We studied the disk of IRS 63 with 5-μm resolution by observing the emission from dust grains, using the Atacama Large Millimeter/submillimeter Array (ALMA) at 1.3 mm. These observations revealed two concentric bright annular substructures (ring-like, R1 and R2) and two dark annular substructures (gap-like, G1 and G2), which are shown in Fig. 1. Although dust structures within disks of class I protostars have been previously observed1–4, IRS 63 is the least evolved protostellar disk with multiple concentric dust annular substructures as shown by different evolutionary indicators (see Methods). The annular substructures we observe towards the disk of the young protostar IRS 63 indicate that the conditions for planetesimal formation probably begin at extremely early times, setting the stage for the first generation of planets to form.

The annular substructures in the disk of IRS 63 appear as plateaus of emission in the initial image (Fig. 2a) but are more apparent in the enhanced-contrast image (Fig. 1; see Methods), which emphasizes compact structures and faint surface-brightness enhancements. The annular substructures are also clearly revealed through the use of radial-intensity profiles (Fig. 3b; see Methods). The inner ring, R1, is located at 27 au with a width of 6 au. The outer ring, R2, is located at 51 au with a width of 13 au. Adding the Gaussian profiles of R1 and R2 together reproduces well the residual radial profile at radii >20 au (see Fig. 3), and together with the underlying smooth-disk model, explains the majority of the disk emission in the vicinity of the rings. We use a similar method to measure the positions and widths of the gaps (Fig. 4). The inner gap, G1, is at a radius of 19 au with a width of 3.2 au. The outer gap at 37 au, G2, has a width of 4.5 au.

Gaps and rings have been previously detected towards disks. The vast majority of ringed disks are found around class II pre-main-sequence stars, a more evolved phase in which nearly all of the envelope has accreted or dissipated and the disk is the main component of the protostellar system1–3, with planetary-mass bodies carving rings and gaps in the disk4. This implies that planet formation may already be underway in even younger disks in the class I phase, when the protostar is still embedded in a larger-scale dense envelope of gas and dust5. Only within the past decade have detailed properties of disks in the earliest star-forming phases been observed6–7. Here we report 1.3-millimetre dust emission observations with a resolution of five astronomical units that show four annular substructures in the disk of the young (less than 500,000 years old)8 protostar IRS 63. IRS 63 is a single class I source located in the nearby Ophiuchus molecular cloud at a distance of 144 parsecs, and is one of the brightest class I protostars at millimetre wavelengths. IRS 63 also has a relatively large disk compared to other young disks (greater than 50 astronomical units)19. Multiple annular substructures observed towards disks at young ages can act as an early foothold for dust-grain growth, which is a prerequisite of planet formation. Whether or not planets already exist in the disk of IRS 63, it is clear that the planet-formation process begins in the initial protostellar phases, earlier than predicted by current planet-formation theories11.

Annular structures (rings and gaps) in disks around pre-main-sequence stars have been detected in abundance towards class II protostellar objects that are approximately 1,000,000 years old8. These structures are often interpreted as evidence of planet formation1–3, with planetary-mass bodies carving rings and gaps in the disk4. This implies that planet formation may already be underway in even younger disks in the class I phase, when the protostar is still embedded in a larger-scale dense envelope of gas and dust5. Only within the past decade have detailed properties of disks in the earliest star-forming phases been observed6–7. Here we report 1.3-millimetre dust emission observations with a resolution of five astronomical units that show four annular substructures in the disk of the young (less than 500,000 years old)8 protostar IRS 63. IRS 63 is a single class I source located in the nearby Ophiuchus molecular cloud at a distance of 144 parsecs, and is one of the brightest class I protostars at millimetre wavelengths. IRS 63 also has a relatively large disk compared to other young disks (greater than 50 astronomical units)19. Multiple annular substructures observed towards disks at young ages can act as an early foothold for dust-grain growth, which is a prerequisite of planet formation. Whether or not planets already exist in the disk of IRS 63, it is clear that the planet-formation process begins in the initial protostellar phases, earlier than predicted by current planet-formation theories11.

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In each panel the resolution is shown by a white ellipse in the lower left. A scale bar is in the lower right. The colour scale is the normalized surface brightness after a contrast-enhancement technique is applied to the original data (see Methods). The enhanced-contrast image clearly reveals two bright annular substructures (ring-like, R1 and R2, marked by solid white curves) and two dark annular substructures (gap-like, G1 and G2, marked by dotted white curves) in the disk surrounding the young protostar.

