LETTER

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A disintegrating minor planet transiting a white dwarf

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Most stars become white dwarfs after they have exhausted their nuclear fuel (the Sun will be one such). Between one-quarter and one-half of white dwarfs have elements heavier than helium in their atmospheres[1,2], even though these elements ought to sink rapidly into the stellar interiors (unless they are occasionally replenished)[3–5]. The abundance ratios of heavy elements in the atmospheres of white dwarfs are similar to the ratios in rocky bodies in the Solar System[6,7]. This fact, together with the existence of warm, dusty debris disks[8–13] surrounding about four per cent of white dwarfs[14–16], suggests that rocky debris from the planetary systems of white-dwarf progenitors occasionally pollutes the atmospheres of the stars[17]. The total accreted mass of this debris is sometimes comparable to the mass of large asteroids in the Solar System[1]. However, rocky, disintegrating bodies around a white dwarf have not yet been observed. Here we report observations of a white dwarf—WD 1145+017—being transited by at least one, and probably several, disintegrating planetesimals, with periods ranging from 4.5 hours to 4.9 hours. The strongest transit signals occur every 4.5 hours and exhibit varying depths (blocking up to 40 per cent of the star's brightness) and asymmetric profiles, indicative of a small object with a cometary tail of dusty effluent material. The star has a dusty debris disk, and the star's spectrum shows prominent lines from heavy elements such as magnesium, aluminium, silicon, calcium, iron, and nickel. This system provides further evidence that the pollution of white dwarfs by heavy elements might originate from disrupted rocky bodies such as asteroids and minor planets.

WD 1145+017 (also designated EPIC 201563164) is a helium-envelope white dwarf (Supplementary Table 1) that was observed by NASA's Kepler space telescope during the first campaign of its two-wheeled mission—a mission referred to hereafter as K2. After processing K2 data taken from WD 1145+017 to produce a light curve and correcting for instrumental systematics[18], we identified a transit-like signal with a period of 4.5 h by using a box-fitting least-squares search algorithm[19]. Using a Fourier analysis on the systematic-corrected K2 data, we identified five other weaker, but statistically significant, periodicities in the data, all with periods between 4.5 h and 5 h (Fig. 1 and Supplementary Table 2). We examined the dominant periodicity and found that the depth and shape of the transits varied substantially over the 80 days of K2 observations (Fig. 2).

We initiated follow-up, ground-based photometry to achieve better time resolution of the transits seen in the K2 data (Supplementary Fig. 1). We observed WD 1145+017 frequently over the course of about a month with the 1.2-metre telescope at the Fred L. Whipple Observatory (FLWO) on Mount Hopkins, Arizona; with one of the 0.7-metre MINiature Exoplanet Radial Velocity Array (MINERVA) telescopes, also at FLWO; and with four of the eight 0.4-metre telescopes that compose the MEarth–South Array at the Cerro Tololo Inter-American Observatory in Chile. Most of these data showed no interesting or noteworthy signals, but on two nights we observed deep (with up to 40% of the star's brightness blocked), short-duration (5-min), asymmetric transits separated by the dominant 4.5-h period identified in the K2 data (Fig. 3). In particular, using the 1.2-m FLWO telescope in the V-band (green visible light), we detected two transits separated by 4.5 h on the night of 11 April 2015; furthermore, using four of the eight MEarth–South array telescopes (all in near-infrared light, using a 715-nm long-pass filter), we detected two transits separated by the same 4.5-h period on the night of 17 April 2015. The transits did not occur at the times predicted from the K2 data, and the two transits detected on 11 April happened nearly 180 degrees out of phase from the two transits detected on 17 April. Observations with MEarth–South in near-infrared light and with MINERVA in white visible light the next night (18 April) showed only a possible transit event, of 10%–15% depth, in phase with the previous night's events. The 5-min duration of the transits is longer than the roughly 1-min duration we would expect for a solid body transiting the white dwarf.

