A tidal disruption event in the nearby ultra-luminous infrared galaxy F01004-2237

C. Tadhunter*, R. Spence, M. Rose, J. Mullaney and P. Crowther

Tidal disruption events (TDEs), in which stars are gravitationally disrupted as they pass close to the supermassive black holes in the centres of galaxies, are potentially important probes of strong gravity and accretion physics. Most TDEs have been discovered in large-area monitoring surveys of many thousands of galaxies, and a relatively low rate of one event every $10^3$–$10^5$ years per galaxy has been deduced. However, given the selection effects inherent in such surveys, considerable uncertainties remain about the conditions that favour TDEs. Here we report the detection of unusually strong and broad helium emission lines following a luminous optical flare in the nucleus of the nearby ultra-luminous infrared galaxy F01004-2237. This particular combination of variability and post-flare emission line spectrum is unlike any known supernova or active galactic nucleus. The most plausible explanation is a TDE — the first detected in a galaxy with an ongoing massive starburst. The fact that this event has been detected in repeat spectroscopic observations of a sample of 15 ultra-luminous infrared galaxies over a period of just 10 years suggests a much higher rate of TDEs in starburst galaxies than in the general galaxy population.

Ultra-luminous infrared galaxies (ULIRGs) have infrared luminosity $L_{\text{IR}} > 10^{12} L_{\odot}$, which are over $10^7$ times brighter than our own Milky Way galaxy. They are powered by supermassive black holes (SMBHs) accreting at a rate of several solar masses per year. The nearby ULIRG F01004-2237 (RA 01 h 02 m 50.007 s, dec. $-22^\circ$ 21 m 57.22 s (J2000); redshift $z=0.017835$) was observed using deep spectroscopic observations in September 2015 as part of a study of 15 ULIRGs to examine the importance of the warm gas outflows driven by active galactic nuclei (AGNs) in such objects. Many of its properties are typical of local ULIRGs, including relatively modest total stellar and SMBH masses (stellar mass $M_\star = 1.9 \times 10^{10}$ solar masses, $M_{\text{bh}}$; black hole mass $M_{\text{bh}} = 2.5 \times 10^7 M_\odot$), and evidence for AGN activity in the form of blue-shifted high ionization emission lines. However, it is unusual in the sense that it is one of the few ULIRGs in which Wolf–Rayet features have been detected at optical wavelengths, indicating the presence of a population of $\sim 3 \times 10^4$ Wolf–Rayet stars with ages $3$–$6$ Myr (see Supplementary Information). Also, unlike similar ULIRGs for which the central starburst regions are heavily enshrouded in dust, this source has a compact nucleus that is barely resolved in optical and ultraviolet observations with the Hubble Space Telescope (HST) and has been attributed to a population of stars that is both young ($<10$ Myr) and massive ($\sim 3 \times 10^5 M_\odot$). Together, these features suggest that we have an unusually clear view of the nuclear star-forming regions in F01004-2237.

Figure 1 compares the optical spectrum of F01004-2237 taken in 2015 with earlier spectra taken in 2000. In common with all the other published optical spectra of the source taken between 1995 and 2005 (Supplementary Information), those obtained in 2000 show emission lines characteristic of a composite of regions photo-ionized by hot stars and AGN, as well as a blend of $N$ ii and $He$ ii emission lines at $\lambda 4,660$ Å that is characteristic of Wolf–Rayet stars of type WN. However, the 2015 spectra are markedly different: the $\sim 4,660$–Å feature is a factor of 5.6 ± 1.1 stronger in flux compared with the 2000 spectra, and the blend has developed broad wings that extend up to $\sim 5,000$ km s$^{-1}$ to the red of the centroid of the narrow $He$ ii $\lambda 4,686$ component (that is, emission at wavelength $\lambda = 4,686$ Å); the $He$ i $\lambda 5,876$ line is also notably stronger (by a factor of 3.7 ± 0.2); and new $He$ i emission features have appeared at 3,889, 4,471, 6,678, and 7,065 Å. In contrast, the broad, blueshifted forbidden lines associated with the AGN-induced outflow have not varied significantly between the two epochs (Supplementary Information), whereas the $H\beta$ line has increased by a factor of 1.52 ± 0.12. If the broader component of the blend at $\lambda 4,660$ Å detected in the 2015 spectrum is attributed to $He$ ii $\lambda 4,686$, the ratio of the flux of this broad line to that of the broader $H\beta$ component is $He$ ii $\lambda 4,686$/H$\beta = 1.82 \pm 0.09$; however, the ratio is much larger if we consider only the component of $H\beta$ that has changed between the two epochs: $He$ ii $\lambda 4,686$/H$\beta = 5.3 \pm 0.85$. Similarly, we derive $He$ i $\lambda 5,876$/H$\beta = 0.46 \pm 0.04$ and $He$ i $\lambda 5,876$/H$\beta = 1.34 \pm 0.23$ when comparing the broad $He$ i $\lambda 5,876$ flux to the total and variable broad $H\beta$ component fluxes respectively. In comparison, typical quasars have $He$ ii $\lambda 4,686$/H$\beta \approx 0.02$ and $He$ i $\lambda 5,876$/H$\beta \approx 0.009$ for their wavelength-integrated broad emission line fluxes.

