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A dust-enshrouded tidal disruption event with a resolved radio jet in a galaxy merger

S. Mattila^{1,2*}, M. Pérez-Torres^{3,4*}, A. Efstathiou⁵, P. Mimica⁶, M. Fraser^{7,8}, E. Kankare⁹, A. Alberdi³, M. Á. Aloy⁶, T. Heikkilä¹, P. G. Jonker^{10,11}, P. Lundqvist¹², I. Martí-Vidal¹³, W. P. S. Meikle¹⁴, C. Romero-Cañizales^{15,16}, S. J. Smartt⁹, S. Tsygankov¹, E. Varenius^{13,17}, A. Alonso-Herrero¹⁸, M. Bondi¹⁹, C. Fransson¹², R. Herrero-Illana²⁰, T. Kangas^{1,21}, R. Kotak^{1,9}, N. Ramírez-Olivencia³, P. Väisänen^{22,23}, R. J. Beswick¹⁷, D. L. Clements¹⁴, R. Greimel²⁴, J. Harmanen¹, J. Kotilainen^{2,1}, K. Nandra²⁵, T. Reynolds¹, S. Ryder²⁶, N. A. Walton⁸, K. Wiik¹, G. Östlin¹²

¹Tuorla Observatory, Department of Physics and Astronomy, FI-20014 University of Turku, Finland. ²Finnish Centre for Astronomy with ESO (FINCA), FI-20014 University of Turku, Finland. ³Instituto de Astrofísica de Andalucía - Consejo Superior de Investigaciones Científicas (CSIC), PO Box 3004, 18008, Granada, Spain. ⁴Departamento de Física Teórica, Facultad de Ciencias, Universidad de Zaragoza, 50019, Zaragoza, Spain. ⁵School of Sciences, European University Cyprus, Diogenes Street, Engomi, 1516 Nicosia, Cyprus. ⁶Departament d'Astronomia i Astrofísica, Universitat de València Estudi General, 46100 Burjassot, València, Spain. ⁷School of Physics, O'Brien Centre for Science North, University College Dublin, Belfield, Dublin 4, Ireland. ⁸Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK. ⁹Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, UK. ¹⁰SRON, Netherlands Institute for Space Research, Sorbonnelaan 2, NL-3584 CA Utrecht, the Netherlands. ¹¹Department of Astrophysics/Institute for Mathematics, Astrophysics and Particle Physics, Radboud University, P.O. Box 9010, 6500GL Nijmegen, Netherlands. ¹²Department of Astronomy and The Oskar Klein Centre, AlbaNova University Center, Stockholm University, SE-106 91 Stockholm, Sweden. ¹³Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden. ¹⁴Astrophysics Group, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, UK. ¹⁵Chinese Academy of Sciences South America Center for Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China. ¹⁶Núcleo de Astronomía de la Facultad de Ingeniería y Ciencias, Universidad Diego Portales, Av. Ejército 441, 8370191 Santiago, Chile. ¹⁷Jodrell Bank Centre for Astrophysics, The University of Manchester, Oxford Rd, Manchester M13 9PL, UK. ¹⁸Centro de Astrobiología (CSIC-INTA), ESAC Campus, E-28692 Villanueva de la Cañada, Madrid, Spain. ¹⁹Istituto di Radioastronomia - Istituto Nazionale di Astrofisica (INAF), Bologna, via P. Gobetti 101, 40129, Bologna, Italy. ²⁰European Southern Observatory, Alonso de Córdova 3107, Vitacura, Casilla 19001, Santiago de Chile, Chile. ²¹Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA. ²²South African Astronomical Observatory, PO Box 9, Observatory 7935, Cape Town, South Africa. ²³Southern African Large Telescope, PO Box 9 Observatory 7935, Cape Town, South Africa. ²⁴Institute of Physics, Department for Geophysics, Astrophysics, and Meteorology, NAWI Graz, Universitätsplatz 5, 8010 Graz, Austria. ²⁵Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße, 85748, Garching, Germany. ²⁶Australian Astronomical Observatory, 105 Delhi Rd, North Ryde, NSW 2113, Australia.

*These authors contributed equally to this work.

[†]Corresponding author. Email: sepma@utu.fi (S.M.); torres@iaa.es (M.P.-T.)

Tidal disruption events (TDEs) are transient flares produced when a star is ripped apart by the gravitational field of a supermassive black hole (SMBH). We have observed a transient source in the western nucleus of the merging galaxy pair Arp 299 that radiated $>1.5 \times 10^{52}$ erg in the infrared and radio but was not luminous at optical or x-ray wavelengths. We interpret this as a TDE with much of its emission reradiated at infrared wavelengths by dust. Efficient reprocessing by dense gas and dust may explain the difference between theoretical predictions and observed luminosities of TDEs. The radio observations resolve an expanding and decelerating jet, probing the jet formation and evolution around a SMBH.

