A triple protostar system formed via fragmentation of a gravitationally unstable disk

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Binary and multiple star systems are a frequent outcome of the star formation process1,2 and as a result almost half of all stars with masses similar to that of the Sun have at least one companion star3. Theoretical studies indicate that there are two main pathways that can operate concurrently to form binary/multiple star systems: large-scale fragmentation of turbulent gas cores and filaments1,4,5 or smaller-scale fragmentation of a massive protostellar disk due to gravitational instability6,7. Observational evidence for turbulent fragmentation on scales of more than 1,000 astronomical units has recently emerged8,9. Previous evidence for disk fragmentation was limited to inferences based on the separations of more-evolved pre-main-sequence and protostellar multiple systems10-13. The triple protostar system L1448 IRS3B is an ideal system with which to search for evidence of disk fragmentation as it is in an early phase of the star formation process, it is likely to be less than 150,000 years old14 and all of the protostars in the system are separated by less than 200 astronomical units. Here we report observations of dust and molecular gas emission that reveal a disk with a spiral structure surrounding the three protostars. Two protostars near the centre of the disk are separated by 61 astronomical units and a tertiary protostar is coincident with a spiral arm in the outer disk at a separation of 183 astronomical units15. The inferred mass of the central pair of protostellar objects is approximately one solar mass, while the disk surrounding the three protostars has a total mass of around 0.30 solar masses. The tertiary protostar itself has a minimum mass of about 0.085 solar masses. We demonstrate that the disk around L1448 IRS3B appears susceptible to disk fragmentation at radii between 150 and 320 astronomical units, overlapping with the location of the tertiary protostar. This is consistent with models for a protostellar disk that has recently undergone gravitational instability, spawning one or two companion stars.

L1448 IRS3B is located in the Perseus molecular cloud at a distance of around 230 pc (ref. 15) and contains three protostars out of the six that collectively make up L1448 IRS313,14, which spans a region that is 0.05 pc wide. L1448 IRS3B is a Class 0 protostar system16, which represents an early phase of the star formation process when the protostars are deeply enshrouded in an envelope of accreting material17. The three protostars in L1448 IRS3B (denoted -a, -b, and -c) have a hierarchical configuration: the central protostar, IRS3B-a, has projected separations from IRS3B-b and IRS3B-c of 61 au and 183 au, respectively15. The new observations of L1448 IRS3B conducted with the Atacama Large Millimeter/submillimeter Array (ALMA) at a resolution of 0.27″ × 0.16″ (62 au × 37 au) provide images of the dust and gas emission surrounding the three protostars at 1.3 mm with a sensitivity that is ten times higher and a resolution that is two times higher than previous studies.

The ALMA 1.3 mm image of L1448 IRS3B is shown in Fig. 1, revealing dust emission towards each of the three distinct protostars, which were identified in previous Karl G. Jansky Very Large Array (VLA) observations15. The ALMA images also reveal a disk with substructure surrounding the entire system, extending to a radius of around 400 au. The disk appears to have a dominant one- or two-armed spiral that links IRS3B-a and IRS3B-b with the more widely separated IRS3B-c, which is embedded in the outermost arm. The disk geometry and rotation profile (see below) place the centre of mass of the system near the close pair, IRS3B-a and IRS3B-b, rather than towards the more distant (and brighter at 1.3 mm and 8 mm) IRS3B-c. A VLA 8 mm image that has a comparable resolution to the ALMA data is also shown in Fig. 1. The 8 mm emission towards the protostar positions may be a combination of both concentrated dust emission and free-free emission from the base of the jets driven by the protostar18. However, the weak 8 mm emission associated with the disk and spiral arms surrounding the three protostars is from dust only. The weaker emission from the disk at 8 mm is unsurprising, because thermal dust emission at submillimetre and longer wavelengths decreases in brightness with the inverse square of wavelength, modified by the dust opacity spectral index (see Methods).

The resolved disk in the ALMA observations also enables us to estimate the inclination of the system to be 45.4° and to calculate the deprojected separations of the companions (see Methods). The deprojected separations of IRS3B-b and IRS3B-c from IRS3B-a are 78 au and 254 au, respectively. We estimate the mass of the entire disk using the dust continuum emission (with IRS3B-c removed). Assuming that the dust and gas are well mixed, we find \( M_{\text{disk}} = 0.30 \pm 0.03 \text{M}_\odot \) using the integrated 1.3 mm flux density of 0.52 ± 0.002 Jy. Finally, the mass surrounding IRS3B-c in the outer disk is estimated to be 0.085 M\(_\odot\) from the 1.3 mm flux density of 0.19 ± 0.003 Jy, this is a lower limit to the gas mass given that IRS3B-c is probably opaque at 1.3 mm (see Methods). The surface density profile of the disk is subsequently derived from the 1.3 mm continuum data (see Methods).

The velocity structure of the disk is shown in Fig. 2, using the Doppler shift of the O\(^{16}\) molecular line emission as the gas orbits the centre of mass in the system. The distinct separation between the blueshifted and redshifted emission is indicative of a rotation pattern that is centred on IRS3B-a and IRS3B-b. The rotation pattern reinforces the conclusion from the dust continuum that IRS3B-a and IRS3B-b comprise the dominant mass in the system. Furthermore, the overall mass of IRS3B-c must be low relative to IRS3B-a and IRS3B-b, despite being the brightest source at 1.3 mm and 8 mm. We estimate that IRS3B-a and IRS3B-b have a combined mass of approximately 1.6 M\(_\odot\) from the disk rotation profile (see Methods). We are unable to make an estimate of the protostellar mass for IRS3B-c from molecular line

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Kinematics, but the value of 0.085 $M_\odot$ derived from the surrounding dust emission can be considered a lower limit. Note that the C$^{18}$O emission does not trace the entire disk structure seen in the dust because any emission at velocities around ±1 km s$^{-1}$ of the system velocity (approximately 4.5 km s$^{-1}$) is filtered out along with the large, surrounding envelope.

