Models of terrestrial planet formation predict that the final stages of planetary assembly—lasting tens of millions of years beyond the dispersal of young protoplanetary disks—are dominated by planetary collisions. It is through these giant impacts that planets like the young Earth grow to their final mass and achieve long-term stable orbital configurations. A key prediction is that these impacts produce debris. So far, the most compelling observational evidence for post-impact debris comes from the planetary system around the nearby 23-million-year-old A-type star HD 172555. This system shows large amounts of fine dust with an unusually steep size distribution and atypical dust composition, previously attributed to either a hypervelocity impact or a massive asteroid belt. Here we report the spectrally resolved detection of a carbon monoxide gas ring co-orbiting with dusty debris around HD 172555 between about six and nine astronomical units—a region analogous to the outer terrestrial planet region of our Solar System. Taken together, the dust and carbon monoxide detections favour a giant impact between large, volatile-rich bodies. This suggests that planetary-scale collisions, analogous to the Moon-forming impact, can release large amounts of gas as well as debris, and that this gas is observable, providing a window into the composition of young planets.
optically thin assumption. This corresponds to total CO masses of $(1.4 \pm 0.3) \times 10^{-5} M_\odot$ at 169 K. However, we find that colder ($<<100$ K) temperatures would require higher optical depth and much higher CO masses to reproduce our observed CO line emission (Fig. 2b). This temperature–mass degeneracy can be resolved by the detailed spectral shape of the emission as models of optically thin, warm gas constrained to a narrow ring produce sharper peaks compared with the optically thick, cold models (Fig. 2a). We find that the data are better fit by less massive, warmer models (lower $\chi^2$).

The observed CO gas in the circumstellar environment around HD 172555 will be subject to photodissociation from the stellar and interstellar ultraviolet (UV) field. The former dominates at the 7.5 au location of the CO ring and causes CO (if unshielded) to be rapidly destroyed on a timescale of around one day. However, the lifetime of CO is extended when taking into account shielding effects from atomic carbon$^{13}$ (C, as produced by CO photodissociation), molecular hydrogen (H$_2$) and CO itself (self-shielding), which prevent UV photons from penetrating into the ring. Self-shielding alone, in the warm-temperature, low-CO-mass scenario, extends the gas lifetime by around two to four years. Given the lack of observational constraints on C and H$_2$ column densities, we cannot definitively estimate the shielding and hence the CO destruction timescale. However, CO could have easily survived over the system age (23 Myr) both in a scenario where C and CO dominate the gas mass (C/CO ratio of >0.16–0.43; Methods) and in a H$_2$-dominated scenario (H$_2$/CO ratio of around >10$^5$). Therefore, CO could either be the result of a very recent production and/or replenishment mechanism, or have survived for a large fraction of the system age. The CO detection constrains the gas to be located in the roughly 6–9 au region of the HD 172555 planetary system, co-located with the dust$^{12}$. Accounting for the difference in luminosity between the Sun

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**Fig. 1** | Cleaned emission maps of the HD 172555 system. Left: 4σ detection of the dust continuum emission (surface brightness $I_\nu$). Right: the moment-0 (spectrally integrated surface brightness $I$) map of the CO/J = 2–1 transition, with 9σ detection. Contour levels are at 2σ intervals, with $\sigma$ being 0.029 mJy per beam and 15 mJy km s$^{-1}$ per beam for the continuum and CO moment-0 maps, respectively. The beam size is denoted in lower left corner of each panel. Note that the 2σ peaks are background noise and not significant.

**Fig. 2** | Mass–temperature degeneracy of the CO data. a, CO/J = 2–1 spectrum of HD 17255 (grey solid line), compared with the output of two radiative transfer models: a low-mass, warm-temperature CO model (red dashed line), and a high-mass, cold-temperature CO model (blue dotted line). b, $\chi^2$ map (where $\chi^2$ is relative to the best-fit model) showing a clear CO temperature–mass degeneracy for models that are good fits to the data (darker on the colour scale). The red and light blue dots correspond to the red (warm) and blue (cold) CO models shown in a. Dotted contours enclose models that are consistent with the data at the >1,2,3,4σ confidence level.
and HD 172555, this region corresponds to the same thermal conditions as at about 2.1–3.3 au—the asteroid belt region—in our Solar System. This makes the presence of CO, a highly volatile gas with sublimation temperatures as low as 20 K, extremely surprising in a system with age 23 Myr. Some physical mechanism must explain the presence of gas and dust in the outer terrestrial planet-forming region of HD 172555. We test four hypotheses for the origin of the debris, and examine them in light of existing evidence from both dust observations and from the ALMA detection of CO in the system. These scenarios are: (1) leftover gas and dust from a primordial, protoplanetary disk; (2) collisional production within an extrasolar asteroid belt; (3) inward transport of material from an external reservoir; and (4) release in the aftermath of a giant impact between planetary-sized bodies.