Although protostellar disks are certainly the sites of planet formation, in smooth disks the planet-formation process faces a severe obstacle in the form of the so-called radial-drift problem. Dust in disks experiences aerodynamic drag forces from the gas content of the disk, which causes a loss of angular momentum of the dust, and the dust particles will move inwards towards the protostar. This effect occurs on faster timescales for larger particles, and large solids will accrete onto the central protostar long before they can reach planetesimal sizes. Annular substructures in planet-forming disks have been invoked to overcome this radial-drift problem, and a more conservative interpretation of these substructures in the disk of IRS 63 is to consider that planets have not yet formed. Rings face serious barriers to growing to such large masses on short time scales as well as avoiding runaway accretion at later stages of their formation.
Fig. 3 | Ring positions and widths are measured from the radial profile of the residuals. a, The radial intensity profiles of the images from the 1.3-mm data (solid blue line), the radiative-transfer model (dotted orange line), and the data minus the model residual (dashed green line), which have been deprojected, azimuthally averaged and radially binned into 1-AU bins. The grey shaded area represents the resolution of the observations, and the vertical grey dotted lines show the positions of the R1 and R2 rings. The light-blue and green ribbons represent the local standard deviation of each bin for the data and residual, respectively. b, A magnification of the y-axis showing the residual (dashed green line, representing extra emission in the rings not explained by a smooth disk profile), which was fitted with two one-dimensional Gaussian profiles (dotted purple lines) to determine the positions and widths of the two rings. The sum of the fitted Gaussian profiles (solid thick purple line) reproduces well the residual profile of the disk exterior to 20 AU.

Fig. 4 | Gap positions and widths are measured from the radial profile of the residuals. The same residual profile as in Fig. 3 is given by the green dashed line; the light-green ribbon shows the local standard deviation of each bin. The grey shaded area represents the resolution of the observations, and the vertical grey dotted lines show the positions of the G1 and G2 gaps. The residual profile was fitted with two one-dimensional Gaussian profiles (dotted purple lines), using the solid grey horizontal line as the baseline, to determine the positions and widths of the two gaps. The thick purple line is the sum of the fitted gap Gaussian profiles.

Extended Data Fig. 7). We note that the G1, R1 and R2 substructures do not coincide with other major volatile species27, and if G2 formed as the result of a snowline, the other annular substructures probably formed via a different mechanism. Another ring-formation mechanism that could apply to the IRS 63 dust rings is self-induced dust traps28. These traps can form naturally from initially smooth disks on timescales of approximately 100,000 years in simulations at radii >20 AU when the aerodynamic drag, or back-reaction, of the dust on the gas is taken into account in addition to the drag of the gas on the dust, even in cases in which the dust-to-gas ratio is 0.01. For protostellar-disk densities and dust-grain sizes that are probed by millimetre observations, these often negligible back-reactions can become important and give rise to gas-pressure maxima in the disk that trap particles. When combined with the effects of snowlines, back-reaction simulations have shown that rings can form that are wider the further they are from the central protostar28. In the disk of IRS 63, the wider R2 ring is indeed at a larger radius, and the R1 and R2 rings may reflect a self-induced dust trap in the process of formation. Although none of the annular substructure formation mechanisms can be completely confirmed or ruled out with the information to hand, the annular substructures of IRS 63 present an observational benchmark against which simulations of early evolutionary phases can be tested.

Dust within the outer dust disk (radii >20 AU), where the R1 and R2 rings are located, could overcome the radial-drift problem and eventually be incorporated into planets. The dust mass available to form future planets in this outer dust disk reservoir of material is 154M_{Earth} = 0.49M_{Jupiter} (where M_{Earth} is the mass of the Earth), estimated by converting the continuum emission to mass30 (see Methods). For a planetary embryo made of solids to trigger runaway accretion of gaseous material—required in the core-accretion model of gas-giant planet formation—the critical mass of 10M_{Earth} must be met by the solid core31. This condition is readily met in the young IRS 63 disk, even for a somewhat low efficacy (<10%)32 of core formation out of the available dust grains. The large dust mass in the outer dust disk—combined with the 27 and 51 AU radii of the rings of IRS 63—is consistent with evidence that Jupiter’s core could have formed beyond 30 AU in our own Solar System and later migrated inward32,33. Giant-planet cores may often form in the exterior regions of large disks starting from the early phases of star formation.