Alerted by our spectra to the possibility of an unusual transient event in the nucleus of F01004-2237, we examined the Catalina Sky Survey (CSS) database for evidence of variability in its optical continuum over the period 2003–2015. The resulting V-band light curve for F01004-2237 is presented in Fig. 2, where it is compared with those of the other 14 ULIRGs in our spectroscopic sample. Owing to their low spatial resolution, the Catalina measurements include a substantial fraction of the total light of each galaxy, not just that of the nucleus. Whereas the light curves of all the other ULIRGs are flat within ±0.1 magnitudes, that of F01004-2237 showed a significant spike in 2010, when it was 0.45 ± 0.02 magnitudes (a factor of 1.51 ± 0.03) brighter than the average of the four earliest epochs.

A supernova origin for the phenomenon observed in F01004-2237 is ruled out by the fact that the light curve and post-flare spectrum are unlike any known supernova. Although high rates of supernova events are expected in ULIRGs because of their high star formation rates ($>100 M_\odot$ yr$^{-1}$), and a rate of $4 \pm 2$ yr$^{-1}$ has been measured for the closest ULIRG, Arp220, using radio observations, most core-collapse supernovae would not be sufficiently bright to detect in the integrated-light CSS observations of F01004-2237. The peak luminosity of the flare in F01004-2237 ($M_V < -20.1$ mag) approaches that...
As far as we are aware, the variability observed in F01004-2237, in which the broad helium emission lines dominate the high-state spectrum, is without precedent for an AGN. Moreover, the He ii λ4686/Hβ and He i λ5876/Hβ ratios measured for the broad, variable emission lines in F01004-2237 are significantly higher than those measured for even the innermost, highest ionization zones of typical AGN broad line regions (He ii λ4686/Hβ ≈ 1; He i λ5876/Hβ ≈ 0.5–0.6)\textsuperscript{16,17}, as represented by extreme red and blue wings of the emission line profiles.

Although not typical of AGN, unusually strong and variable broad He i and He ii lines have been observed in some tidal disruption events (TDEs)\textsuperscript{18–20}. Therefore, the most plausible explanation for the unusual properties of F01004-2237 is a TDE that took place ~5 years before the 2015 spectroscopic observations. The absolute V-band luminosity of the peak of the transient event (M_v < −20.1 mag) is characteristic of TDEs\textsuperscript{18}. However, the flare in F01004-2237 is unusually prolonged compared with typical TDEs\textsuperscript{18}, with the light curve appearing to flatten at late times rather than follow the (t/\(t_{\text{peak}}\))\textsuperscript{−5/3} decline predicted by theory (\(t_{\text{peak}}\) is the time taken for the flare to reach peak brightness following the disruption of the star). To explain the slow decline in the light curve of F01004-2237 for the first 3 years following the peak brightness, a relatively long \(t_{\text{peak}}\) would be required (\(t_{\text{peak}}\approx 1\) yr). Assuming that the star was disrupted by a single SMBH of mass M_\(\odot\) = 2.5 × 10\(^6\)M_\(\odot\), this in turn would favour a relatively high polytropic index (\(\gamma \approx 5/3\))\textsuperscript{21}, corresponding to a low-mass star (M_\(\odot\) ≲ 0.3M_\(\odot\)) with a fully convective envelope. The prolonged nature of the continuum flare might also help to explain why we observe emission lines from the debris 5 years after the event, whereas in some other well-observed TDEs with shorter \(t_{\text{peak}}\), the emission lines had become undetectable on such timescales. Explaining the apparent flattening of the light curve ~5 years after the peak — albeit based on only one photometric point with a relatively large error bar — is more challenging, but it is notable that flattening or re-brightening has recently been detected in the light curves of some other TDEs\textsuperscript{22–23}.

