LETTER

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Rapid disappearance of a warm, dusty circumstellar disk

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Stars form with gaseous and dusty circumstellar envelopes, which rapidly settle into disks that eventually give rise to planetary systems. Understanding the process by which these disks evolve is paramount in developing an accurate theory of planet formation that can account for the variety of planetary systems discovered so far. The formation of Earth-like planets through collisional accumulation of rocky objects within a disk has mainly been explored in theoretical and computational work in which post-collision ejecta evolution typically is ignored[1–3], although recent work has considered the fate of such material[4]. Here we report observations of a young, Sun-like star (TYC 8241 2652 1) where infrared flux from post-collisional ejecta has decreased drastically, by a factor of about 30, over a period of less than two years. The star seems to have gone from hosting substantial quantities of dusty ejecta, in a region analogous to where the rocky planets orbit in the Solar System, to retaining at most a meagre amount of cooler dust. Such a phase of rapid ejecta evolution has not been previously predicted or observed, and no currently available physical model satisfactorily explains the observations.

TYC 8241 2652 1 (stellar parameters are reported in Table 1), was found as part of a survey to identify main-sequence stars with excess emission at mid- and far-infrared wavelengths. To accomplish this goal, we cross-correlated the Tycho-2 catalogue[5] with those of the Infrared Astronomical Satellite, AKARI[6] and the Wide-field Infrared Survey Explorer[7] (WISE) and performed our own observations using the Thermal-Region Camera Spectrograph[8] (T-ReCS) at the Gemini South telescope. Figure 1 and Table 2 show how the 11-μm excess emission of this source evolved from being a factor of ~30 times the stellar photosphere flux before 2009 to being ~13 times the photospheric flux in mid 2009 and being barely detectable in 2010 (details regarding each measurement can be found in Table 2). The pre-2009 measurements indicate significant mid-infrared excess emission and, hence, that warm dusty material orbited in the star's inner planetary system (Fig. 1 and Table 2). Remarkably, two epochs of WISE measurements show that the excess mid-infrared emission has all but disappeared, leaving only a weak (~3 times the stellar photosphere) excess at a wavelength of 22 μm (Fig. 1 and Table 2). We note that the two WISE epochs have a time separation of roughly six months and yet still report identical flux levels. Measurements made after the WISE epochs using the SpeX spectrograph at the NASA Infrared Telescope Facility[9–11], the Photodetector Array Camera and Spectrograph (PACS) for the Herschel Space Observatory[12] and again with T-ReCS are consistent with the WISE data (Fig. 1; note especially the 2012 T-ReCS data), thus indicating that the mid-infrared emission from the dust orbiting this star has been consistently depleted to barely detectable levels since at least early 2010.

To determine the age of TYC 8241 2652 1, we obtained high-resolution optical spectra over four epochs from February 2008 to January 2009 with an echelle spectrograph mounted on the Siding Spring Observatory 2.3-m telescope. From these optical spectra, we estimate the age of the system from the lithium content in the stellar photosphere, Galactic space motion and rotational broadening of absorption lines; details can be found in Supplementary Information. We adopt an age of ~10 Myr for TYC 8241 2652 1.

An important ingredient in understanding the vanishing mid-infrared emission from the dust orbiting TYC 8241 2652 1 is the initial state of the disk system. Given an age of ~10 Myr, the star could have been host either to an accreting protoplanetary disk rich in gas and dust or to a second-generation debris disk formed from the collisions of rocky objects orbiting the star[13]. The absence of strong Balmer Hα emission from our optical spectroscopic measurements indicates that the star was not undergoing accretion of hydrogen-rich material at any significant level[14] (see also Supplementary Information), and thus it is unlikely that such material was being transported inwards to the star as would be expected in a system with an active protoplanetary accretion disk. Another argument against TYC 8241 2652 1 having a protoplanetary accretion disk in the two decades before 2009 lies with the Herschel/PACS measurements. The sensitive upper limits in the far-infrared robustly rule out the presence of a substantial reservoir of cold disk material typical of those seen in protoplanetary disks. We thus conclude that the dusty material orbiting TYC 8241 2652 1 is the result of the collisions of rocky objects.