Young A-type stars are born surrounded by protoplanetary disks of primordial gas and dust, but only 2–3% survive beyond the first 3 Myr of a star’s lifetime. Even if the CO observed around HD 172555 were primordial, with its lifetime extended through shielding, the system would remain a remarkable outlier not only in age (at 23 Myr old) but also in dust mass (orders of magnitude lower than protoplanetary disks) and in radial distribution of CO and dust (constrained within 10 au, and with a CO cavity, in contrast to protoplanetary disks typically extending out to tens/hundreds of astronomical units). The extreme depletion in dust mass would require efficient dust removal, either through accretion onto the star or grain growth. At the same time, the confined radial extent would require interior/exterior truncation, for example, by as-yet- undiscovered companions. Finally, the peculiar dust mineralogy of HD 172555 (requiring energetic processing) is seldom seen in young protoplanetary disks, although it may have arisen in nebular shocks analogous to those that could have led to chondrule formation in the Solar System. In conclusion, a primordial scenario would make HD 172555 an extreme outlier among other protoplanetary disks, favouring instead second-generation production.

In the second-generation case, a steady-state collisional cascade within an asteroid belt can explain the dust mass detected in the system, but not its abnormally steep particle size distribution, or its mineralogy requiring high-energy collisions at velocities higher than expected within typical belts. Although CO gas is commonly observed within collisional cascades in colder extrasolar Kuiper belt analogues at tens of astronomical units, there its presence can be explained by the release of CO gas initially trapped within icy bodies, or by desorption of CO$_2$ ice followed by rapid photodissociation of CO$_2$ gas. This picture is not plausible at 7.5 au; studies of ice-bearing asteroids in the Solar System show that although retaining water ice in the deep subsurface is possible—explaining the presence of outgassing main-belt comets in the asteroid belt—CO and CO$_2$ cannot remain trapped at these temperatures. In addition, any bodies forming at this location would be too warm to have formed with a substantial reservoir of CO or CO$_2$.

Alternatively, the observed dust and CO might originate from inward scattering of small bodies (exocomets) from an outer, cold reservoir akin to the Solar System’s Edgeworth–Kuiper belt. We first explore the possibility of gas and dust production through sublimation of Solar-System-like, 10-km-sized exocomets. We find that this scenario can reproduce the observations only if exocomets can be delivered on low-eccentricity orbits, finding that the exocomet replenishment rate could potentially be reconciled with the non-detection of an outer belt (Methods). However, this scenario cannot explain the relatively narrow radial distribution of the CO ring, or the mineralogy of the observed dust, and is thus not likely. However, it is possible that a single, cold, massive icy body is scattered inwards from an undetected outer belt. To produce the observed, largely axisymmetric distribution of material and dust mineralogy, the icy body would need to undergo a giant impact and release its CO or CO$_2$ content. Assuming a 25% CO + CO$_2$ ice mass fraction, and complete ice release at impact, we find that a dwarf planet (at least half the size of Pluto) would be needed to produce the lower limit on the CO gas mass observed.

Finally, CO gas and dust could be produced by a giant impact between planetary bodies formed in situ at around 7.5 au. The epoch of terrestrial planet formation, lasting from about 10 Myr to 100 Myr, is expected to be dominated by giant impacts. Within the Solar System, there is abundant evidence for the occurrence of giant impacts; the iron enrichment of Mercury, the formation of the Moon, the Martian hemispheric dichotomy, and the retrograde rotation of Venus are all hypothesized to have their origins in giant impacts. The HD 172555 system, at 23 Myr, is at the expected age that terrestrial planet formation proceeds through giant impacts; the dust and gas observed in the system are located in a region that is analogous to the terrestrial zone in our own Solar System. Studies of post-impact dynamics allow us to set constraints on progenitor masses and time since impact by considering the current spatial distribution and mass of dust (Methods). The dust in the system is axisymmetric within observational uncertainties, implying that the time since impact is at least the debris symmetrization timescale, which at 7.5 au is of the order of about 0.2 Myr (ref. 40). The width of the dust debris, as resolved at shorter wavelengths, suggests a progenitor mass of the order of about 8 $M_{\oplus}$, although the exact value is dependent on the radial width of the dust debris (Methods). Impacts between such bodies produce debris that would survive encounters with leftover planets, on a timescale longer than symmetrization; this indicates that impacts of such planets could be responsible for the observed, long-lived debris field.

