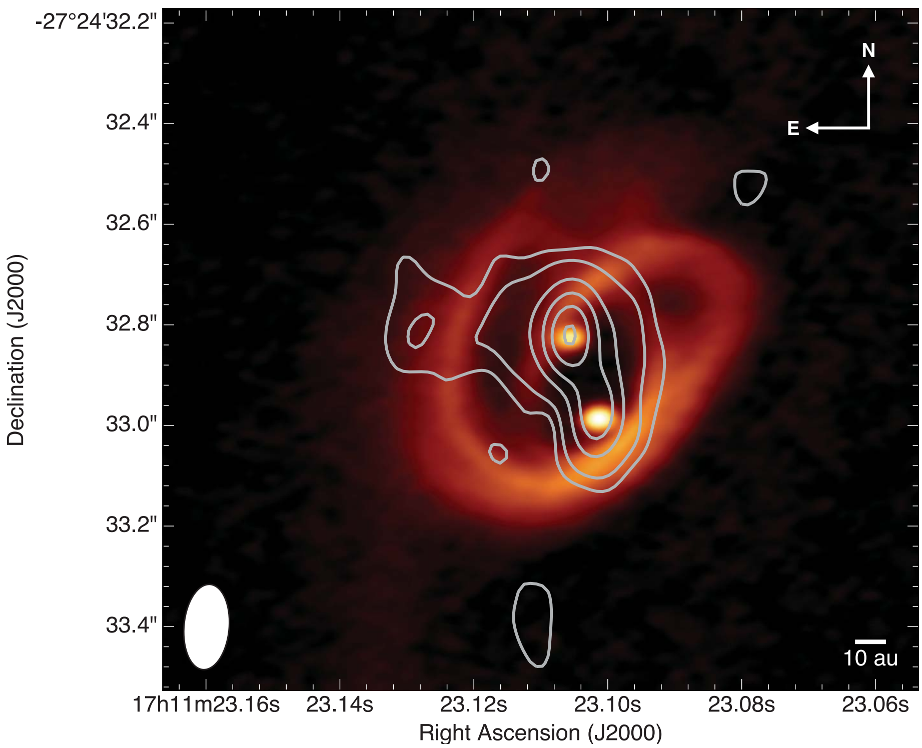

Fig. 3. Centimetric emission associated with the binary system. Continuum emission at 0.94 cm (32.5 GHz) associated with the [BHB2007] 11 binary system, observed with the VLA. Contours are at 3, 5, 10, 15, 20, and 25 times the map noise of 12 μJy per beam; the background image is the ALMA map from Fig. 1C. The extended emission to the east of [BHB2007] 11A suggests a radio jet associated with this source. The VLA synthesized beam is shown in the bottom left corner.

Earth masses. The gas accretion is more prominent in the secondary, less massive object of the system, whereas the disk-star accretion inferred by the ionized free-free emission is higher in the primary object instead. We expect that this two-level accretion process, circumbinary disk to circumstellar disks, then circumstellar disks to stars, drives the dynamics of the binary system during its mass accretion phase.

REFERENCES AND NOTES

1. D. Raghavan *et al.*, *Astrophys. J. Suppl. Ser.* **190**, 1–42 (2010).
2. K. M. Kratter, C. D. Matzner, M. R. Krumholz, R. I. Klein, *Astrophys. J.* **708**, 1585–1597 (2010).
3. L. D. G. Sigalotti, F. Cruz, R. Gabbasov, J. Klapp, J. Ramírez-Velasquez, *Astrophys. J.* **857**, 40 (2018).
4. M. R. Bate, I. A. Bonnell, *Mon. Not. R. Astron. Soc.* **285**, 33–48 (1997).
5. M. R. Bate, I. A. Bonnell, V. Bromm, *Mon. Not. R. Astron. Soc.* **336**, 705–713 (2002).
6. T. Matsumoto, K. Saigo, S. Takakuwa, *Astrophys. J.* **871**, 36–52 (2019).
7. T. Y. Brooke *et al.*, *Astrophys. J.* **655**, 364–374 (2007).
8. F. O. Alves *et al.*, *Astron. Astrophys.* **603**, L3 (2017).
9. Materials and methods are available as supplementary materials.
10. S. A. Dzib, L. Loinard, G. N. Ortiz-León, L. F. Rodríguez, P. A. B. Galli, *Astrophys. J.* **867**, 151–166 (2018).
11. F. O. Alves *et al.*, *Astron. Astrophys.* **616**, A56 (2018).
12. S. A. Dzib, L. F. Rodríguez, A. T. Araudo, L. Loinard, *Rev. Mex. Astron. Astrofis.* **49**, 345–349 (2013).
13. B. Liu, C. W. Ormel, *Astron. Astrophys.* **615**, A138 (2018).