Even if planets have not yet formed or dust has not yet grown to large masses, the dust rings in the disk of IRS 63 at such an early evolutionary
phase may serve as ideal zones for future dust-grain growth and stable planetesimal formation. Even in the most conservative case, in which the annular substructures are interpreted as variations in the density power law of the disk instead of as clear rings or gaps, these features are indications of dust beginning to accumulate at particular radii in the disk. It is probable that the structure of the disk has an effect on planet evolution starting early in the star-formation process. Class I protostars remain embedded in a larger-scale envelope of gas and dust, which can replenish the disk as material is accreted, indicating that if planet formation in the disk of IRS 63 has already begun, then it is probable that planets and protostars grow and evolve together from early times.

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methods

observations and data reduction

We observed IRS 63 with ALMA under the Cycle 3 program 2015.1.01512.S. The observations were made on 2015 November 01 and 05 UTC, and 2017 September 18 in extended configurations with 41–mt to 16.2-km baselines. Compact configurations with 15-m to 1-km baselines were made on 2016 May 24 and 2016 November 10 and 17. The total on-source integration time was 121 min. The correlator was configured for continuum observations with four 2-GHz spectral windows of 128 channels in dual polarization mode. The central frequency of the band 6 observations was 233.002 GHz (1.3 mm) with a usable aggregate bandwidth of 7.5 GHz. Standard ALMA calibrators were used.

The extended and compact configuration data were first calibrated separately by ALMA staff using the standard pipeline calibration procedure with CASA\textsuperscript{14} versions 4.7.2 and 4.7.0, respectively. We performed further manual flagging on the extended configuration observations to remove time periods of unstable phases and bad baselines and re-ran the pipeline with the additional flags. The estimated flux calibration uncertainty is 10%, and in this work we present the statistical uncertainties only (at one standard deviation), without the flux calibration uncertainty included, unless otherwise noted. Self-calibration and imaging were performed with CASA\textsuperscript{5.5.0}. We concatenated all data and performed self-calibration iteratively, with shortest solution intervals of 10 s for phase and 60 s for amplitude cycles. The signal-to-noise ratio improved from 138 to 441 after self-calibration, with considerable reduction of imaging artefacts.

The final continuum image (Fig. 2a) was created using multifrequency synthesis, a Briggs weighting with robust parameter of 1.0, and multi-scale clean with scales of 0, 5, and 15 (0.1, 1, and 3 the synthesized beam). We chose the robust parameter of 1.0 as a compromise between spatial resolution and noise level in the final image. Although the overall signal-to-noise ratio of the data is high, the substructures are low contrast compared to the overall disk emission. Lower robust-parameter values, which would have resulted in smaller synthesized-beam sizes, increased the noise level and made the detection of the annular substructures less clear. The synthesized beam is 0.05″ × 0.03″ (7 AU × 4 AU), assuming a distance of 144 pc\textsuperscript{9} with a position angle of 59.7°, and the image has a noise level of 18.4 μJy per beam. IRS 63 peaks at (α(2000), δ(2000)) = (16 h 31 m 35.6577 s, −24° 01′ 29.897″) with a peak flux of 7.78 mJy per beam and a total flux of 335.02 mJy.

To highlight the ringed structure in the disk, we created an enhanced-contrast image (Fig. 1), which is a strategy used to bring out faint features in images that include bright components\textsuperscript{10,11}. We smoothed the dust continuum image with a two-dimensional Gaussian with a full-width at half maximum (FWHM) of 0.06″, corresponding to 2× the minor axis of the synthesized beam, and multiplied all pixels in the smoothed image by a factor of 0.25. We subtracted the smoothed and scaled image from the original image and normalized the resulting image to produce the final enhanced-contrast image. This procedure in essence removes the larger-scale emission to emphasize more compact structures in the disk, including the bright central area near the protostar and the more subtle rings in the outer dust disk.

The youngest example of multiple annular substructures

The two previously youngest known disks with multiple annular substructures are HL Tau (ref.\textsuperscript{12}) and GWY 91 (ref.\textsuperscript{13}). HL Tau, with clear symmetric rings, is regarded as lying between the class I and class II phases, whereas GWY 91, with clumpy structures within rings, is firmly in the younger class I phase. IRS 63 is even younger than these sources based on two evolutionary indicators: the bolometric temperature of an object (T\textsubscript{bol})\textsuperscript{14} and the ratio of the disk mass to the envelope mass (M\textsubscript{disk}/M\textsubscript{env})\textsuperscript{38}. The values of both evolutionary indicators are expected to be lower in younger or less-evolved sources with more surrounding envelope material. For IRS 63, the values of T\textsubscript{bol} and M\textsubscript{disk}/M\textsubscript{env} are, respectively, 290 K (ref.\textsuperscript{39}) and 1.41 (ref.\textsuperscript{10}). The higher values of T\textsubscript{bol} of 576 K (ref.\textsuperscript{40}) and 370 K (ref.\textsuperscript{39}), and of M\textsubscript{disk}/M\textsubscript{env} of 9.43 (ref.\textsuperscript{12}) and 8.26 (ref.\textsuperscript{13}), for HL Tau and GWY 91, respectively, demonstrate that IRS 63 is the youngest amongst these three sources.