Further supporting this scenario, we find that the optically thin CO gas mass detected in the system (0.45 $\times$ 10$^{-5}$ $M_{\oplus}$) is consistent with post-impact release from a planetary atmosphere. We note that any CO$_2$ in a planetary atmosphere will rapidly be converted into observable CO if liberated from the atmosphere, as CO$_2$ cannot be substantially shielded by C in the same way as CO because its photodissociation bands extend further towards the optical. Simulations show that up to 60% of a modestly sized, heavy atmosphere can be stripped in the initial shock of an impact. We find that the observed CO mass as well as the C needed to shield the CO for at least the symmetrization timescale require the release of an amount of CO$_2$ corresponding to just 9–23% of the total present in the Venusian atmosphere. More (less) massive planets with similar heavy atmospheres would require a smaller (larger) fraction of the atmosphere removed, or a smaller (larger) abundance of CO and/or CO$_2$. For lighter, H$_2$-dominated atmospheres, longer-term thermal effects can result in the stripping of the entire atmospheric envelope, in which case, once again, an amount of CO and/or CO$_2$ consistent with the observations could plausibly be liberated.

The detection and morphology of CO gas, combined with previous evidence from dust imaging and spectroscopy, supports a picture where a giant impact took place at least 0.2 Myr ago in the outer terrestrial planet-forming region of the 23-Myr-old HD 172555 system. Planetary-scale impacts are predicted to be commonplace in the latest stages of planet formation; the discovery of CO gas in the terrestrial planet-forming region, in amounts consistent with the expectation from atmospheric stripping, suggests that giant impacts may release not only copious, observable dust but also detectable amounts of gas. Furthermore, this discovery reveals the importance of gas release in post-impact dynamics, and highlights the potential of using gas as a tool to search for giant impacts in nearby planetary systems, while providing a unique window into the composition of young planets and their atmospheres.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions.
and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03872-x.

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Methods

ALMA observations

We analysed archival data from the ALMA telescope taken during cycle 1 in band 6 (project code 2012.1.00437.S). The observations were performed with the 12-m array in a compact antenna configuration. The on-source time was 76 min. The spectral setup included four spectral windows, of which three were set up in time-division mode for continuum observations and centred at 213 GHz, 215 GHz and 228 GHz. One window was set in frequency-division mode (with a high spectral resolution of 488.29 kHz) to target the 12CO/ J = 2–1 line (rest frequency 230.538 GHz). We calibrated the visibility data using scripts provided by the ALMA observatory. The CASA (Common Astronomy Software Applications) software (version 5.6.1, https://casa.nrao.edu/casadocs/casa-5.6.0) was used for visibility imaging. For both the continuum and the CO line emission, we removed data from antennas 7, 19 and 25. These data were taken in a hybrid configuration, with the three flagged antennas far from the compact group of antennas; removing these data substantially improves the imaging.

The CLEAN algorithm has been used to image both the continuum and CO line emission through the CASA ‘tclean’ task. To achieve maximum sensitivity, we used natural weighting for both datasets, resulting in a synthesized beam size of 0.16′′ × 0.75′′, corresponding to 32.9 au × 21.3 au at the system distance (28.5 pc) and a position angle of 81°. Before line imaging, we subtracted the continuum (measured in line-free regions of the spectrum) in visibility space using the CASA ‘uvcontsub’ task. We then imaged the CO to produce a cube with frequencies within ±25 MHz of the rest frequency, corresponding to velocities within ±30 km s⁻¹ of the radial velocity of the star. The data were imaged at the native spectral resolution (twice the original channel width) of 488.29 kHz. To obtain the CO moment-0 map, shown in Fig. 1, we integrated along the velocity axis between ±15 km s⁻¹ of the stellar velocity.