With these physical parameters in hand, we can now assess whether L1448 IRS3B hosts a gravitationally unstable disk that recently fragmented to form IRS3B-c. Gravitational instabilities arise in protostellar disks when the self-gravity of the disk becomes non-negligible compared with the gravity of the central protostar(s). Although disk fragmentation is the nonlinear outcome of a complex hydrodynamic instability, the canonical analytic estimate for when instability occurs is that the Toomre Q parameter$^{19}$ is of order unity (see Methods for details). For Keplerian disks, Q can be expressed as:

$$Q = \frac{M_d}{\pi R_d \sigma^2}$$

where $M_d$ is the mass of the disk, $R_d$ is the radius of the disk, and $\sigma$ is the velocity dispersion.

**Figure 1** | ALMA and VLA images of the disk and triple protostar system L1448 IRS3B. a. ALMA 1.3 mm image of the extended disk, showing an evident bright source on the left (IRS3B-c) in the outer disk and another blended source on the right near the centre of the disk (IRS3B-a and IRS3B-b). The positions of the three protostars identified from the VLA data are shown by red crosses. b. VLA 8 mm image smoothed to a similar resolution as the ALMA image, capturing some of the faint, extended disk at longer wavelengths. The contours in b are from a higher-resolution VLA 8 mm image and clearly show the individual protostars with corresponding designations. All three protostars are embedded within apparent spiral arms that emerge from IRS3B-a/IRS3B-b and extend to IRS3B-c in the outer disk. The contours start at and increase by 5$\sigma$, where $\sigma = 0.009$ mJy per beam. The resolution of each image is shown with an ellipse(s) drawn in the lower right corner: 0.27$''$ × 0.16$''$ (62 au × 37 au) for the ALMA image in a, 0.24$''$ × 0.20$''$ (55 au × 46 au) for the VLA image in b and 0.18$''$ × 0.16$''$ (41 au × 37 au; blue ellipse) for the contour image in b. J2000 refers to the coordinate epoch.

**Figure 2** | Images of the C$^{18}$O emission and its corresponding velocity maps from the disk around L1448 IRS3B, showing a rotation signature. a. Redshifted and blueshifted C$^{18}$O (J = 2 → 1) emission is overlaid on the ALMA 1.3 mm continuum image (greyscale) as red and blue contours that start at 4$\sigma$ and increase in 1$\sigma$ intervals. b. Line-centre velocity map of the C$^{18}$O emission with 1.3 mm continuum contours overlaid in grey (the contours start at and increase by 10$\sigma$; at 100$\sigma$ the levels increase in steps of 30$\sigma$ and at 400$\sigma$ the levels increase by 100$\sigma$ steps; $\sigma = 0.14$ mJy per beam). The C$^{18}$O traces higher-velocity emission near IRS3B-a and IRS3B-b, consistent with the centre of mass of the system being near these protostars. Lower-velocity gas is found to be associated with the outer spiral arm detected in dust emission. The molecular line emission does not fully trace the disk owing to spatial filtering of emission with velocities close to that of the system (around 4.5 km s$^{-1}$). The source positions are marked with white or yellow crosses. The outflow direction is denoted by the blue and red arrows. The angular resolution of these data is given by the ellipse in the lower right corners: 0.36$''$ × 0.25$''$ (83 au × 58 au). The C$^{18}$O emission was integrated over 1.25–4.0 km s$^{-1}$ and 5.5–7.0 km s$^{-1}$ for the blueshifted and redshifted maps, respectively. The noise levels for C$^{18}$O are $\sigma_{\text{blue}} = 2.25$ K km s$^{-1}$ and $\sigma_{\text{red}} = 1.65$ K km s$^{-1}$.
where $M_c$ is the mass of the central protostar(s), $M_d$ is the disk mass, $r$ is the disk radius at which $Q$ is being calculated and $H = c_s / \Omega$ is the disk scale height ($c_s$ is the speed of sound of the disk and $\Omega$ is the Keplerian angular velocity). Using the masses derived above, we can immediately see that for typical disk temperatures of 30 K ($c_s = 0.3 \text{ km s}^{-1}$) at a radius of 200 AU ($\Omega \approx 7 \times 10^{-11} \text{ rad s}^{-1}$), $Q \approx 1$. While suggestive of instability, a more robust model is desirable—a simple analytic disk model$^{20}$ illustrating that the IRS3B disk probably underwent gravitational instability in the recent past is described in the Methods. Our analytic model is consistent with many previous numerical simulations of fragmenting disks that replicate this type of disk morphology (for example, spiral arms) with parameters that are comparable to the observed quantities$^{21,22}$.

We show the result of our analysis in Fig. 3, where we plot the range of possible $Q$ values for different inferred mass accretion rates as a function of disk radius. Given the mass of the central protostars (both assumed to be around 0.5$M_\odot$) and the luminosity of 3.2$L_\odot$ (ref. 23), a current mass accretion rate of around $10^{-7} M_\odot$ yr$^{-1}$ is most consistent with the model. For a wide range of accretion rates, the disk around IRS3B is marginally unstable ($Q \approx 1$) at radii between 150 AU and 320 AU. This conclusion is consistent with both the continued presence of the spiral arms and IRS3B-c forming near its current deprojected separation of 254 AU. The evolutionary phase of IRS3B-c is also consistent with it forming within the last few dynamical times (that is, orbital periods of approximately 4 kyr assuming Keplerian rotation around IRS3B-a/b with a semi-major axis of 254 AU). Before IRS3B-c formed, the outer disk is likely to have been more unstable, and the subsequent accretion of disk mass onto IRS3B-c is now stabilizing the disk. A fragment formed by instability in this disk would probably begin with a mass of roughly $10^{-2} M_\odot$, consistent with IRS3B-c undergoing accretion to arrive at our measured surrounding mass of at least 0.085$M_\odot$ (see Methods).