Nonetheless, we confirmed that these events are indeed transits by a low-mass object in orbit around the white dwarf. The depth and morphology of the transits that we see in the ground-based data cannot be explained by stellar pulsations, and archival and adaptive optics imaging place strong constraints on scenarios involving a binary star in the background, whose eclipses might mimic transits of the white dwarf (Supplementary Fig. 2). We also obtained spectroscopic observations with the MMT Blue Channel spectrograph; we used these observations to place limits on radial-velocity variations that would indicate stellar companions. The radial-velocity measurements exclude companions larger than ten Jupiter masses at the 95% confidence level.

The spectra also reveal that the atmosphere of the white dwarf contains magnesium, aluminium, silicon, calcium, iron, and nickel (Supplementary Fig. 3). These elements, which are heavier than helium, have settling times that are much shorter than the cooling age of the white dwarf, indicating that they have been deposited in the white dwarf's envelope in the past million years[5]—much more recently than it formed, about 175 ± 75 million years ago. Archival photometry for this system is well fitted by a 15,900-K, metal-rich white-dwarf model spectrum, and we find evidence for excess infrared emission consistent with a warm (1,150 K) dusty debris disk (Supplementary Fig. 4).

We interpret these observations as evidence that at least one, and probably six or more, disintegrating planetesimals are transiting this white dwarf. Disintegrating planets have been observed transiting main-sequence stars[20–22], and show asymmetric transit profiles and

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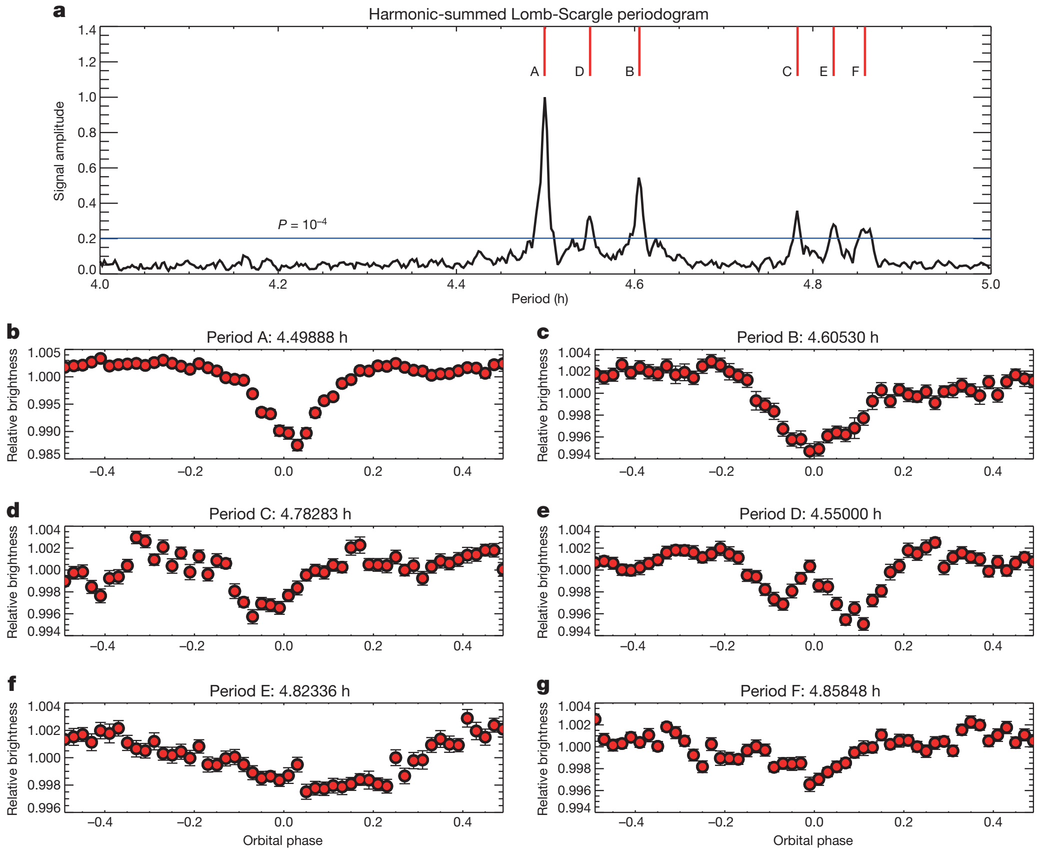