The emission is spatially unresolved in both the continuum and CO images, which have root-mean-square noise levels of 0.029 mJy per beam and 26 mJy km s⁻¹ per beam, respectively. This yields a peak detection at a signal-to-noise ratio per beam of 4 and 9 for the continuum and CO/ J = 2–1 spectrally integrated emission, and total fluxes of 0.12 ± 0.03 mJy and 170 ± 30 mJy km s⁻¹, respectively. Note that the flux calibration is expected to be accurate within 10%; this uncertainty was added in quadrature to obtain the quoted errors (https://almascience.nrao.edu/documents-and-tools/cycle-1/alma-ot-reference-manual). The uncertainty in each velocity bin was assumed to be equal to the root mean square measured in the region of the spectrum outside the detected emission. Flat priors were applied for the radial location, width, integrated line flux and stellar velocity. A Gaussian prior was applied to the inclination, assuming the gas shares the same inclination as the dust disk, as determined from previous resolved imaging. We carried out an additional run where a flat prior was applied to the inclination, to confirm the assumption of shared inclination. Extended Data Fig. 1 shows the posterior probability distributions of the parameters obtained from our MCMC runs and Extended Data Table 1 indicates the best-fit values, obtained as the 50th ± 34th percentiles of the posterior distributions of each parameter, marginalized over all other parameters. Best-fit values from both runs assuming a Gaussian or flat prior on the inclination are included.

Optically thin CO mass calculation

To derive a CO mass from the best-fit spectrally integrated line flux, we begin by assuming that the line is optically thin and considering the excitation conditions the gas may be subject to, which affect this conversion. We follow an existing framework, which considers that the energy levels of a CO molecule may be populated by collisions with other species (or by one dominant species, the main collisional partner), or by absorption and emission of radiation, giving rise to two limiting regimes, a radiation-dominated regime (low gas densities) and a collision-dominated regime (local thermodynamic equilibrium (LTE) at high gas densities). The choice or density of collisional partners (in our case, electrons) does not affect the level populations in these two limiting regimes, and therefore the range of CO masses derived.

To account for the full range of excitation conditions, we therefore use a non-LTE code to solve the statistical equilibrium equations and calculate the level populations. This includes the effect of fluorescence induced by stellar UV and IR radiation as seen by a CO molecule at 7.5 au from the central star. For the star, we adopt a PHOENIX stellar model spectrum. Subtracting this stellar contribution to the detected millimetre emission yields a contribution due to dust of 85 ± 30 μJy. The dust grain opacity is assumed to be 10 cm² g⁻¹ at 1.000 GHz and scaled to the frequency of the observation with an opacity power-law index of β = 1 (ref. 46). These assumptions yield a dust mass of (1.8 ± 0.6) × 10⁻⁴ M⊙.

Optically thin CO ring modelling

To model the velocity spectrum expected from a circular orbiting ring or disk of material, we calculate Keplerian velocities assuming a stellar mass of 1.76 M⊙ (ref. 48). Two-dimensional orbital velocity vectors are calculated for a radial and azimuthal grid, assuming a vertically thin ring/disk of gas that has radially and azimuthally uniform surface density between an inner boundary and an outer boundary. They are transformed to the sky plane using the ring/disk inclination to obtain radial velocities along the line of sight. These velocities in the reference frame of the star are then added to the radial velocity of the star in the barycentric frame (left as a free parameter) to obtain barycentric velocities as observed by ALMA. A histogram of these velocities, with the same binning as the observed data, serves as a model spectrum. We normalize the unitless spectrum such that the integral of the spectrum is equal to the integrated flux of the line, a free parameter in the fit. This spectrum is then convolved with a Gaussian of full-width at half-maximum equal to twice the channel width to reproduce the spectral response of the instrument due to Hanning smoothing (https://safe.nrao.edu/wiki/pub/Main/ALMAWindowFunctions/Note_on_Spectral_Response.pdf). In addition to these parameters, the model fits the inclination, radial location of the midpoint and width of the ring/disk.