Models of protostars evolving with time from the onset of collapse show that for a 1.0M\textsubscript{Sun} protostar (appropriate for IRS 63, see below) with a T\textsubscript{bol} of 290 K, the age of the protostar is 130,000–140,000 years\textsuperscript{41}. A lower protostellar mass would yield even lower ages for the same T\textsubscript{bol} (ref.\textsuperscript{42}). This value is also consistent with the class I protostellar half-life of 135,000 years\textsuperscript{8}. The determination of age from T\textsubscript{bol} is uncertain; however, a relative comparison between similar sources using these models identifies IRS 63 as the youngest protostellar disk with multiple annular substructures. The most conservative upper limit of the age of IRS 63 is approximately 500,000 years, the total lifetime of all embedded protostellar phases before the class II pre-main-sequence phase\textsuperscript{42}.

Two other class I protostars with dust structures in the disk are WL 17 (ref.\textsuperscript{14}) and DG Tau B (ref.\textsuperscript{15}). The disk of WL 17 has a hole in its inner 12 AU, and, with all other radial features in the disk, is considered an embedded transition disk\textsuperscript{1} and is not a direct analogue to the multiple annular substructures of IRS 63. DG Tau B is part of a wide binary system and has a dust spiral feature in addition to a broad dust ring\textsuperscript{2}. The more complicated DG Tau B dust disk morphology probably reflects that there are additional underlying physical processes at play compared to the isolated disk of IRS 63. L1527 IRS is an even younger class 0/I protostar that was recently shown to have possible dust substructures in the disk\textsuperscript{44}; however, owing to the nearly edge-on disk orientation, the true morphology of the possible azimuthal substructures as rings or spirals is unclear.

Radiative-transfer disk model

We produce a radiative-transfer model of a smooth disk to compare to the original image and determine the geometry of the annular substructures. Because we use the model to determine the location and widths of the rings or gaps (see below), which will not vary with the relative intensity of the model, we choose to model a smooth disk, which will best highlight the rings. Any annular substructures in the disk that are not explained by the smooth-disk model are a result of disk radial-density variations. We use the radiative-transfer framework Pandora\textsuperscript{45}, which uses the three-dimensional radiative-transfer code RADMC-3D\textsuperscript{46}, version 0.41, for a self-consistent calculation of the dust temperature.

For the best-fit model, we use CASA\textsuperscript{5.5.0} for post-processing of the synthetic model image. We sample the synthetic model image at the same u–v points as the original image with the CASA ft task and clean the resulting model u–v points with the same parameters as the original image. We subtract the model from the u–v data, and create the residual image with the original imaging parameters. The resulting model image and residual images thus have the same beam as the original image (Fig. 2).

The density distribution in cylindrical coordinates, ρ(R, z, φ), of the smooth disk\textsuperscript{47} is given as

$$\rho(R, z, \phi) = \rho_0^{\text{disk}} \left(\frac{R}{R_0}\right)^{\beta - q} \exp\left(- \frac{1}{2} \left(\frac{z}{h(R)}\right)^2\right),$$

where \(\rho_0^{\text{disk}}\) is defined by the disk mass M\textsubscript{disk}, \(R_0\) is the characteristic radius (set to 15.0 AU), \(\beta\) is the disk flaring power, \(q\) is the surface density radial exponent (\(\beta - q\) is set to 2.25), and \(h(R)\) is the disk scale height defined as

$$h(R) = h_0 \left(\frac{R}{R_0}\right)^{\beta}.$$ 

Here \(h_0\) is the scale height at \(R_0\). The disk starts at an inner radius \(R_0\) (set to 1.0 AU) and is truncated at an outer radius \(R_\text{out}\). Heating is provided by a 1.0L\textsubscript{Sun} point source located at the centre of the disk\textsuperscript{48}, where L\textsubscript{Sun} is...
the luminosity of the Sun. A L0L_	ext{sun} protostar implies a mass of <1.0M_	ext{sun} because a portion of the luminosity is from accretion, and protostars are bigger and more luminous than main-sequence stars of the same masses. We also attempted modelling with a central luminosity value of 1.5L_	ext{sun}, which always resulted in emission profiles too peaked towards the centre, and the residuals were always lower for the 1.0L_	ext{sun} protostar family of models. We do not include heating by the interstellar radiation field, because the disk is heavily embedded in a thick envelope. The centre of the disk was fixed to (α(2000), δ(2000)) = (16 h 31 m 35.6572 s, −24° 01′ 29.896″), determined from a Gaussian fit to the data. We set the viewing angles for ray tracing on the basis of the position angle and inclination angle determined from the original image of the disk (see below).