Figure 1 | Six notable periodicities found in the K2 data. **a**, Harmonic-summed Lomb–Scargle periodogram of the K2 data. We label the signals A–F in order of amplitude. **b–g**, K2 light curves folded on the six statistically significant ($P < 10^{-4}$) peaks and binned in phase. When plotting each fold, we sequentially removed stronger signals by dividing the data set by the binned, phase-folded light curves of the stronger signals. Note the differences in scales on the y-axes. Error bars are the standard errors of the mean within each bin. Brightness is shown relative to the median brightness measurement of WD 1145+017.

variable transit depths—behaviours similar to those seen here. These previously detected disintegrating planets are believed to be heated by the host star and to be losing mass through Parker-type thermal winds, in which the molecules condense into the obscuring dust observed to be occulting the star[23]. The solid bodies themselves are too small to detect, so the transits are dominated by the much larger dust clouds trailing the planets. The density of the dust cloud is presumed to be highly variable, which gives rise to the variable transit depths; in addition, a comet-like structure for the dust tails would explain the asymmetric transit shapes[20–22]. In the case of WD 1145+017, we have identified six stable periodicities in the K2 light curve that could be explained by occultations of the central star by dust clouds. We propose that each of these periodicities could be related to a different planetesimal (or to multiple fragments of one minor planet) that is orbiting the white dwarf near the tidal radius for rocky bodies. Each planetesimal would sporadically launch winds of metal gases, which are probably streaming freely from the planetesimal and which condense into dust clouds that periodically block the light of the white dwarf. A trailing dust cloud would explain the variable transit depths, the asymmetric transit profiles, and the longer-than-expected transit durations that we see in the light curves of WD 1145+017 (Supplementary Fig. 5).

We have simulated the dynamics of six planetesimals in circular orbits with periods of between 4.5 h and 4.9 h, and find that such a configuration is stable for at least 10^6 orbits, provided that their masses are smaller than or comparable to that of the dwarf planet Ceres ($1.6 \times 10^{-4}\, M_{\oplus}$, where $M_{\oplus}$ is the mass of the Earth), or possibly that of Haumea ($6.7 \times 10^{-4} M_{\oplus}$). These six planetesimals must be rocky (because gaseous bodies would overflow their Roche lobes, the region within which gaseous material can be stably retained by gravity), and must have densities greater than about $2\,\mathrm{g\,cm^{-3}}$ in order not to be tidally disrupted in such short-period orbits[24,25]. We also simulated the dynamics of two planetesimals in 1:1 mean motion orbital resonances (for example, in horseshoe orbits), and find that two different planetesimals in such orbits outbursting at different times could plausibly explain the difference in orbital phases that we see between the K2 light curve, the 11 April events, and the 17 April events.

We estimate that a rate of mass loss of roughly $8 \times 10^9\,\mathrm{g\,s^{-1}}$ is necessary to explain the transits that we see. Various refractory materials (including iron, fayalite, albite, and orthoclase) heated by the white dwarf could plausibly sublimate from a planetesimal roughly the size of Ceres at this rate, despite the white dwarf's relatively low luminosity (Supplementary Fig. 6). These metal vapours would be lost quickly via free-streaming winds or by Jeans escape (a classical thermal escape mechanism), because the planetesimal escape velocity is comparable to the metal vapour's thermal speed. We simulated a dust cloud condensed from the escaped metal vapour in orbit[20–22], and found that the radiation environment in which these planetesimals are situated can give rise to dust tails like those we infer from the ground-based transit observations (Supplementary Fig. 7). Collisions with disk debris[26] could also plausibly cause mass from the planetesimal to be lost into orbit.