14. J. J. Tobin *et al*., *Nature* **538**, 483–486 (2016).
15. A. Toomre, *Astrophys. J.* **139**, 1217–1238 (1964).
16. M. M. Dunham *et al*., in *Protostars and Planets VI*, H. Beuther, R. S. Klessen, C. P. Dullemond, T. Henning, Eds. (Univ. of Arizona Press, 2014), pp. 195–218.
17. P. Mösta, R. E. Taam, P. C. Duffell, *Astrophys. J.* **875**, L21 (2019).
18. G. M. Kennedy *et al*., *New Astron.* **3**, 230–235 (2019).
19. S. P. Reynolds, *Astrophys. J.* **304**, 713–720 (1986).
20. P. André *et al*., *Astron. Astrophys.* **518**, L102 (2010).

ACKNOWLEDGMENTS

We thank the reviewers for helpful and detailed comments that improved the manuscript and the ALMA and VLA staff for performing the observations and quality assessment of the data. We also thank M. Fernández López, W. Lyra, and P. Cortes for useful discussions on the data analysis and interpretation. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. The VLA is an instrument of the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has also made use of data from the Herschel Gould Belt survey (HGBS) project (http://gouldbelt-herschel.cea.fr). The HGBS is a Herschel Key Programme jointly carried out by SPIRE Specialist Astronomy Group 3 (SAG 3), scientists of several institutes in the PACS Consortium (CEA Saclay, INAF-IFSI Rome and INAF-Arcetri, KU Leuven, and MPIA Heidelberg), and scientists of the Herschel Science Center (HSC). **Funding:** F.O.A., P.C., D.S.-C, A.S., and B.Z. acknowledge financial support from the Max Planck Society. P.C. and B.Z. acknowledge support of the European Research Council (ERC, project PALs 320620). J.M.G. is supported by the MINECO (Spain) grant AYA2017-84390-C2. G.A.P.F. acknowledges support from CNPq and FAPEMIG (Brazil). **Author contributions:** F.O.A. led the project and ALMA observing proposal, analyzed the ALMA data (calibration and imaging), conducted the molecular line data analysis, and led the preparation of the manuscript. P.C. contributed to paper preparation, molecular line interpretation, and derivation of dust properties. J.M.G. led the VLA observing proposal and the VLA data analysis, including calibration, imaging, and spectral index derivation. D.S.-C. performed the self-calibration of the continuum image and contributed to the continuum data analysis. G.A.P.F. developed the analytical approach for the mass accretion rate and contributed to the manuscript preparation. A.S. and B.Z. contributed to the theoretical interpretation of the results. All authors contributed to the discussion and interpretation of the data. **Competing interests:** There are no competing interests. **Data and materials availability:** The ALMA observations are archived in the ALMA Science Archive http://almascience.nrao.edu/aq/ under project codes 2016.1.01186.S and 2013.1.00291.S. The VLA data are archived at https://science.nrao.edu/facilities/vla/archive/index under VLA project code 16B-290.

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/366/6461/90/suppl/DC1
Materials and Methods
Figs. S1 to S3
Table S1
References (*21*–*29*)

17 December 2018; accepted 9 September 2019
10.1126/science.aaw3491

Science

Gas flow and accretion via spiral streamers and circumstellar disks in a young binary protostar

F. O. Alves, P. Caselli, J. M. Girart, D. Segura-Cox, G. A. P. Franco, A. Schmiedeke and B. Zhao

Science **366** (6461), 90-93.
DOI: 10.1126/science.aaw3491

Gas flows and disks in a young binary

Many stars are in binary systems, pairs of stars gravitationally bound to each other, often with the two components having similar masses. It remains unclear how these systems assemble and accrete material. Alves *et al.* made high-resolution observations of a young binary star that is still in the process of forming. A large disk surrounds both stars, and each component also has its own smaller circumstellar disk. Spiral filaments of dust and gas connect the small disks to the larger one. Material is accreting preferentially onto the star that currently has a lower mass, driving the masses toward similar values.

Science, this issue p. 90

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.