In addition to IRS3B-c, IRS3B-b may have formed from an earlier episode of disk fragmentation$^{21}$. IRS3B-b could have formed near its current location if the disk was more unstable in the past. It could also have formed in the outer disk before IRS3B-c and migrated inwards to its current location over a few tens of orbital timescales$^{24}$. Fragments formed early in the evolution of the disk can grow to comparable masses to the primary star$^{21}$. Finally, we note that if all three protostars were on roughly circular, co-planar Keplerian orbits with semi-major axes equal to their deprojected separations, they would be marginally dynamically unstable$^{25}$. Thus we expect the orbits to evolve on rapid timescales (with respect to the expected stellar lifetime), especially as the disk dissipates. A natural outcome of this dynamical instability is the formation of a more hierarchical system with a tighter inner pair (separated by a few astronomical units) and wider (hundreds to thousands of astronomical units separation) tertiary$^{26}$, consistent with observed triple systems$^{27}$.

Our results demonstrate that protostellar disks can experience gravitational instability at young ages, leading to the formation of hierarchical multiple systems. Such disks may also show spiral structure associated with the linear growth phase of gravitational instability. The spiral structure in L1448 IRS3B is consistent with simulated ALMA observations of unstable disks that assume a comparable ratio of disk mass to stellar mass$^{28}$. A spiral structure has been detected previously in more-evolved disks from observations of near-infrared scattered light originating from the disk upper layers$^{29}$. However, those disks are not sufficiently massive to generate the spiral structure by gravitational instability, and thus far there has been only one other case of a proto-planetary disk with spiral structure in its midplane, possibly resulting from gravitational instability$^{30}$.

Although the frequency of fragmenting disks such as IRS3B is still unknown, we do not expect them to be intrinsically rare. Our conclusion is based on the typical multiplicity and separation distributions observed in the star forming region in which IRS3B resides, Perseus. Close multiples such as the IRS3-a/b or IRS3B-a/c pairs are frequently found in protostar systems$^{10,12,13}$. This discovery, together with the recent work supporting turbulent fragmentation at larger scales (thousands of astronomical units)$^{8,9}$, provides direct observational support for the two dominant theoretical models for binary/multiple star formation. We predict that systems similar to IRS3B will be discovered in larger samples with facilities such as ALMA, and their frequency will help to benchmark the relative contribution of disk fragmentation to the population of binary/multiple stars.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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1. Duchêne, G. & Kraus, A. Stellar multiplicity. Annu. Rev. Astron. Astrophys. 51, 269–310 (2013).
2. Reipurth, B. et al. in Protostars and Planets Vol. VI (eds Beuther, H. et al.) 267–290 (Univ. Arizona Press, 2014).
3. Ragavan, D. et al. A survey of stellar families: multiplicity of solar-type stars. Astrophys. J. Suppl. Ser. 190, 1–42 (2010).
4. Fisher, R. T. A turbulent interstellar medium origin of the binary period distribution. Astrophys. J. 600, 769–790 (2004).
5. Padoan, P. & Nordlund, Å. The “mysterious” origin of brown dwarfs. Astrophys. J. 617, 559–564 (2004).
6. Adams, F. C., Ruden, S. P. & Shu, F. H. Eccentric gravitational instabilities in nearly Keplerian disks. Astrophys. J. 347, 959–976 (1989).
7. Bonnell, I. A. & Bate, M. R. The formation of close binary systems. Mon. Not. R. Astron. Soc. 271, 999–1004 (1994).
8. Pineda, J. E. et al. The formation of a quadruple star system with wide separation. Nature 518, 213–215 (2015).
9. Lee, K. I. et al. Misalignment of outflow axes in the proto-multiple systems in Perseus. Astrophys. J. Lett. 820, L2 (2016).
10. Connelley, M. S., Reipurth, B. & Tokunaga, A. T. The evolution of the multiplicity of embedded protostars. II: binary separation distribution and analysis. Astron. J. 135, 2526–2536 (2008).
11. Kraus, A. L., Ireland, M. J., Martinache, F. & Hillenbrand, L. A. Mapping the shores of the brown dwarf desert. II: multiple star formation in Taurus-Auriga. Astrophys. J. 731, 8 (2011).
12. Takakuwa, S. et al. A Keplerian circumbinary disk around the protostellar system L1551 NE. Astrophys. J. 754, 52 (2012).
13. Tobin, J. J. et al. The VLA nascent disk and multiplicity survey of Perseus protostars (VANDAM): II; multiplicity of protostars in the Perseus molecular cloud. *Astrophys. J.* **818**, 73 (2016).

14. Lee, K. I. et al. Mass assembly of stellar systems and their evolution with the SMA (MASSES): multiplicity and the physical environment in L1448N. *Astrophys. J.* **814**, 114 (2015).

15. Hirota, T. et al. Astrometry of H$_2$O masers in nearby star-forming regions with VERA. *IV. L. 1448 C. Publ. Astron. Soc. Jpn* **63**, 1–8 (2011).

16. Sadavoy, S. I. et al. Class 0 protostars in the Perseus molecular cloud: a correlation between the youngest protostars and the dense gas distribution. *Astrophys. J. Lett.* **787**, L18 (2014).

17. André, P., Ward-Thompson, D. & Barsony, M. Submillimeter continuum observations of Rho Ophiuchi A: the candidate protostar VLA 1623 and prestellar clumps. *Astrophys. J.* **406**, 122–141 (1993).

18. Anglada, G. et al. Spectral indices of centimeter continuum sources in star-forming regions: implications on the nature of the outflow exciting sources. *Astron. J.* **116**, 2953–2964 (1998).

19. Toomre, A. On the gravitational stability of a disk of stars. *Astrophys. J.* **139**, 1217–1238 (1964).

20. Kratter, K. M. & Lodato, G. Gravitational instabilities in circumstellar disks. *Annu. Rev. Astron. Astrophys.* **54**, 271–311 (2016).

21. Kratter, K. M., Matzner, C. D., Krumholz, M. R. & Klein, R. I. On the role of disks in the formation of stellar systems: a numerical parameter study of rapid accretion. *Astrophys. J.* **708**, 1585–1597 (2010).

22. Bate, M. R. Stellar, brown dwarf and multiple star properties from a radiation hydrodynamical simulation of star cluster formation. *Mon. Not. R. Astron. Soc.* **419**, 3115–3146 (2012).