A possible scenario for the formation of the disintegrating planetesimals involves minor planets that are left over from the progenitor stellar system, before the star evolved into a white dwarf[4,17]. In this scenario, mass loss from the host star disturbs the stability of the planetary system. This can lead to planets or smaller objects (such as asteroids or comets) being scattered inwards, into orbits with radii much smaller than the size of the progenitor star when it was an

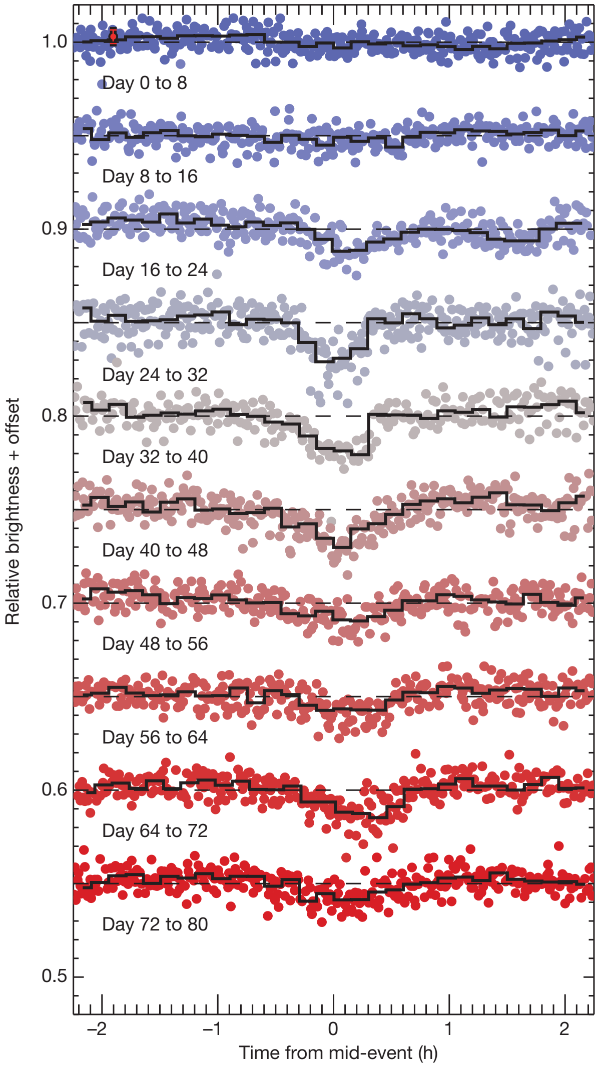

Figure 2 | Evolution of the K2 transit light curve over 80 days of observations. We show the K2 light curve broken into segments eight days in length and folded on the most notable, 4.5-h period. The individual data points (sampled with a 30-min integration time) are shown as dots, with different colours representing different time segments. The averaged light curve for each bin is shown as a solid black line. Each segment is vertically offset for clarity. We show the typical measurement uncertainty (standard deviation) with a red error bar on one data point in the upper left.

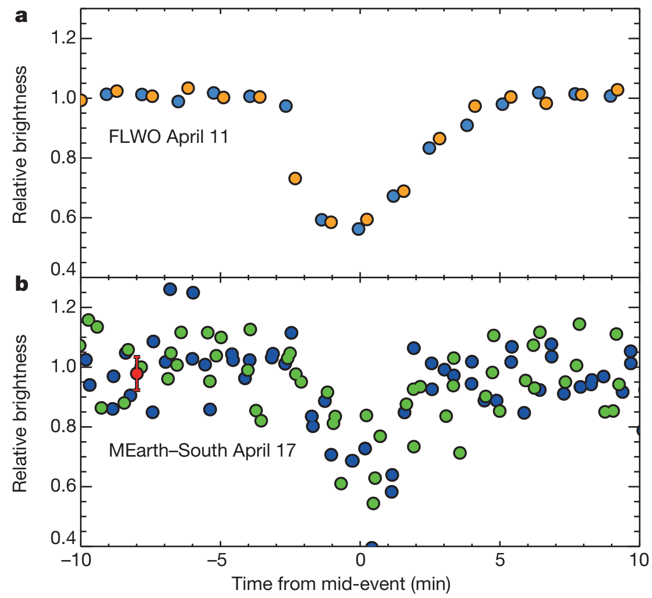

Figure 3 | Transit light curves measured from two ground-based facilities. **a**, Two events observed at FLWO with a separation equal to the 4.5-h period labelled A in Fig. 1, detected by K2. The first event is blue, and the second is orange. **b**, Two events observed by MEarth–South separated by the 4.5-h A-period. The first event is blue, and the second is green. The typical MEarth–South measurement uncertainty (standard deviation) is shown as a red error bar on one data point. The FLWO error bars are smaller than the size of the symbols.