Table 1 | Parameters of TYC 8241 2652 1

Parameter	Value
Right ascension	12 h 9 min 2.25 s
Declination	−51° 20′ 41.0″
Galactic longitude	296.2104°
Galactic latitude	+10.9728°
Visual magnitude	11.5 mag
Spectral type	K2±1
Effective temperature	4950 ± 150 K
Proper motion in right ascension	−34.1 ± 2.1 mas yr^{-1}
Proper motion in declination	−9.4 ± 2.0 mas yr^{-1}
Heliocentric radial velocity	15 ± 1 km s^{-1}
Lithium 6,708-Å EW	370 ± 10 mÅ
Balmer Hα EW	0.0 ± 0.1 Å
Ca II K emission core EW	4.5 ± 0.5 Å
$v\sin(i)$	10 ± 1 km s^{-1}
Distance from Earth	140 ± 20 pc (456 light yr)
Galactic space motions	−12 km s^{-1} (U), −24 km s^{-1} (V), −7 km s^{-1} (W)
Age	~10 Myr

J2000 equinox right ascension and declination are from the Two Micron All Sky Survey (2MASS) catalogue. Galactic longitude and latitude are derived from the 2MASS right ascension and declination. The spectral type and effective temperature are determined from line ratios[28] in the echelle spectra from the Siding Spring Observatory. Proper motion measurements are from the Tycho-2 catalogue[5]. The radial velocity is measured from our Siding Spring echelle spectra by cross-correlating a target spectrum with a standard star spectrum of known radial velocity. Four epochs of radial velocity measurements (14 February 2008, 14 June 2008, 13 July 2008 and 12 January 2009 UT) show no evidence for radial velocity variability within the measured errors (~1–2 km s^{-1}), ruling out any short-orbital-period stellar companions to TYC 8241 2652 1. The radial velocity quoted in the table is the average of the four separate measurements. The listed Balmer Hα, Ca II K core reversal emission and lithium 6,708-Å equivalent widths (EWs) are averages over the four Siding Spring echelle epochs, and the uncertainty quoted is the standard deviation of those measurements. The stellar rotational velocity (v in $v\sin(i)$, where i is the angle of inclination of the stellar spin axis with respect to the line of sight towards Earth) was measured from the full-width at half-maximum (FWHM) depth of single absorption lines in the Siding Spring echelle spectra (which have an intrinsic resolution-element FWHM of ~13 km s^{-1}, a value that we subtract in quadrature from the FWHM measured in the spectra). Velocities of the TYC 8241 2652 1 system (relative to the Sun) towards the centre of the Galaxy, around the Galactic Centre and perpendicular to the Galactic plane (U, V, W) are calculated from Tycho-2 proper motions, our estimated photometric distance and the optical-echelle-measured radial velocity. Uncertainties in these values are roughly 2 km s^{-1}. See Supplementary Information for a discussion of the age.

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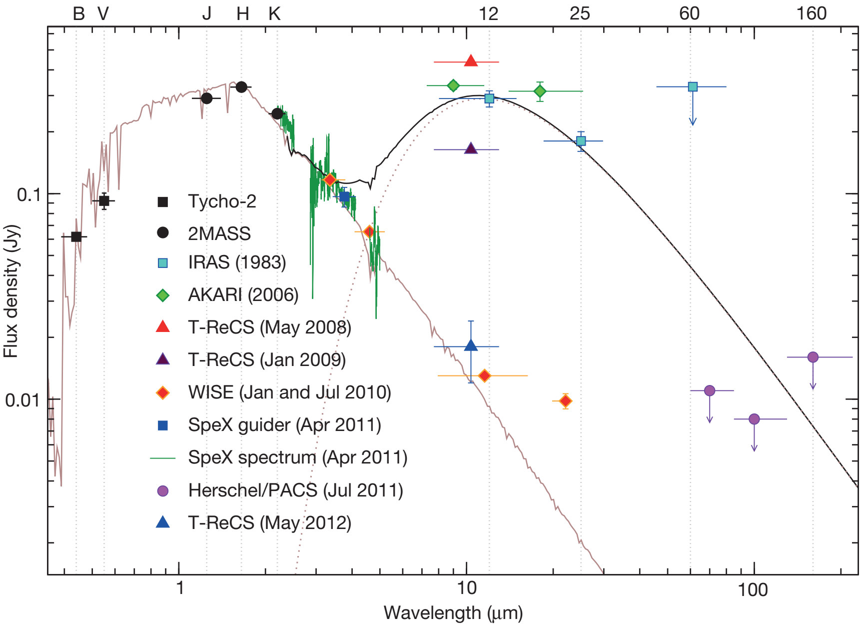