23. Murillo, N. M., van Dishoeck, E. F., Tobin, J. J. & Fedele, D. Do siblings always form and evolve simultaneously? Testing the coevality of multiple protostellar systems through SEDs. *Astron. Astrophys.* **592**, A56 (2016).

24. Zhu, Z., Hartmann, L., Nelson, R. P. & Gammie, C. F. Challenges in forming planets by gravitational instability: disk irradiation and clump migration, accretion, and tidal destruction. *Astrophys. J.* **746**, 110 (2012).

25. Valtonen, M., Myllärni, A., Orlov, V. & Rubinov, A. in *Dynamical Evolution of Dense Stellar Systems* Vol. 246 (eds Vesperini, E. et al.) A209–A217 (Cambridge Univ. Press, 2008).

26. Kisleva, L. G., Eggelton, P. P. & Orlov, V. V. Instability of close triple systems with coplanar initial doubly circular motion. *Mon. Not. R. Astron. Soc.* **270**, 936 (1994).

27. Tokovinin, A. Low-mass visual companions to nearby G-dwarfs. *Astron. J.* **141**, 52 (2011).

28. Dibepiro, G., Lodato, G., Testi, L. & de Gregorio Monsalvo, I. How to detect the signatures of self-gravitating circumstellar discs with the Atacama Large Millimeter/sub-millimeter Array. *Mon. Not. R. Astron. Soc.* **444**, 1919–1929 (2014).

29. Grady, C. A. et al. Spiral arms in the asymmetrically illuminated disk of MWC 758 and constraints on giant planets. *Astrophys. J.* **762**, 48 (2013).

30. Pérez, L. M. et al. Spiral density waves in a young protoplanetary disk. *Science* **353**, 1519–1521 (2016).

### Supplementary Information

Supplementary Information is available in the online version of the paper.

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### Author Contributions

J.J.T.: M.M.D., L.W.L., D.S.-C., C.J.C., L.M.P., C.M., S.I.S. and R.J.H. participated in data acquisition and J.J.T., K.M.K. and M.V.P. contributed to data analysis and reduction. J.J.T. and K.M.K. led the writing of the manuscript, incorporating the feedback, suggestions and discussion of results from all authors.

### Author Information

Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.J.T. (jjtobin@ou.edu).
METHODS

Observations. L1448 IRS3B was observed with ALMA during Cycle 2 on 27 September 2015 with 33 antennas sampling baselines between 32 and 2,000 m. The observations were executed within a 1.8 h block and the total time spent on L1448 IRS3B was approximately 2.9 min. The precipitable water vapour was approximately 0.7 mm throughout the observing session. The phase calibrator was J0319+4310 (3C84), the bandpass calibrator was J0257+2848, and the amplitude and bandpass calibrator was the monitored quasar J0258+166. The correlator was configured to observe a 2 GHz continuum band centred at 232.5 GHz, and with 60 MHz bands centred on the following molecular transitions: 12CO (J = 2 → 1), 13CO (J = 2 → 1), C18O (J = 2 → 1), SO (J = 3s → 5s), and H2CO (J = 3s → 2s), for which J is the rotational quantum number. The flux calibration accuracy is expected to be better than 10%.

The raw data were manually reduced by the North American ALMA Regional Center staff using CASA13 version 4.5.0. We performed self-calibration on the continuum data to increase the signal-to-noise ratio by correcting for short timescale fluctuations in phase and amplitude. The phase and amplitude solutions from the continuum self-calibration were also applied to the spectral line bands. The data were then imaged using the clean task within CASA 4.5.0; the ALMA images shown in Fig. 1 were generated using Briggs weighting with a robust parameter of 0.5. Within the clean task, we only include data at uλ distances > 50,000 Å (where uλ refers to the coordinate plane in the Fourier domain, versus right ascension–declination in the image domain, and λ refers to wavelength) to mitigate striping in the images from large-scale emission detected on the shortest baseline, which could not be properly imaged. The molecular line images shown in Fig. 2 and Extended Data Figs 1 and 2 were imaged with natural weighting, tapering at 500,000 Å uλ distances > 50,000 Å. Tapering reduces the weight of longer-baseline data in the deconvolution to facilitate the detection of larger structures with lower surface brightness.

The beam size of the continuum image is 0.27″ × 0.16″ (62 Å x 37 Å) and the beam size of the molecular line data are 0.36″ × 0.25″ (83 Å x 58 Å). The resultant noise in the 1.3 mm continuum was 0.14 mJy per beam and 15 mJy per beam in 0.25 km s−1 channels for the spectral line observations.

We show the 12CO (J = 2 → 1) and H2CO (J = 3s → 2s) integrated intensity maps in Extended Data Fig. 1. The 12CO map clearly shows an outflow that originates from the region of the three protostars. The redshifted emission shows a clear, wide outflow cavity with another redshifted feature within it. We suggest that this secondary redshifted feature within the outflow cavity is a jet-like outflow from IRS3B-c and that the arc-like shape is due to the orbital motion of the source. The blue-shifted outflow is much more diffuse and not as well-recovered in our data, but there appears to be emission associated with all three protostars. Nonetheless, it is clear that the outflow map towards these three sources is quite complex and made even more complex by the two more widely separated systems (IRS3A and IRS3C)15 that also drive outflows that extend across this map. The larger-scale outflow has been examined more thoroughly at lower resolution14.

We also detect faint 13CO emission from L1448 IRS3B, shown in Extended Data Fig. 1. The emission has low intensity, but also shows a velocity gradient in the same direction as 12CO and C18O. SO (J = 3s → 5s) emission was not detected towards L1448 IRS3B. H2CO is expected to trace the inner envelope around L1448 IRS3B-c; note that we adopt 40 K for IRS3B-c as the region that the Gaussian fit to IRS3B-c is not strongly affected by the emission in the surrounding, extended disk.