A Markov chain Monte Carlo (MCMC) approach was used to determine the best fit to the data. We used the Python package emcee. The uncertainty in each velocity bin was assumed to be equal to the root mean square measured in the region of the spectrum outside the detected emission. Flat priors were applied for the radial location, width, integrated line flux and stellar velocity. A Gaussian prior was applied to the inclination, assuming the gas shares the same inclination as the dust disk, as determined from previous resolved imaging.23 We carried out an additional run where a flat prior was applied to the inclination, to confirm the assumption of shared inclination. Extended Data Fig. 1 shows the posterior probability distributions of the parameters obtained from our MCMC runs and Extended Data Table 1 indicates the best-fit values, obtained as the 50th ± 34th percentiles of the posterior distributions of each parameter, marginalized over all other parameters. Best-fit values from both runs assuming a Gaussian or flat prior on the inclination are included.

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possible CO masses between $0.45 \times 10^{-5} M_\odot$ and $1.25 \times 10^{-5} M_\odot$ for kinetic temperatures between 100 K and 250 K, encompassing the blackbody temperature of 169 K at 7.5 AU.

Three-dimensional radiative transfer modelling

We use the RADMC-3D (http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/) radiative transfer code to check the impact of optical depth in more detail. We use the same ring geometry as obtained from optically thin fitting (Extended Data Table 1, Gaussian prior). We vary the input CO mass and kinetic temperature over a two-dimensional grid (Fig. 2b), and connect the latter to the vertical aspect ratio by assuming a vertically isothermal gas disk with a mean molecular weight of 14 (that is, the gas mass is dominated by atomic C and O, as expected in a second-generation scenario). To sample the ring well spatially and spectrally, we create cubes of $J = 2$ emission with a pixel size of 6 mas (corresponding to a physical scale of 0.18 AU), and the same native channel width as our data. We then spectrally convolve with a Gaussian to reproduce the spectral response of the instrument and extract a one-dimensional model spectrum by spatially integrating the model emission. We then compared this model spectrum to the data (as shown in Fig. 2a) and calculated $\chi^2$ for every mass and temperature in our grid, to obtain a $\chi^2$ map (Fig. 2b).

CO survival lifetime against photodissociation

The observed CO gas in the circumstellar environment around HD 172555 will be subject to photodissociation from the stellar and interstellar UV field. The photodissociation rate in s$^{-1}$ of a molecule in a radiation field $I(\lambda)$ is $k = \int \sigma(\lambda) I(\lambda) d\lambda$, where $\lambda$ is the wavelength, and $\sigma(\lambda)$ is the photodissociation cross-section in cm$^2$. We use the CO photodissociation cross-sections from the Leiden database46 (https://home.strw.leidenuniv.nl/~ewine/photo/display_co_42983b05e2f2cc22822e30beb7bd6668.html). We adopt the stellar spectrum from the optically thin mass section above, scaled to the centre of the gas ring (7.5 AU) to obtain the stellar radiation field. We find that the star dominates over the interstellar radiation field, and that the CO photodissociation timescale (1/k) at the ring’s radial location is approximately one day. The shielding effects are estimated using pre-computed shielding constants46; we interpolate the constants for stars of 4,000 K and 10,000 K to a stellar temperature of 8,000 K, closest to the effective temperature of HD 172555. The CO column density is calculated from the centre of the ring along the line of sight to the star, using our best-fit uniform ring model parameters. To find the H$_2$ and C column densities that provide sufficient shielding, we interpolate the shielding constants along the column-density axis and find the column density required.

Delivery from an outer belt

Replenishment requirement. We consider a scenario where the dust grains and CO gas are produced from sublimation-driven release by Solar-System-like comets entering the inner region of the HD 172555 system. This requires replenishment of the observed total dust mass (in grains up to centimetres in size) on timescales comparable to their removal (assuming steady state). We assume that their removal is dominated by collisions, setting up a cascade down to the smallest grains (of size approximately 3.5 µm for a grain density of 2,700 kg m$^{-3}$) that are then removed by radiation pressure from the central star, to derive a mass-loss rate of $2.2 \times 10^{-3} M_\oplus$ Myr$^{-1}$ (using equation (21) in ref. 28). We neglect the effect of gas drag, assuming that the larger, centimetre grains are unaffected.