Figure 1 | Spectral energy distribution of TYC 8241 2652 1. Measurements and the associated epoch (for mid- and far-infrared data) are indicated in the legend. The solid brown curve is a synthetic stellar photosphere[15] for a star with an effective temperature of 4,950 K that is fitted to the optical and near-infrared data. The dotted line is a black-body fit to the 12- and 25-μm IRAS excess data points. The temperature of this black body is 450 K and it suggests that roughly 11% of the optical and near-infrared starlight was being reprocessed into the mid-infrared by orbiting dust. The black solid line is the sum of the photosphere and the black body at 450 K. Fitting a black body to the WISE and Herschel measurements suggests a dust temperature of roughly 200 K and a fractional infrared luminosity of 0.1%. Plotted flux density errors are 1 s.d. Some, for example those of the two earlier epochs of T-ReCS measurements, are smaller than the point sizes on the plot; for these measurements, the uncertainty is comparable to or less than 10% of the corresponding measurement. Horizontal lines through each data point represent the filter FWHM.

To estimate the dust temperature and the fractional infrared luminosity (L_{IR}/L_*, where L_* is the total stellar luminosity) of the dusty debris disk, we fit optical and near-infrared measurements out to the K_s band (2.1 μm) with a synthetic stellar atmosphere spectrum[15] along with a black body at 450 K (Fig. 1) that models the pre-2009-epoch dust excess. Grains with a temperature of 450 K that are sufficiently large to radiate like black bodies at 10 μm and are situated in a disk optically thin to the stellar radiation field would orbit TYC 8241 2652 1 with a semi-major axis of ~0.4 AU. From the black-body fit, we find that $L_{IR}/L_* \approx 11\%$ (Fig. 1); such a value is significantly greater than those found previously for stars with warm debris disks[16], but is less than that of the recently discovered, ~60-Myr-old V488 Per system[17]. A geometrically thin, flat dust disk (such as Saturn's rings or some circumstellar debris disks) cannot absorb 11% of the luminosity of TYC 8241 2652 1 (ref. 18). To intercept such a large fraction of the incoming stellar light, the disk must be geometrically thick or otherwise deformed into a non-flat shape. Such a morphology could be suggestive of a substellar body that dynamically excites the dust particles, warps the disk, or both[19–21]. Fits to WISE and Herschel/PACS data allow a dust temperature only in the range $120\,K < T_{dust} < 250\,K$, indicating cool grains that orbit TYC 8241 2652 1 at a distance of ~2 AU, and a fractional infrared luminosity of ~0.1%.

Given the luminosity of TYC 8241 2652 1 ($L_* \approx 0.7L_\odot$, where $L_\odot$ is the solar luminosity), grains with radii of ~0.2 μm and smaller will be radiatively ejected from the disk system. Roughly 5×10^{21} g of grains with radii of order 0.3 μm, which is slightly larger than the critical radius for radiative ejection, are required to produce the observed pre-2009-epoch infrared excess from TYC 8241 2652 1 (ref. 22). For a debris disk, the copious amounts of dust that were present suggest a system undergoing an active stage of terrestrial planet formation[16,23]. The excess emission detected by WISE requires roughly 4–5 times less mass in cool, small (~0.3-μm) dust grains than that estimated for the grains at 450 K detected closer to the star in the pre-2009 epoch. To have no WISE-detectable signature of grains at 450 K requires that such dust contribute less than 0.1% to the total fractional infrared luminosity in the post-2009-epoch measurements.