We explore the parameter space ($\rho_{\text{disk}}$, $r_{\text{out}}$, $r_{\text{in}}$, $h_0$, $\beta$ – $q$) in a grid-based fashion and find the best fit for ($\rho_{\text{disk}}^0$ = $4 \times 10^4$ H$_2$ cm$^{-3}$, $r_{\text{in}}$ = 115 AU, $r_{\text{out}}$ = 76 AU, $h_0$ = 40 AU, $\beta$ = 1.25, $q$ = 1.0). We assume the dust to be covered in thin ice layers and coagulated at a density of $10^5$ cm$^{-3}$ (ref. 48). At a wavelength of 1.3 mm, this yields a dust absorption coefficient of $\kappa$ = 0.7006 cm$^{-2}$ g$^{-1}$. We also assume a canonical dust-to-gas ratio of $\epsilon_\text{mod}$ = 0.01 (ref. 48). We explored values of $\beta$ between 1.0 and 1.5, representing both flatter and more flared disk profiles. We note that because this is a single-wavelength model, several degeneracies between parameters do exist. We give the parameter values of the best-fit model for reproducibility, and we caution against taking any value as a concrete determination or constraint of that individual parameter. The overall model reproduces well the disk emission, and morphological deviations between the observations and model reflect physical disk structures not accounted for by the smooth-disk model.

**Geometric properties of the disk and annular substructure**

Because the disk is well resolved, a simple two-dimensional Gaussian fit to the disk only fits the central bright peak near the protostar. To determine the radius and inclination of the dust disk, we draw a 1σ contour and measure the major and minor axis lengths ($b_{\text{maj}}$ and $b_{\text{min}}$, respectively) where they pass through the peak of the emission. This yields $b_{\text{maj}} = 1.13 ± 0.02$ and $b_{\text{min}} = 0.79 ± 0.02$; the major axis has a position angle of 153° ± 2°. We define the radius as half the length of the major axis (the axis free from geometric projection effects), yielding a disk radius of 0.57″ or 82 AU. The inclination angle with respect to the plane of the sky is then 45° ± 2° (uncertainties are 1σ). The coordinates of the centroid of the fit ($x_0$ and $y_0$), the disk position angle (PA) and the disk inclination angle (IA). We used uniform priors for all parameters: 1.0 mJy per beam < $I_{\text{obs}}$ < 2.0 mJy per beam, 10 AU < $R_{\text{out}}$ < 100 AU, 0.0 < $y$ < 1.0, $x_0$ and $y_0$ within a five-pixel radius of (α(2000), δ(2000)) = (16 h 31 m 35.6567 s, −24° 01′ 29.890″), 145.0° < PA < 155.0°, and 40.0° < IA < 50.0°. The run consisted of 3,840 walkers each with 5,000 steps; we discarded the first 200 steps as a burn-in phase. The resulting median values of the parameters and their uncertainties (see Extended Data Fig. 2 for a plot of the posterior distributions) are $\Sigma_0 = 1.6985 ± 0.0007$ mJy per beam, $R_{\text{out}} = 51.96 ± 0.02$ AU, $y = 0.4847 ± 0.0002$, $x_0 = −0.409±0.001$ pixel offset, $y_0 = −0.555±0.001$ pixel offset, $PA = 147.57±0.03$° and $IA = 44.95±0.02$°. Here, the uncertainties reflect the 16th and 84th percentiles of the samples from the marginalized distributions. The best-fit $x_0$ and $y_0$ centroid of the emission corresponds to (α(2000), δ(2000)) = (16 h 31 m 35.6575 s, −24° 01′ 29.901″). Using the median values of the parameters from the MCMC modelling, we construct an analytic model image, and subtract it from the data image to produce a residual image (Extended Data Fig. 3). This method, with the flat-disk geometry and fit centroid, also shows the four annular substructures and the asymmetry with excess emission in the northwest side of the disk. Therefore, we eliminate both model centring and flared-disk geometry as being able to fully explain the asymmetric dust emission.