We use the results of thermochemical modelling45 calibrated on Solar System comets to estimate the mass-loss rate per unit surface area of an exocomet at 7.5 AU around 7.7 L$_\odot$ to be $5.6 \times 10^{-10}$ kg m$^{-2}$ s$^{-1}$ of dust in grains up to centimetres in size. Dividing by an assumed bulk density of 560 kg m$^{-3}$, and assuming a 1:1 dust/ice ratio, this corresponds to an erosion rate of 0.62 m yr$^{-1}$. Therefore, a comet with a 10-km radius will be emitting dust at a rate of 7,040 kg s$^{-1}$ (3.72 $\times$ 10$^{-8} M_\oplus$ Myr$^{-1}$) and will survive (if continuously sublimating at this rate) for about 16 kyr.

High-eccentricity exocomet population. In the first case, we assume exocomets arise from a yet-undetected belt at 100 AU (a typical location of cold exocometary belts around A stars56) and approach the inner regions on eccentric orbits. The velocity distribution from the observed cold exocometary belts around A stars implies line-of-sight velocities for the gas of about 14.5 km s$^{-1}$, corresponding to 7.5 AU for circular orbits around HD 172555. However, these velocities will be achieved at larger radii for comets with non-zero eccentricities, random pericentre directions and orbiting in the same plane as the inner system of HD 172555. The pericentre distance corresponding to pericentre velocities of about 14.5 km s$^{-1}$ will increase with the apocentre (and therefore the eccentricity) of the orbits; for an apocentre of 100 AU, we derive a pericentre distance of 3.2 AU. Therefore, we expect gas released from exocomets on these orbits to be located at and beyond about 13.2 AU from the central star. For comparison, this is 80% larger than the radial location derived for circular orbits (7.5 AU). However, eccentric exocomets with the observed velocities would produce a CO ring with diameter about 26 AU (0.9$''$), which is comparable to the resolution element of our observations, implying that the ring would have been marginally resolved, which is not the case. In addition, scattered light observations currently constrain dust emission to less than 0.9$''$ (3$\sigma$) diameter, with a sharp outer edge. The fact that the expected radius of a CO ring would significantly exceed the observed value makes the eccentric exocomet scenario inconsistent with the available observations. Note that reasonably changing the apocentre location, and therefore the radius of the hypothetical cold belt where the exocomets originate, does not alter our conclusions significantly. For example, assuming an outer belt location of 20 AU instead of 100 AU implies exocomet pericentres at 10 AU. This would produce CO emission with a minimum expected diameter of 20 AU (0.7$''$) and extending much beyond it, which probably would have been spatially resolved in the ALMA data.

Low-eccentricity exocomet population. In the second case, we assume exocomets are being continuously scattered inward from an outer belt by a chain of low-mass planets, undergoing multiple scatterings and producing a low-eccentricity comet population at about 7.5 AU. We here assume circular orbits for simplicity. The dust observed requires replenishment at a rate of $2.2 \times 10^{-2} M_\oplus$ Myr$^{-1}$. Assuming exocomets of 10 km in size with an exocometary dust release rate of $3.72 \times 10^{-6} M_\oplus$ Myr$^{-1}$, 5.9 x 10$^5$ exocomets are required to be sublimating at around 7.5 AU at any point in time. For a bulk density of 560 kg m$^{-3}$, this corresponds to 2.3 x 10$^{-6}$ M$_\oplus$ km$^{-3}$ in 10-km exocomets. While sublimating at this rate, such an exocomet would survive for about 16 kyr, so comets would need to be resupplied by inward scattering to the inner planetary system at a rate of $1.4 \times 10^{-8} M_\oplus$ yr$^{-1}$. Inward scattering is an inefficient process; simulations maximizing inward scattering by chains of low-mass planets indicate that only a few per cent of comets encountering an outermost planet make it into the inner regions, as the vast majority are ejected47. Therefore, higher supply rates of the order of $10^{-7} M_\oplus$ yr$^{-1}$ from a putative outer belt are probably needed, which would imply that a currently undetected outer belt would have resupplied 23 M$_\oplus$ in 10-km exocomets into the inner regions over the 23 Myr age of the system.