Table 2 | Mid-infrared flux measurements of TYC 8241 2652 1

Observation date (UT)	Instrument	Beam size (″)	~10-μm flux density (mJy)	~20-μm flux density (mJy)
February–November 1983	IRAS	45 × 270 (PA = 132°)	309 ± 31	224 ± 22
May–November 2006	AKARI	5.5	335 ± 14	315 ± 34
6 May 2008	T-ReCS	0.4	436 ± 44	—
7 January 2009	T-ReCS	0.4	164 ± 16	—
8–10 January 2010	WISE	6.1	12.8 ± 0.4	9.4 ± 0.8
14–18 July 2010	WISE	6.1	12.3 ± 0.5	9.2 ± 1.0
1 May 2012	T-ReCS	0.4	18 ± 6	—

Central wavelengths for each instrument are 12 and 25 μm for the Infrared Astronomical Satellite (IRAS), 9 and 18 μm for AKARI, 10 μm for T-ReCS N-band imaging, and 11 and 22 μm for WISE. For each of the IRAS and WISE measurements, all available ancillary data products were examined to ensure reliability of the measured flux densities. T-ReCS observations were performed in clear, photometric conditions and were flux-calibrated using consecutive observations of stars with known mid-infrared fluxes. For instruments other than IRAS, the quoted beam size is the point spread function FWHM. The large, irregular IRAS beam size is a result of the focal plane detector mask used, and the position angle (PA) is the orientation of this rectangular mask on the sky when IRAS observed TYC 8241 2652 1. A PA of 0° is North and a PA of 90° is East. For each of the IRAS, AKARI and WISE measurements, the satellite-measured stellar position agrees with the Two Micron All Sky Survey position quoted in Table 1 to within the stated errors (after taking into account the stellar proper motion listed in Table 1). For T-ReCS measurements, the stellar position is not absolutely determined by the observations but instead is determined relative to the calibration star that is observed immediately before or after observations of TYC 8241 2652 1. On the T-ReCS detector array, the position of the mid-infrared source detected towards TYC 8241 2652 1 relative to the position of the calibration star is a reflection of how close the detected source position is to the input position, because the telescope slew precision is roughly 1″ or better for small slews. We determine that, for each observation of TYC 8241 2652 1 with T-ReCS, the detected source lies within 1″ of the stellar position in Table 1. We also note that there is only one source detected in the 28.8″ × 21.6″ T-ReCS field of view, and that each observation was sensitive enough to detect the photospheric flux level of TYC 8241 2652 1.

It is desirable to develop a physical model that can explain the observed disappearance of the disk of dust grains at 450 K. In Supplementary Information, we consider and reject models that rely on the disk material somehow being hidden from view, thus resulting in the diminished flux. In lieu of these models, we explore others in which the disk material is physically removed from its pre-2009-epoch location. If the number of grains with radius *a* that orbit the star follows a conventional $a^{-3.5}$ size distribution—and, hence, the fractional infrared luminosity scales like $a^{-0.5}$ (ref. 22)—we expect that removal of grains with radii up to ~1 mm would be required to eliminate the observational signature of dusty material orbiting at a separation of ~0.4 AU. For an $a^{-3.5}$ size distribution, the diminished mid-infrared flux requires that the total mass of dust particles with *a* less than ~1 mm located near 0.4 AU be smaller by a factor of ~100. A steeper grain size distribution, with an exponent of −3.7 to −3.8, would require removal of grains with radii up to ~100 μm and would result in a reduction in the total grain mass by a factor of ~10.

Of the models explored in Supplementary Information, only the collisional avalanche[24] and runaway accretion[25] models are potentially viable, although each has its problems (details regarding these models and their shortcomings can be found in Supplementary Information). It is worth noting that both models benefit if the steeper grain size distribution is assumed and that modelling of other stars with warm debris disks indicates that such a steep power-law slope may be present in such systems[26,27]. Clear identification of a physical model that can reproduce the observations will require modelling specific to the case of TYC 8241 2652 1 and its continued observation. Although the exact circumstances are not yet clear, this system has clearly undergone a drastic event that promises to provide unique insight into the process by which rocky planets form.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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