The cause of the strong helium lines detected in the optical spectra of TDEs is the subject of debate. Recently, it has been proposed that, even in the case of solar abundances, the ratio of the helium to hydrogen lines might be substantially enhanced if the emitting gas is both matter-bounded and has a sufficiently high density that the Balmer lines of hydrogen are optically thick\textsuperscript{24}. In the case of F01004-2237, this explanation is favoured over the alternative that the He/H abundance ratio is substantially super-solar in the tidal debris\textsuperscript{25}. This is because such an enhanced helium abundance would require the disrupted star to be sufficiently massive (>10M_\(\odot\)) that it had converted much of its hydrogen to helium over the <10-Myr lifetime of the nuclear star cluster; the tidal disruption of such a massive star is expected to be extremely rare for a typical initial mass function.

The detection of one event in a sample of just 15 ULIRGs over a period of ~10 years suggests that the rate of TDEs in such objects is orders of magnitude higher than the 10\(^{−5}–10^{−4}\) TDE yr\(^{−1}\) galaxy\(^{−1}\) deduced for the field galaxy population\textsuperscript{26–29}, and perhaps as high as 10\(^{−3}\) TDE yr\(^{−1}\) galaxy\(^{−1}\). This is also higher than the TDE rate recently deduced for the population of post-starburst galaxies (10\(^{−3}\) TDE yr\(^{−1}\) galaxy\(^{−1}\))\textsuperscript{26}. However, considering that we have an unusually clear view of the nucleus in F01004-2237, whereas in the remainder of our sample the nuclear regions are likely to be heavily obscured by dust at optical wavelengths, the true rate of TDEs in the ULIRG population could be higher still (~10\(^{−1}\) TDE yr\(^{−1}\) galaxy\(^{−1}\)).

Several mechanisms could enhance the rate of TDEs in ULIRGs, including concentrated nuclear star formation leading to high densities of stars close to the central SMBHs\textsuperscript{27}, the formation of close black hole binaries comprising the SMBHs of the progenitor galaxies\textsuperscript{28}, and black hole recoils that might follow the coalescence of such binaries\textsuperscript{29}. We note that the disruptive effect of a SMBH binary on...
the debris stream of the TDE\textsuperscript{th} might also help to explain the fact that the flare observed in F0104-2237 is unusually prolonged.

The simultaneous detection of a TDE, a massive young stellar population and an AGN in the nucleus of a ULIRG provides striking evidence of the close proximity of star formation and growing SMBHs at the centres of starburst galaxies. The TDE flare in F0104-2237 has required the consumption of a total mass of 0.02–0.61 M\(_\odot\) by its SMBH (see Methods). This corresponds to an average accretion rate of 2 \times 10^{-4} < \dot{M} < 6.1 \times 10^{-2} M\(_\odot\) yr\(^{-1}\), assuming a TDE rate in the range 10^{-2} < \dot{R}_{\text{TDE}} < 10^{-1} yr\(^{-1}\). If this rate were maintained for the ~100–Myr timescale typical of starbursts in ULIRGs, the SMBH in F0104-2237 would grow in mass by between 2 \times 10^0 M\(_\odot\) and 6.1 \times 10^0 M\(_\odot\) (0.1–25\%) owing to TDEs alone. Although not sufficient to trigger a luminous, quasar-like episode of AGN activity, the integrated photonizing effect of the frequent TDE flares would be capable of sustaining lower-level LINER- or Seyfert-like narrow emission-line activity in ULIRGs in periods of relative quiescence, when the rates of direct gas accretion onto the SMBH are low.

Methods

We have estimated the absolute magnitude of the peak of the flare in F0104-2237 by assuming a cosmology with \(H_0 = 73.0 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.27\), \(\Omega_\Lambda = 0.73\), which results in a luminosity distance of \(D_L = 523 \text{ Mpc}\) for the redshift of F0104-2237 (\(z = 0.117835\)). The spectral energy distribution (SED) of the flare is unknown, but if we assume that it follows the Rayleigh–Jeans tail of a hot black body (temperature \(T > 20,000 K\)), the K-correction is 0.24 magnitudes. Applying this K-correction and a Galactic extinction correction of \(A_V = 0.05\) mag, we derive an absolute magnitude for the peak of the flare of \(M_V = -20.1\) mag. However, this is likely to represent a lower limit on the luminosity, since we have not corrected for intrinsic dust extinction.