To remove IRS3B-c as cleanly as possible, we fit a two-component Gaussian with a constant zero-level offset. The two-component Gaussian is comprised of a point-source component superposed with a more extended Gaussian, and the zero-level offset is used to preserve emission from the disk in the vicinity of IRS3B-c. The fitting region is also restricted to a 0.7″ × 0.6″ ellipse around IRS3B-c, ensuring that the Gaussian fit to IRS3B-c is not strongly affected by the emission in the surrounding, extended disk.

We used the imfit task in CASA 4.5.0 to fit the Gaussian components. We then used these components to construct a model image of IRS3B-c within CASA Next, we used the setjy task to generate visibility data from the model image via a Fourier transform, and then filled the model column of the CASA measurement set with the visibility data. Finally, we use the viswsub task to subtract the model column from the data column, producing a data set with IRS3B-c subtracted. Images with IRS3B-c removed were then generated with clean, and we show the resultant images in Extended Data Fig. 3.

With IRS3B-c removed, we fit the major and minor axes of the disk to estimate the inclination with respect to the line of sight and position angle. To do this, we first generated an image from the data set with IRS3B-c subtracted using the CASA clean task, but taper (for example, smooth; see Methods section ‘Observations’) the visibility data to have a resolution of 0.43″ × 0.36″; this image smoothes over the spiral structure such that a single Gaussian can better fit the disk emission from the entire source. We use the imfit task in CASA to fit a single Gaussian, with the centre position fixed at the location of IRS3B-a, which appears to be the most centrally located source in the system.

The deconvolved major (θa) and minor (θb) axes of the resulting Gaussian were 1.78″ × 1.25″ (409 Å × 280 Å). Assuming symmetry, this corresponds to an inclination angle of 45.4° ± 0.4° (arcsec/θa/θb) and the position angle is 28.9° east of north. The uncertainty in the inclination results from the disk being asymmetric, as shown by Fig. 1 and Extended Data Fig. 3 (see Methods section ‘Disk surface density’). We estimate that there could be a systematic uncertainty of 20% in the minor axis of the disk because of the disk asymmetry.

Disk mass. The dust emission from L1448 IRS3B can be used to estimate the mass of the surrounding disk and the material around IRS3B-c itself. Assuming that the dust around L1448 IRS3B is optically thin, isothermal, and that the gas and dust are well mixed, we can calculate the mass with the equation

\[ M_{\text{dust}} = \frac{D^2 F_\lambda}{\kappa \lambda (T_{\text{dust}})} \]  

\[ F_\lambda \] is the integrated flux density at 1.3 mm, B_\lambda is the Planck function and D = 230 pc is the distance to the Perseus molecular cloud13. We adopt T_{\text{dust}} = 30 K as a typical dust temperature at a radius of 100 au, derived from radiative transfer models40,41. The disk does have a temperature gradient, but 30 K is a reasonable average value for the outer disk where most of the mass resides. The remaining term \( \kappa_\lambda \) is the dust opacity at the observed wavelength, which is adopted from dust opacity models42. While there are a multitude of possible models to consider42, we adopt two limiting cases for simplicity. The first value is \( \kappa_\lambda = 0.899 \text{ cm}^2 \text{g}^{-1} \) (ref. 43), appropriate for dense cores in molecular clouds such as L1448 IRS3B. The second value we adopt is \( \kappa_\lambda = 2.3 \text{ cm}^2 \text{g}^{-1} \), which is typically used for protoplanetary disks44,45. The second value is derived from a parametrization of the dust opacity to have a value of 10.0 cm^2 g^-1 at \( \lambda = 0.3 \text{ mm} \) and \( \kappa_\lambda = 10.0 \times (\lambda/0.3)^{-3/2} \), where \( \beta = 1 \) (refs 44–46). We then adopt a standard dust gas mass ratio of 1:100 (ref. 47) and assume that this ratio is constant throughout the disk. We note that the dust to gas ratio may be changing in more-evolved protoplanetary disks46,47, but we assume the constant, canonical value for this much younger system. Additionally, young protostellar disks may not be optically thin at 1.3 mm, and thus our mass estimates using equation (2) are likely to be lower limits. Note that a higher disk mass would only strengthen our conclusion that the disk is unstable. We show below that analytic models of the disk suggest that the inner parts are becoming opaque at shorter wavelengths.

Keeping the assumptions and caveats from the previous paragraph in mind, we can now calculate the masses of the disk surrounding the three protostars. We calculate a total mass of 0.39 M⊙ for the disk surrounding L1448 IRS3B, assuming \( \kappa_\lambda = 0.899 \text{ cm}^2 \text{g}^{-1} \). Of the total, 0.085 M⊙ is contained within the concentrated dust around IRS3B-c; note that we adopt T_{\text{dust}} = 40 K for IRS3B-c as the region directly around it should be warmer and the peak brightness temperature \( T_B \) in the disk is approximately 40 K towards this source. This high peak \( T_B \) is indicative of increased opacity in IRS3B-c because \( T_B = T \) when the emission source is optically thick. Thus, the mass estimate of 0.085 M⊙ is also likely to be a lower limit because of optical depth effects. If we instead adopt \( \kappa_\lambda = 2.3 \text{ cm}^2 \text{g}^{-1} \), assuming that the dust has already grown substantially from the size of interstellar medium as in older protoplanetary disks, we find a total mass of 0.15 M⊙ (disk plus IRS3B-c) and 0.03 M⊙ around IRS3B-c alone.

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To conclude, the higher mass estimates using $n_{\text{f},\text{min}} = 0.899 \text{ cm}^{-2} \text{ g}^{-1}$ are favoured because that opacity model is meant to reflect the dust typically found in dense molecular clouds. Since L1448 IRS3B is still in a very early stage of the star formation process, the bulk of its dust should reflect the molecular cloud content rather than the dust in protoplanetary disks that has been able to undergo significant dust evolution.\(^{42,50}\)

**Disk surface density.** The asymmetry and complexity of the dust continuum around L1448 IRS3B prohibit us from directly fitting symmetric disk models to the data to determine the underlying density structure. However, given that the disk is well resolved, we can empirically determine the azimuthally averaged surface density profile as a function of radius from the data. We first deprojected the visibility data using the inclination of 45.4° and position angle of 29.5°, determined from the Gaussian fitting in Methods section 'Subtracting the tertiary IRS3B-c'. The $uv$ data are deprojected using standard methods\(^{31}\) that adjust the $u$ and $v$ coordinates based on the geometric projection. We then generate deprojected images using the CASA clean task in the same manner as for the non-deprojected data (see Methods section 'Observations'). The deprojected image is shown in Extended Data Fig. 3.