evolving giant. A challenge for this model is placing the planetesimals in close concentric orbits so near the star without being totally disrupted. Current models suggest that planetesimals can be scattered inwards on highly eccentric orbits, tidally disrupted into elliptical dust disks, and circularized by Poynting–Robertson drag[27]. However, bodies that could release enough dust to cause the transits of WD 1145+017 that we have detected are too large to be circularized in this way. Recent theoretical work[28] on smaller bodies has shown that outgassing material can quickly circularize orbits, but it is unclear how this process scales to the massive bodies inferred here.

Our interpretation of this system is still uncertain. In particular, it is difficult to explain the phase shifts observed between the transits detected by ground-based photometry and those detected by K2; further ground-based observations are necessary to understand this effect. Another possible model is that small rings[27] or debris clouds of disrupted planetary material in a disk occasionally cross in front of the star and block its light. Although this could explain the large phase shifts that we see between the FLWO and MEarth transits, it is difficult to explain the highly stable periods ($\Delta P/P < 10^{-4}$) seen in the K2 data without massive orbiting bodies (Supplementary Fig. 8). Fortunately, the large transit depths make follow-up observations that could distinguish among these scenarios feasible both from the ground and from space. It might be possible to detect periodic infrared emission[29] from the orbiting planetesimals with the James Webb Space Telescope. Additional follow-up observations such as transit spectroscopy could constrain both scenarios by detecting the presence of molecules in the dust tails or the wavelength dependence of the dust scattering[30].

The evidence presented here—in particular, for the heavy-element pollution of the white dwarf WD 1145+017, for a warm dusty debris disk around this star, and for transits of disintegrating planetesimals—is consistent with a scenario, suggested over the past decade, in which the orbits of rocky bodies are occasionally perturbed and pass close enough to white dwarfs to become tidally disrupted, leading to the infall of debris onto the star's surface. Observations have shown that this scenario could be quite common among white dwarfs, with between 25% and 50% of white dwarfs showing evidence of heavy-element pollution. Our observations indicate that disintegrating planetesimals may be common as well (Supplementary Fig. 9). The transits of WD 1145+017 provide evidence of rocky, disintegrating bodies around a white dwarf, and support the planetesimal accretion model for the pollution of white dwarfs.

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

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Author Contributions A.V. processed and searched the K2 data, identified this system, analysed the K2 data for WD 1145+017 (with help from S.R., D.K., and J.T.W.), processed the MINERVA data, measured radial velocities (with help from W.R.B. and D.W.L.), and was the primary author of the manuscript. S.R. performed the dynamical calculations and dust simulations. W.R.B. obtained and reduced the MMT spectra. P.D. analysed the MMT spectra and SDSS photometry to measure spectroscopic properties. J.A.L. analysed archival photometric measurements and modelled the excess infrared emission. A.B. and D.W.L. obtained and processed the FLWO data. J.I. and D.C. obtained and processed the MEarth data. D.R.C. and C.B. obtained and processed the Keck data. R.A. calculated the systematics insensitive periodogram. L.S. calculated vapour pressures for some minerals with MAGMA. J.A.J., J.E., N.M., R.A.W., and J.T.W. made it possible to use MINERVA. J.A.J. provided scientific leadership.

Author Information The raw K2 data are available at http://archive.stsci.edu/k2/data_search/search.php under the identification number 201563164. The processed K2 data are available at https://archive.stsci.edu/missions/hlsp/k2sff/html/c01/ep201563164.html. We have opted not to make the code used in this work available. 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 A.V. (avanderburg@cfa.harvard.edu).