To calculate the bolometric luminosity associated with the flare, it is necessary to assume a bolometric correction factor (BCF) to convert between the V-band monochromatic luminosity and the bolometric luminosity. This BCF depends on the (unknown) SED of the flare. Assuming that the SED of the flare in F0104-2237 is similar to that of other TDEs with multi-wavelength photometry and follows a black body with temperature in the range 10–50 K, the BCF will be in the range 1.75 < \(L_{\text{bol}}/L_V\) < 60. For comparison, typical AGN have \(L_{\text{bol}}/L_V\) \approx 8.

Considering the full range of likely black body temperatures, the peak bolometric luminosity of the TDE flare in F0104-2237 falls in the range 4 \times 10^4 < \(L_{\text{bol}}\) (peak) < 1.4 \times 10^6 erg s\(^{-1}\), and performing a simple trapezium-rule integration of the light curve, the total energy associated with the flare up to the end of 2015 was in the range 3 \times 10^{48} < E_{\text{tot}} < 1.1 \times 10^{49} erg.

The mass consumed by the black hole in order to produce the flare is \(M_{\text{SNBH}} = E_{\text{tot}}/(c^2\eta)\), where \(\eta\) is the efficiency. Therefore, for a typical SMBH accretion disk efficiency of \(\eta = 0.1\), the total mass consumed so far to produce the TDE flare observed in F0104-2237 is in the range 0.02 < \(M_{\text{SNBH}} < 0.61 M_{\odot}\).

Data availability. The data used to make the photometric light curve presented in Fig. 2 are available from the CSS data release 2 website (http://nnumaku.caltech.edu/cgi-bin/getcssconedb_release_img.cgi); the data that support Fig. 1 within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Received 23 September 2016; accepted 24 January 2017; published 1 March 2017

References

1. Rees, M. J. Tidal disruption of stars by black holes of 10\(^-10^5\) M\(_\odot\) in nearby galaxies. Nature 333, 523–528 (1988).
2. Donley, J. L., Brandt, W. N., Eracleous, M. & Boller, Th. Large-amplitude X-ray outbursts from galactic nuclei: a systematic survey using ROSAT archival data. Astron. J. 124, 1308–1321 (2002).
3. Gezari, S. et al. UV/optical detections of candidate tidal disruption events by GALEX and CEHTLS. Astrophys. J. 676, 944–950 (2008).
4. van Velzen, S. & Farrar, G. R. Measurement of the rate of stellar tidal disruption flares. Astrophys. J. 792, 53–61 (2014).
5. Sanders, D. B. & Mirabel, I. F. Luminous infrared galaxies. Annu. Rev. Astron. Astrophys. 34, 749–792 (1996).
6. Rodríguez Zaurín, J., Tadhunter, C. N., Rose, M. & Holt, J. The importance of warm, AGN-driven outflows in the nuclear regions nearby ULIRGs. Mon. Not. R. Astron. Soc. 432, 138–166 (2013).
7. Rodríguez Zaurín, J., Tadhunter, C. N. & González Delgado, R. M. The properties of the stellar populations in ULIRGs – I. Sample, data and spectral synthesis modeling. Mon. Not. R. Astron. Soc. 400, 1139–1180 (2009).
8. Daszynski, M. M. et al. The dynamical properties of ultraluminous infrared galaxies II. Tracers of dynamical evolution and end products of local ultraluminous mergers. Astrophys. J. 651, 835–852 (2006).
9. Armus, L., Heckman, T. M. & Miley, G. K. The detection of Wolf-Rayet stars in a very powerful far-infrared galaxy: direct evidence for a starburst. Astrophys. J. 326, 145–149 (1988).
10. Surace, J. A., Sanders, D., Vacca, W. D., Veilleux, S. & Mazzarella, J. M. HST/ WFPC2 observations of warm ultraluminous infrared galaxies. Astrophys. J. 492, 116–136 (1998).
11. vanden Berk, D. E. et al. Composite quasar spectra from the Sloan Digital Sky Survey. Astron. J. 122, 549–564 (2001).
12. Drake, A. J. et al. First results from the Catalina Real-time Transient Survey. Astrophys. J. 696, 870–884 (2009).
13. Lonsdale, C. J. et al. VLBI images of 49 radio supernovae in Arp 220. Astrophys. J. 649, 185–193 (2006).
14. La Massa, S. M. et al. The discovery of the first changing look quasar: new insights into the physics and phenomenology of active galactic nucleus. Astrophys. J. 800, 144–153 (2015).
15. MacLeod, C. L. et al. A systematic search for changing look quasars in SDSS. Mon. Not. R. Astron. Soc. 457, 389–404 (2016).
16. Gaskell, C. M. & Rojas Lobos, P. A. The production of strong broad He ii emission after the tidal disruption of a main sequence star by a supermassive black hole. Mon. Not. R. Astron. Soc. 438, 136–140 (2014).
17. Crenshaw, D. M. Profiles and profile ratios in Seyfert 1 galaxies. Astrophys. J. Suppl. 62, 821–838 (1986).
18. Gezari, S. et al. An ultraviolet–optical flare from the tidal disruption of a helium-rich stellar core. Nature 485, 217–220 (2012).
19. Arcavi, I. et al. A continuum of He- to He-rich tidal disruption events with a preference for E+A galaxies. Astrophys. J. 793, 38–53 (2014).
LETTERS