With the deprojected image, we measure the flux density in a series of circular annuli centred on IRS3B-a; each annulus has a width of half the beam size. Afterwards, we divide the flux density in each annulus by its surface area and converted the surface brightness to a surface density using the methodology described in Methods section 'Disk mass', assuming a radial temperature profile that is described in Methods section 'Stability analysis'. The surface density ($\Sigma$) inferred from the observed intensity profile and the assumed temperature profile are shown in Extended Data Fig. 4.

**Protostar masses.** It is essential to know the masses of the central protostars (IRS3B-a and IRS3B-b) to quantify the stability of the disk. The angular resolution of the observations is not sufficient to determine the masses of each component of the central pair, and our measurement will be limited to the combined mass of both components. Figure 2 shows the integrated intensity and velocity maps of the $^{13}$CO ($J = 2 \rightarrow 1$) emission and the $^{12}$CO ($J = 2 \rightarrow 1$) is shown in Extended Data Fig. 2. The maps show clear evidence of rotation, centred on IRS3B-a and IRS3B-b, due to the spatial separation of the blue- and redshifted components. Furthermore, the $^{13}$CO emission also traces some of the structure observed in the dust emission in the outer disk.

To examine the molecular line kinematics, we extract position–velocity ($PV$) diagrams along the major axis of the disk, centred on IRS3B-a and IRS3B-b. The $PV$ diagram for $^{13}$CO is shown in Extended Data Fig. 5. The signal-to-noise ratio of the data is not high enough to employ the techniques that have been used to quantitively measure protostellar masses in other works.\(^{43,37,38,52}\). Nevertheless, we can estimate the protostar mass by drawing a Keplerian curve on the $PV$ diagram, accounting for the 45.4° inclination of the system. We find that the combined mass for both IRS3B-a and IRS3B-b is likely to be around 1.0M$_\odot$. We also compare this estimate to a $PV$ diagram of a rotating thin disk model\(^{66}\) with the same central mass and inclination, shown in Extended Data Fig. 4. The thin disk model occupies a very similar domain in $PV$ space as the data. Note that the line we draw in the $PV$ diagrams does not go through the middle of the data, but instead traces the edge of the highest-velocity emission for a given position. This is because observations of a Keplerian disk will measure multiple velocities superposed at a given position and the Keplerian velocity at a given radius only corresponds to the highest velocities.\(^{32}\) Thus, the total protostellar mass cannot be substantially larger than 1.0M$_\odot$ without being inconsistent with the data.

**Stability analysis.** The simplest estimate for when disks are subject to gravitational instability is provided by Toomre's $Q$ parameter\(^{19}\)

$$Q = \frac{c_s}{\pi G S} \Omega$$

(3)

where $c_s$ is the sound speed within the disk, $\kappa$ is the epicyclic frequency (which is $\Omega$, the angular rotation frequency, for Keplerian disks) and $G$ is the gravitational constant. The quantities $c_s$, $\Omega$ and $S$ are all functions of the radius within a disk. If $Q$ reaches order unity, the disk becomes susceptible to the growth of spiral density waves. Disk fragmentation due to gravitational instability is thought to be the nonlinear outcome of this hydrodynamic instability.\(^{20}\) The evolution of disks that are subject to the instability, and in particular their ability to create long-lived, bound objects, is a function of many parameters, including infall from the environment and radiative heating and cooling. The importance of the latter effect can be reasonably well encapsulated by the disk cooling time

$$t_{\text{cool}} = \beta \Omega^{-1} = \frac{4}{9 \gamma (\gamma - 1)} \frac{\Sigma c_s^2}{\sigma T_f f(\tau)}$$

(4)

where $\sigma$ is the Stefan–Boltzmann constant and $\gamma$ is the adiabatic index, and

$$f(\tau) = \tau + 1$$

(5)

where the optical depth $\tau = \kappa/2\pi$ is calculated using the Rosseland mean opacity; the function $f(\tau)$ reasonably captures how the accretion energy diffuses from the midplane in the optically thick and thin regimes.\(^{56}\)

For fragments to survive, the gas must be able to contract by radiating away the heat that is generated by shocks on roughly the orbital timescale.\(^{57}\) $\beta$ is often used in the literature to parameterize cooling via a single dimensionless number to probe disk behaviour in different regimes. Although there is some debate about the critical value of $\beta$ below which fragmentation successfully produces bound object\(^{58-60}\), fragment formation is robust for $\beta < 1$. To assess whether IRS3B is a good candidate for disk fragmentation, we generate a set of one-dimensional analytic disk models. Specifically, we calculate $Q$ and cooling time as a function of disk radius. We use the surface density profile derived for the disk after the removal of IRS3B-c (see Methods section 'Disk surface density'), and treat IRS3B-a and IRS3B-b as equal mass 0.5M$_\odot$ protostars (see Methods section 'Protostar masses'). We use the youngest age available from the models\(^{61}\) (1 Myr) to calculate the stellar radii and intrinsic luminosity. To estimate the disk temperatures, a two component temperature model is used.\(^{62,63}\) The midplane temperature of the disk is found by balancing heating and cooling terms

$$\sigma T^4 = \frac{3}{8 \pi} f(\tau) F_{\text{acc}} + F_i$$

(6)