**Asymmetry in the disk**

As well as the clearly revealed annular substructures, the residual image of the best radiative-transfer model also shows that the northwestern side of the disk is slightly brighter than the southeastern side of the disk (Fig. 2c). To determine the impact of the model centring on the morphology of the residual image, which may be a possible cause of asymmetry in residual images, we shifted the centre of the best radiative-transfer model image to (α(2000), δ(2000)) = (16 h 31 m 35.6567 s, −24° 01′ 29.890″). This position was found by minimizing the root-mean-square (r.m.s.) value of the difference between the data and model images for all possible model image centroid locations:

$$r.m.s. = \sqrt{\sum (I_{\text{observed}} - I_{\text{model}})^2 / N_{\text{pix}}}$$

where $I_{\text{observed}}$ and $I_{\text{model}}$ are the intensity at each pixel in the data and model images respectively, and $N_{\text{pix}}$ is the total number of pixels used to calculate the r.m.s. value. Compared to the original centre of the best radiative-transfer model, determined from a Gaussian fit to the data, the minimized centre shows slightly lower amplitude residuals, although the annular substructures and disk asymmetry remain (Extended Data Fig. 1). These two positions are within a one-pixel radius of each other, where one pixel is 0.007" in size, and both positions are within a two-pixel radius of the location of the peak intensity. From this exercise, we rule out an off-centre model image as the cause of the asymmetry.

The asymmetry does not occur along the minor axis of the disk, which would be expected if the asymmetry was a result of the flared-disk geometry used in the radiative-transfer model. To fully rule out the flared-disk geometry as the cause of the disk asymmetry, we fitted a smooth and geometrically flat analytic model profile to the data. The profile has been previously used to describe embedded protostellar disks\(^5\), has a power-law core with an exponential tail and takes the form

$$\Sigma(R) = \Sigma_0 \left(\frac{R}{R_c}\right)^{-\gamma} \exp\left(-\left(\frac{R}{R_c}\right)^{-\gamma}\right).$$

Here, $\Sigma(R)$ is the intensity as a function of radius, $\Sigma_0$ is a normalization factor, $R_c$ is a characteristic radius, and $\gamma$ is the surface density gradient.

For the fitting, we used emcee\(^6\), a Python Markov chain Monte Carlo (MCMC) sampler. The free parameters in the fit include $\Sigma_0$, $R_c$, $\gamma$, the coordinates of the centroid of the fit ($x_0$ and $y_0$), the disk position angle (PA) and the disk inclination angle (IA). We used uniform priors for all parameters: 1.0 mJy per beam < $\Sigma_0$ < 2.0 mJy per beam, 10 AU < $R_c$ < 100 AU, 0.0 < $\gamma$ < 1.0, $x_0$ and $y_0$ within a five-pixel radius of (α(2000), δ(2000)) = (16 h 31 m 35.6567 s, −24° 01′ 29.890″), 145.0° < PA < 155.0°, and 40.0° < IA < 50.0°. The run consisted of 3,840 walkers each with 5,000 steps; we discarded the first 200 steps as a burn-in phase. The resulting median values of the parameters and their uncertainties (see Extended Data Fig. 2 for a plot of the posterior distributions) are $\Sigma_0 = 1.6985 ± 0.0007$ mJy per beam, $R_c = 51.96 ± 0.02$ AU, $\gamma = 0.4847 ± 0.0002$, $x_0 = −0.409±0.001$ pixel offset, $y_0 = −0.555±0.001$ pixel offset, $PA = 147.57±0.03$° and $IA = 44.95±0.02$°. Here, the uncertainties reflect the 16th and 84th percentiles of the samples from the marginalized distributions. The best-fit $x_0$ and $y_0$ centroid of the emission corresponds to (α(2000), δ(2000)) = (16 h 31 m 35.6575 s, −24° 01′ 29.901″). Using the median values of the parameters from the MCMC modelling, we construct an analytic model image, and subtract it from the data image to produce a residual image (Extended Data Fig. 3). This method, with the flat-disk geometry and fit centroid, also shows the four annular substructures and the asymmetry with excess emission in the northwest side of the disk. Therefore, we eliminate both model centring and flared-disk geometry as being able to fully explain the asymmetric dust emission.
The asymmetry can also be seen as excess emission to the northwest side of the disk in the observed dust continuum image by taking radial intensity cuts passing through the disk centroid. We made three radial intensity cuts across the disk from edge to edge: one along the major axis with PA = 150.0°, one along the minor axis with PA = 60.0°, and one from the southeast to the northwest with PA = 105.0°. The radii are measured from the centroid outwards and deprojected assuming an IA of 45.0° and circular geometry. We performed this for three of the centroids discussed above: the location of the peak intensity, the Gaussian fit centre, and the MCMC fit centre (Extended Data Figs. 4–6, respectively). We then compare the intensities at each radius along a single cut on either side of the given centre. In all centroid cases, the discrepancy between the two sides of the cut is greater for the southeast-to-northwest cut compared to the major- and minor-axis cuts. The northwest side of the disk has higher intensity values at most radii compared to the southeast side of the disk, and the slight asymmetry is hence also detectable without the use of radiative-transfer or analytic disk models.