20. Holoien, T. W.-S. et al. Six months of multiwavelength follow-up of the tidal disruption candidate ASASSN-14li and implied TDE rates from ASAS-SN. *Mon. Not. R. Astron. Soc.* **455**, 2918–2935 (2016).
21. Guillochon, J. & Ramirez-Ruiz, E. Hydrodynamic simulations to determine the feeding radio of black holes by the tidal disruption of stars: the importance of impact factor and stellar structure. *Astrophys. J.* **767**, 25–39 (2013).
22. Brown, J. S. et al. The long term evolution of ASASSN-14li. Preprint at https://arxiv.org/abs/1609.04403 (2016).
23. Leloudas, G. et al. The superluminous transient ASASSN-15lh as a tidal disruption event from a Kerr black hole. *Nat. Astron.* **1**, 0002 (2017).
24. Roth, N., Kasen, D., Guillochon, J. & Ramirez-Ruiz, E. The X-ray through optical fluxes and line strengths of tidal disruption events. *Astrophys. J.* **827**, 3–18 (2016).
25. Kochanek, C. S. Abundance anomalies in tidal disruption events. *Mon. Not. R. Astron. Soc.* **458**, 127–134 (2016).
26. French, K., Arcavi, I. & Zabludoff, A. Tidal disruption events prefer unusual host galaxies. *Astrophys. J.* **818**, L21–L26 (2016).
27. Stone, N. C. & van Velzen, S. An enhanced rate of tidal disruption in the centrally overdense E+A galaxy NGC3156. *Astrophys. J.* **825**, 14–20 (2016).
28. Liu, F. K. & Chen, X. Enhanced off-centre tidal disruptions by supermassive black holes in merging galaxies. *Astrophys. J.* **767**, 18–28 (2013).
29. Stone, N. & Loeb, A. Prompt tidal disruption of stars as a signature of supermassive black hole coalescence. *Mon. Not. R. Astron. Soc.* **412**, 73–80 (2011).
30. Coughlin, E. R., Armitage, P. J., Nixon, C. & Begelman, M. C. Tidal disruption events from supermassive black hole binaries. *Mon. Not. R. Astron. Soc.* **465**, 3840–3864 (2017).

Acknowledgements
The William Herschel Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canaria. Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the Data Archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555, these observations are associated with program no. 8190. This project made use of data obtained by the Catalina Sky Survey. C.T., R.S., M.R. and P.C. acknowledge financial support from the UK Science and Technology Facilities Council. We thank J. Maund for discussions about the possibility of a supernova origin for the flare.

Author contributions
C.T. and R.S. led the project and the scientific interpretation of the data, and C.T. wrote the text of the paper. M.R. extracted the Catalina Sky Survey light curves and contributed to the general interpretation of the emission line spectra. J.M. and P.C. contributed equally to the analysis and interpretation of the results.

Additional information
Supplementary information is available for this paper. Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.T.

How to cite this article: Tadhunter, C. et al. A tidal disruption event in the nearby ultra-luminous infrared galaxy F01004-2237. *Nat. Astron.* **1**, 0061 (2017).

Competing interests
The authors declare no competing financial interests.