Here $F_i$ represents the energy flux associated with irradiation from the protostars:

$$F_i = \sigma T^4 = \frac{1}{4 \pi c} \frac{L_i}{4\pi r^2}$$

(7)

where $r = 0.1$ is based on ray tracing calculations that show that most of the stellar flux impacts the infalling envelope\(^{53}\) and is reprocessed back onto the disk in embedded sources.\(^{64}\) L is includes both the model stellar luminosity and the accretion luminosity, which are comparable to each other. $F_{\text{acc}}$ is the energy flux due to dissipation of accretion energy within the disk:

$$F_{\text{acc}} = \frac{3}{8 \pi} M \Omega^2 \Sigma$$

(8)

where $M$ is the mass accretion rate through the disk. We consider two models for disk opacity: a temperature independent opacity of $\kappa = 0.24 \text{ cm}^2 \text{ g}^{-1}$ (ref. 65), and an interpolated model, where roughly $T_s^\beta$ (ref. 16). The former model is more consistent with grain growth below millimetre sizes, while the latter should capture more ISM-like grains. For the disk models presented here the opacity has negligible effect on the disk temperature because it is dominated by stellar irradiation, which sets the disk surface temperature and therefore is unaffected by optical depth. This is typical of unstable protostellar disks.\(^{20}\) When the midplane heating is relatively weak, the disk becomes nearly vertically isothermal.\(^{56}\) Note that the numerical values for these two models are distinct from those used to derive the disk mass in Methods section 'Subtracting the tertiary IRS3B-c' because calculation of equilibrium temperatures analytically requires a mean opacity, rather than the $1.3 \text{ mm}$ opacity.

We first evaluate the disk properties using temperature independent opacities, and explore the impact of a range of disk accretion rates. Recall that the disk accretion rate contributes both to the local viscous heating through $F_{\text{acc}}$ and the stellar irradiation through $F_i$. Once we have calculated the disk temperature, we can then compute $Q$ as a function of radius. We also calculate the disk cooling time to demonstrate that if the disk is unstable, fragments that form could cool quickly and likely remain bound.\(^{57,68}\) We find that the cooling time is well below the critical threshold of around 10$^7$ yr\(^{-1}\) throughout the entire disk. The discrepancy between our calculated $\beta$ values and those quoted in the literature derives mostly from the difference in radius between this disk and standard models with disk radii of $< 100 \text{ AU}$. Reaching $Q = 1$ at larger radii requires lower values of $\Sigma$; $t_{\text{cool}}$ scales roughly as $\Sigma^{-2}$ in the optically thick regime that is relevant for such disks. In addition, the dimensionless cooling time scales linearly with $\Omega$, which also declines at large radii. In Fig. 3 we show contours of $Q$ as a function of disk radius and model accretion rate. The disk is marginally unstable between 150 and 320AU.\(^{69}\)

While we do not have a direct constraint on $M$, the observed total luminosity provides a benchmark: in a typical viscous accretion disk, the total luminosity is

$$L_{\text{tot}} = L_i + \frac{GM M}{R_s}$$

(9)

where the second term represents the total accretion luminosity, half of which is liberated within the accretion disk, and half at the stellar surface. Thus we can derive the expected accretion rate assuming that the bolometric luminosity of 3.2L$_\odot$ (ref. 16) is equivalent to the internal luminosity. This implies an accretion rate of around $10^{-7} M_\odot \text{ yr}^{-1}$, which is consistent with star formation models and observations of young stars.\(^{67,71}\) This band is highlighted in Fig. 3. We account for the contributions from both protostars in the irradiation models, assuming

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that the accretion luminosity is divided equally between the two. Note that the internal luminosity is not precisely equivalent to the bolometric luminosity; the bolometric luminosity is calculated from integrating the observed spectral energy distribution from the near-infrared to the millimetre range. To relate the bolometric luminosity to the internal luminosity, a correction must be applied to account for the geometric projection of the disk and outflow cavities. For an inclination of 45.4° the correction factor is approximately 0.9 (ref. 72). Furthermore, external irradiation can add an additional (0.1–0.5)ε⊙ to the bolometric luminosity (depending on the local environment); this amount should be subtracted from the bolometric luminosity to relate it to the internal luminosity. However, we do not apply these small corrections given that the uncertainty in the bolometric luminosity is around 10% or greater depending on wavelength coverage, and these corrections would only lower the internal luminosity (and by inference the accretion rate), causing Ω to decrease and imply a greater degree of instability.

We next calculate a disk model using a self-consistently derived temperature profile based on the temperature dependent opacities. For simplicity we only consider the benchmark accretion rate M ≈ 10−3−10−2 M⊙ yr−1. We create a grid of allowed temperatures and identify the radial temperature profile that is consistent with the radiative equilibrium model of equation (6). In Extended Data Fig. 4, we show the derived surface density, temperature Q and β profiles. Once again we find that the disk is marginally unstable at radii in the vicinity of the recently formed tertiary, IRS3B-c. That the disk is marginally unstable at radii in the vicinity of the recently formed tertiary, IRS3B-c.

Finally, we can obtain a rough estimate of the mass scale of a fragment born in such a disk. The most unstable wavelength (that is, the physical scale) on which the disk has probably experienced a recent episode of gravitational instability and fragmentation.

We note that although the surface density profile was derived using the optically thin approximation, our modelling indicates that the innermost regions may be opaque at shorter wavelengths (τ ≳ 2–5). Thus, we are probably underestimating the total disk mass somewhat. This would only corroborate our conclusion that the disk has probably experienced a recent episode of gravitational instability and fragmentation.

Data availability. The ALMA data used to generate Figs 1, 2 and Extended Data Figs 1–3 are from ALMA project 2013.1.00031.S (https://almascience.eso.org/aq/?project_code=2013.1.00031.S). These data will be available in the ALMA archive and from the corresponding author upon request. The data from which Fig. 3 and Extended Data Fig. 4 were generated are provided as Supplementary Data. Code availability. The data were reduced and processed using the Common Astronomy Software Applications (CASA) version 4.5.0. The code for generating the model found in Extended Data Fig. 5 is publicly available. The theoretical calculations presented in Fig. 3 and Extended Data Fig. 4 are derived from solving algebraic equations and thus involve no significant code development.