We can compare this to the upper limit on the presence of an outer belt at 100 AU from our ALMA data. Assuming blackbody temperatures, and the same dust opacity as used for dust in the inner regions, we derive an upper limit of less than $1.8 \times 10^{-8} M_\oplus$ (3$\sigma$) on the mass of solids of sizes up to centimetre sizes. Extrapolating from centimetre-sized grains up to 10-km exocomets (assuming a size distribution with a constant power-law slope of $-3.5$), we obtain an upper limit on the total mass in 10-km-sized exocomets of less than $1.8 M_\oplus$ (3$\sigma$). Therefore, the current mass of the outer belt would be at least a factor of about ten smaller than the mass that has been removed from the belt over its lifetime, which is by itself not impossible. However, it is likely that exocomets reaching their inner regions would retain some eccentricity, which would prolong their survival.
Observations of both CO and dust are consistent with the CO and dust distribution being axisymmetric. Because of this, the time since impact must be at least the symmetrization timescale, which is on the order of a few tens of thousands of orbits (about 0.2 Myr at 7.5 AU). Constraints on the planet mass can be derived from the width of the debris, as a proxy for the velocity dispersion of released material. The width, $\sigma_r$, is given by $\sigma_r = 2\rho_p e_p$, where $e_p$ is the proper eccentricity of the orbiting debris. This eccentricity is related to the velocity dispersion, $\sigma_v$, through $\sigma_v = \sqrt{3} e_p \rho_p$, where $e_p$ is the Keplerian velocity at the given semimajor axis. We assume the velocity dispersion is related to the escape velocity $v_{esc}$ at the surface, of the colliding bodies by $\sigma_v = 0.46 \frac{v_{esc}}{\rho_p R_p}$, where $\rho_p$ is the universal gravitational constant, and $R_p$ is the planetary radius. Thus, for an observed debris width $\sigma_r$, a planet of mass $M_p = 103 \frac{M_{\oplus}}{\rho_p^{3/2} \sigma_r^2 \left( \frac{R_p}{d} \right)}$ in $M_{\oplus}$ is expected, where $\rho_p$ is the planet's bulk density in g cm$^{-3}$, $M_p$ is the stellar mass in $M_{\odot}$, and both $R_p$ and $d$ are in astronomical units. If the planetary bodies colliding have rocky, Earth-like compositions, they will have bulk densities of about 5.5 g cm$^{-3}$ We assume that the solid debris is confined to the same radial width as the dust width derived from mid-IR Q-band imaging, which finds $d_{rad}/r = 1.2$, where $d_{rad}$ is the width of the dust ring. These assumptions yield a planetary mass on the order of about $8 M_{\oplus}$. We note that mid-IR imaging is sensitive to small grains whose width might have been broadened due to radiation pressure from the central star; if radiation pressure inflated the width compared with that expected from the velocity dispersion, the planetary mass involved would be reduced. If instead the bulk planetary density is lower, the mass of planet involved in the collision would be larger.

**Data availability**

The ALMA programme number for the presented data is 2012.1.00437.S and data can be found in the online ALMA archive. The cleaned .fits files are available upon request from the corresponding author.

**Code availability**

RADMC-3D is available at https://github.com/dulmonde/radmc3d-2.0 and emcee is available at https://emcee.readthedocs.io/en/stable/. Custom code, including the ring model and non-LTE code, is available at https://github.com/tmschneiderman/hd172555_CO_2021.

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**Author contributions**

T.S. led the optically thin modelling and discussion. L.M. led the radiative transfer modelling. T.S. and L.M. were involved in data reduction, processing and writing of the manuscript. All authors contributed to discussions of the results and commented on the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

**Supplementary information**

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Extended Data Fig. 1 | Posterior probability distributions for the model parameters obtained from the emcee fitting process. All parameters are well constrained, with best-fit values listed in Extended Data Table 1. This model was fitted to spectral data retaining original channel widths, assumed a Gaussian prior on the inclination, and assumed a stellar mass of 1.76 $M_\odot$. 
Extended Data Table 1 | Best fit values (50 ± 34 percentile) to the optically thin model of gas emission. Left column indicates values derived from the MCMC run where a Gaussian prior was applied to the inclination. Right column indicates values derived from the MCMC run where flat priors were applied to all model parameters

| Best fit parameters | Gaussian       | Flat           |
|---------------------|----------------|----------------|
| Inclination (°)      | 102 ±6.0 -6.5  | 107 ±12.1 -17.6|
| Midpoint (au)        | 7.4 ±0.5 -0.4  | 7.4 ±1.8 -0.6  |
| Width (au)           | 3.4±0.5        | 3.1 ±0.9 -0.7  |
| \(V_\ast\) (km/s)   | 2.3±0.2        | 2.3±0.2        |
| Int. Flux (mJy km/s) | 122 ±8.9 -9.0  | 122 ±8.5 -8.8  |