Upper limit on the planet mass from the gap width

If we assume that the origins of the annular substructures in the disk of IRS 63 arise from planets clearing disk material, and that the dust is well coupled to the gas content of the disk, we can apply the empirically derived relationship between the gap width and the dust content of the disk, and the slightly asymmetry is hence also detectable without the use of radiative-transfer or analytic disk models. Similarly derived as increased dust absorption coefficients of $k = 0.78 \pm 0.03 \text{ cm}^2 \text{ g}^{-1}$ in R1 and $k = 0.89 \pm 0.03 \text{ cm}^2 \text{ g}^{-1}$ in R2. Although these values of $\epsilon_{\text{observed}}$ do not yet reach the order of unity—corresponding to the most efficient avenue of solid growth via the streaming instability—further condensing of dust in the rings may trigger rapid growth at later times.

Correspondence between annular substructure locations and snowlines

To determine the in-band spectral index ($\alpha$) and the dust temperature ($T$), we follow the methodology of a previous study of a snowline in a class I disk41. We split the data into two separable datasets (with frequencies of $v_1 = 241.002 \text{ GHz}$ and $v_2 = 225.002 \text{ GHz}$, and respective fluxes $F_1$ and $F_2$) and calculate $\alpha = \ln(F_2/F_1)/\ln(v_2/v_1)$. We produced the radial profile of $\alpha$ with 1-au bins (Extended Data Fig. 7a). We calculated the optical depth, $\tau$, via greybody fitting42 of the data at both frequencies, with the resulting radial profile shown in Extended Data Fig. 7b. Where $r > 3$, the greybody fit converged to the brightness temperature of the observations. Owing to degeneracies in the optically thin regime between $F$ and $r$, where $r < 3$ we extrapolate $T$ to larger radii with $T \sim r^{-1/2}$ power law (Extended Data Fig. 7c).

Using the observationally derived $T$ of the disk, we compare the locations of the annular structures with the condensation temperatures of major volatile gas species, which have been previously computed for gas densities of $10^{10} – 10^{13} \text{ H}_2 \text{ cm}^{-3}$ (ref. 10). $G2$ corresponds with the location of the CO snowline27. The spectral index increases across $G2$, whereas the optical depth decreases sharply, in agreement with previous observations and model signatures of snowlines42 (Extended Data Fig. 7). Further, we find $r > 1$ through most of the disk, indicating that self-scattering may be important and that the true radial variations in intensity may have higher contrast than we observe here46. Self-scattering can also explain the anomalously low $\alpha < 2$ at the disk centre27, where $\alpha = 2$ is the blackbody Rayleigh–Jeans limit.

Estimation of the dust mass

To estimate the dust mass of the disk, we follow the canonical flux-to-mass conversion used to estimate the disk mass of IRS 63 from continuum at the same wavelength as in a previous study30, and we maintain the same assumptions as that study, including $T = 20 \text{ K}$. This method assumes optically thin emission with a uniform temperature in the disk. The dust mass in the outer dust disk (at radii $> 20$ au, corresponding to the inner edge of the inner dust ring, determined from the one-dimensional Gaussian fitting of the radial profile) is $154.3 M_{\text{Jupiter}}$. $G2$ corresponds with the location of the CO snowline27. The spectral index increases across $G2$, whereas the optical depth decreases sharply, in agreement with previous observations and model signatures of snowlines42 (Extended Data Fig. 7). Further, we find $r > 1$ through most of the disk, indicating that self-scattering may be important and that the true radial variations in intensity may have higher contrast than we observe here46. Self-scattering can also explain the anomalously low $\alpha < 2$ at the disk centre27, where $\alpha = 2$ is the blackbody Rayleigh–Jeans limit.

Data availability

This paper makes use of ALMA data with the project code: ADS/JAO. ALMA#2015.1.05152.S. The archival data are available at http://almascience.eso.org/daq by querying the project code. The final calibrated version of the data analysed in this work is available from the Harvard Dataverse at https://doi.org/10.7910/DVN/LPVDSF. Other material in this work is available from the corresponding author on reasonable request.