31. McMullin, J. P., Waters, B., Schiebel, D., Young, W. & Golap, K. in Astronomical Data Analysis Software and Systems XVIII (eds Shaw, R. et al.) 127–130 (Astronomical Society of the Pacific, 2007).
32. Looney, L. W., Mundy, L. G. & Welch, W. J. Unveiling the circumstellar envelope and disk: a subarcsecond survey of circumstellar structures. Astrophys. J. 529, 477–498 (2000).
33. Sakai, N. et al. A chemical view of protostellar-disk formation in L1527. Astrophys. J. Lett. 791, L38 (2014).
34. Oya, Y. et al. A substellar-mass protostar and its outflow of IRS15398-3599 revealed by subarcsecond-resolution observations of H₂O and CO. Astrophys. J. 795, 152 (2014).
35. Wakeham, V. et al. Sulphur chemistry and molecular shocks: the case of NGC 1333-IRAS 2. Astron. Astrophys. 437, 149–158 (2005).
36. Sakai, N. et al. Change in the chemical composition of infalling gas forming a disk around a protostar. Nature 507, 78–80 (2014).
37. Oya, Y. et al. Infalling-rotating motion and associated chemical change in the envelope of IRS 16293-2422 Source A studied with ALMA. Astrophys. J. 824, 88 (2016).
38. Tobin, J. J. et al. A ~0.2-solar-mass protostar with a Keplerian disk in the very young L1527 IRS system. Nature 492, 83–85 (2012).
39. Harsono, D. et al. Rotationally-supported disks around Class I sources in Taurus: disk formation constraints. Astron. Astrophys. 562, A77 (2014).
40. Jørgensen, J. K. et al. PROSAC: a submillimeter array survey of low-mass protostars. II: the mass evolution of envelopes, disks, and stars from the class 0 through I stages. Astron. Astrophys. 507, 861–879 (2009).
Extended Data Figure 1 | Images of the $^{12}$CO and $\text{H}_2\text{CO}$ emission in the vicinity of L1448 IRS3B. a, $^{12}$CO (a) and $\text{H}_2\text{CO}$ (b) redshifted and blueshifted contours overlaid on the 1.3 mm continuum. The $^{12}$CO emission in a most clearly shows a redshifted outflow from the three protostars. There is a wide cavity that is traced back to IRS3B-a/b and a more collimated outflow is emitted from IRS3B-c, which potentially generates the redshifted arc within the wide outflow cavity. The blueshifted side of the outflow is more diffuse and not well recovered in our data, but appears to be associated with all three sources. The $\text{H}_2\text{CO}$ emission in b has low intensity and traces a rotation gradient in the inner envelope and disk surrounding the sources. The source positions are marked with white crosses and the outflow direction is marked with the blue and red arrows in a. The contours in both plots start at 3σ and increase in 2σ intervals. The $^{12}$CO emission was integrated over $-5.5$–$1.5\text{ km s}^{-1}$ and $6.5$–$10.0\text{ km s}^{-1}$ for the blueshifted and redshifted maps, respectively; $\sigma_{\text{blue}} = 6.88\text{ K km s}^{-1}$ and $\sigma_{\text{red}} = 5.02\text{ K km s}^{-1}$. The $\text{H}_2\text{CO}$ emission was integrated over $2.75$–$4.0\text{ km s}^{-1}$ and $5.25$–$6.25\text{ km s}^{-1}$ for the blueshifted and redshifted maps, respectively; $\sigma_{\text{blue}} = 2.25\text{ K km s}^{-1}$ and $\sigma_{\text{red}} = 2.05\text{ K km s}^{-1}$. The angular resolution of these data is given by the ellipses in the lower right corners: $0.36'' \times 0.25''$ (83 au $\times$ 58 au).
Extended Data Figure 2 | Images of the $^{13}$CO emission and its corresponding velocity maps from the disk around L1448 IRS3B, showing a rotation signature. a, Redshifted and blueshifted $^{13}$CO ($J = 2 \to 1$) emission overlaid on the ALMA 1.3 mm continuum image (greyscale) as red and blue contours. b, Line-centre velocity map of the $^{13}$CO emission with 1.3 mm continuum contours overlaid in grey. The $^{13}$CO traces higher-velocity emission near IRS3B-a and IRS3B-b and little of the extended disk due to spatial filtering. The source positions are marked with white or yellow crosses. The outflow direction is denoted by the blue and red arrows. The angular resolution of these data is given by the ellipses in the lower right corners: 0.36″ × 0.25″ (83 au × 58 au). The contours in a start at 4σ and increase in 1σ intervals. The $^{13}$CO emission was integrated over 1.25–4.0 km s$^{-1}$ and 5.5–7.0 km s$^{-1}$ for the blueshifted and redshifted maps, respectively; noise levels for $^{13}$CO are $\sigma_{\text{Blue}} = 4.99$ K km s$^{-1}$ and $\sigma_{\text{Red}} = 3.2$ K km s$^{-1}$. The continuum (grey) contours in b start at and increase by 10σ; at 100σ the levels increase in steps of 30σ and at 400σ the levels increase by 100σ steps; $\sigma = 0.14$ mJy per beam.
Extended Data Figure 3 | ALMA 1.3 mm images with the brightest protostar (IRS3B-c) removed. a, Image with IRS3B-c removed, as observed. b, Image deprojected (rotated and corrected for system inclination) and IRS3B-c removed.
Extended Data Figure 4 | Plot of observed disk surface density ($\Sigma$), temperature ($T$), Toomre's $Q$ and dimensionless cooling ($\beta$). $Q$ is calculated self-consistently from the inferred surface density profile (red) using the temperature-dependent opacities. The black line demarcates unity, where the disk is expected to be gravitationally unstable.
Extended Data Figure 5 | Position–velocity diagrams of L1448 IRS3B and a model disk showing the rotation profile. A position–velocity (PV) cut is taken along the major axis of the disk (analogous to a long-slit spectrum), across the position of IRS3B-a and IRS3B-b (left). The solid green line is a Keplerian rotation curve for a 1.0$M_\odot$ central protostar, assumed to be the combined mass of IRS3B-a/b. A thin disk model with the same inclination angle shows a consistent PV diagram (right).