Code availability

The radiative-transfer modelling makes use of RADMC-3D, which is publicly available at http://www.ita.uni-heidelberg.de/~dullemond/
software/radmc-3d/. The radiative-transfer modelling also uses the Pandora framework for the setup and interfacing with RADMC-3D; Pandora is not open source and is available upon request. The MCMC modelling uses emcee, which is publicly available at https://emcee.readthedocs.io/en/stable/.

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Author contributions D.M.S.-C. led the observing proposal and project, led the analysis, reduced the ALMA data, and wrote the manuscript. A.S. performed the radiative-transfer modelling. J.E.P. performed the MCMC modelling. I.W.S., M.F.-L., L.W.L., Z.-Y.L., L.G.M., W.K. and R.J.H. contributed to the ALMA proposal. P.C. provided discussion and interpretation of the results. All authors discussed the results and implications, and commented on the manuscript.

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Extended Data Fig. 1 | Asymmetry remains after re-centring the best radiative-transfer model. 

**a**, The residual of the data minus the best radiative-transfer model, which had a centroid set to the Gaussian fit centre (same as Fig. 2c). **b**, The residuals of the best radiative-transfer model with a shifted centroid from minimizing the r.m.s. of the data minus model residuals. The asymmetry to the northwest portion of the disk is clear in both cases.
Extended Data Fig. 2 | Posterior distributions of the analytic disk model parameters. From left to right, the parameters are: normalization factor $\Sigma_c$, surface density gradient $\gamma$, characteristic radius $R_c$, the coordinates of the centroid of the fit $x_0$ and $y_0$, disk position angle $PA$ and disk inclination angle $IA$. 
Extended Data Fig. 3 | A geometrically flat analytic model shows asymmetry in the residuals. a, The original dust continuum data (same as Fig. 2a). b, The image of the flat analytic model, generated from the median parameter values resulting from the MCMC fit. c, The residuals of the observed data minus the analytic model. Again, here the annular substructures and the asymmetry with excess emission to the northwest are seen.
Extended Data Fig. 4 | Position–intensity cuts of the dust continuum image centred at the position of the peak intensity. The centroid is (α(2000), δ(2000)) = (16 h 31 m 35.6577 s, −24° 01′ 29.897″). a–c, The cuts are taken at position angles of 150.0° or along the minor axis (a), of 60.0° or along the minor axis (b), and of 105.0° or along a cut from the southeast to northwest (c). d, The orientation of these cuts across the disk are shown in blue, orange and green, corresponding to a–c, respectively. The radii in a–c are deprojected assuming a disk inclination angle of 45.0° and are measured starting from the centroid outwards. The grey shaded areas represent the resolution of the observations, and the black horizontal lines show the 1σ noise level of 18.4 μJy per beam. We plot the radial intensities along either side of the centroid for each cut (solid and dashed lines). The 105.0° cut in c, along the southeast to northwest direction, shows the highest difference in intensities on either side of the centroid, and is consistent with the asymmetric and excess emission to the northwest previously seen in the residuals from the disk models.
Extended Data Fig. 5 | Position–intensity cuts of the dust continuum image centred at the Gaussian fit position. As in Extended Data Fig. 4, with a centroid of $(\alpha(2000), \delta(2000)) = (16\, h\, 31\, m\, 35.6572\, s, -24^\circ\, 01'\, 29.896'\, s)$.
Extended Data Fig. 6 | Position–intensity cuts of the dust continuum image centred at the centre determined from the MCMC fit to the analytic model. As in Extended Data Fig. 4, with a centroid of (α(2000), δ(2000)) = 16 h 31 m 35.6575 s, −24° 01′ 29.901″.
Extended Data Fig. 7 | Radial properties derived from observations. 

a–c, The radial profiles of the in-band spectral index (α, a), the optical depth (τ, b) and the temperature (T, c) derived from the observational data. The grey shaded area represents the resolution of the observations, and the vertical grey dashed and dotted lines show the positions of the bright annular substructures R1 and R2 and dark annular substructures G1 and G2. For the spectral index the light-blue ribbon represents the local standard deviation of each bin, and the horizontal dashed grey line shows the $\alpha = 2$ blackbody Rayleigh–Jeans limit. Optical depth is determined from a greybody fit to the intensity profile of the two in-band wavelengths. The temperature profile is determined from the greybody fit at radii where $\tau > 3$ (solid blue line), and extrapolated to larger radii, $r$, as an inverse square-root law (dot–dash black line). For optical depth and temperature, the light-blue ribbons reflect the 10% amplitude uncertainty of the observations. The orange shaded region shows the location of the CO snowline based on dust temperature, reflecting the range of gas densities used to compute the condensation temperature.