The tidal disruption of stars by supermassive black holes (SMBH) in the nuclei of galaxies was predicted theoretically 30 years ago (*1, 2*). In a tidal disruption event (TDE), roughly half of the star's mass is ejected, whereas the other half is accreted onto the SMBH, generating a bright flare that is normally detected at x-ray, ultraviolet (UV), and optical wavelengths (*3–5*). TDEs are also expected to produce radio transients, lasting from months to years and including the formation of a relativistic jet, if a fraction of the accretion power is channelled into a relativistic outflow (*6*). TDEs provide a means of probing central black holes in quiescent galaxies and testing scenarios of accretion onto SMBHs and jet formation (*3, 6*).

On 2005 January 30, we discovered a bright transient in the near-infrared (IR) (*7*) coincident with the western nucleus

B1 (Fig. 1) of the nearby [44.8 Mpc (*7*)] luminous infrared galaxy (LIRG) Arp 299. In galaxy mergers like Arp 299, large amounts of gas fall into the central regions, triggering a starburst. The long-term radio variability (*8*) and the IR spectral energy distribution (SED) (*9*) indicate a very high core-collapse supernova (SN) rate of $\sim 0.3 \text{ year}^{-1}$ within the B1 nucleus. The B1 region also harbors a Compton-thick active galactic nucleus (AGN) that has been seen directly only in hard x-rays (*10*). This is consistent with an extremely high extinction A_V of ~ 460 magnitudes through an almost edge-on AGN torus (*11*). Galaxy mergers like Arp 299 are expected to have TDE rates several orders of magnitude higher than in field galaxies, albeit for relatively short periods of time [$\sim 3 \times 10^5 \text{ year}$ (*12*)].

The transient source (henceforth Arp 299-B AT1) was

discovered as part of a near-IR (2.2 μm) survey for highly obscured SNe in starburst galaxies (13). Over the following years it became luminous at IR and radio wavelengths, but was much fainter in the optical (7), implying substantial extinction by interstellar dust in Arp 299. Our follow-up observations show that the nuclear outburst had a peak brightness comparable to the entire galaxy nucleus at both near-IR and radio wavelengths (Fig. 1) (8). Based on the energetics and multi-wavelength behavior of Arp 299-B AT1 over a decade of observations (Figs. 1 to 3), two broad scenarios to explain its origin are plausible: (i) an event unrelated to the SMBH, such as an extremely energetic SN, or a gamma-ray burst; or (ii) accretion-induced SMBH variability, such as an AGN flare, or a TDE.

High angular resolution [100 milliarcseconds (mas)], adaptive optics assisted, near-IR imaging observations from the Gemini-North telescope (7) show that Arp 299-B AT1 remained stationary and coincident (within 37 mas, corresponding to ~ 8 pc projected distance) with the near-IR *K*-band nucleus, as seen in pre-outburst imaging from the *Hubble* Space Telescope (*HST*) (Fig. 1). Radio observations obtained with very long baseline interferometry (VLBI) constrain its position with milliarcsecond angular precision (7). Pre-discovery Very Long Baseline Array (VLBA) observations showed several compact sources at 2.3 GHz within the central few parsecs of the B1 nucleus, but no counterparts at higher frequencies (14). A new compact radio source was detected on 2005 July 17 at 8.4 GHz with the VLBA (7, 14). The coincidence of the near-IR and VLBI positions, together with the appearance of the VLBI source soon after the near-IR detection and their subsequent evolution (see below; 7), point to a common origin for both.

High angular resolution radio observations of Arp 299-B AT1 with VLBI show that the initially unresolved radio source developed a prominent extended, jet-like structure, which became evident in images taken from 2011 onwards (Fig. 1 (7)). The measured average apparent expansion speed of the forward shock of the jet is $(0.25 \pm 0.03)c$ between 2005 and 2015 (7), where c is the speed of light. The radio morphology, evolution and expansion velocity of Arp 299-B AT1 rule out a SN origin. Similarly, a gamma-ray burst is inconsistent with both the observed peak flux density and time to reach that peak in the radio (15). Therefore, the most likely explanation is that Arp 299-B AT1 is linked to an accretion event onto the SMBH. The persistent 2.3 GHz radio emission most likely corresponds to the quiescent AGN core (7).

The multi frequency radio light curves of Arp 299-B AT1 (Fig. 2) are well reproduced by a model (16) of a jet powered by accretion of part of a tidally disrupted star onto a SMBH (7). The jet initially moves at relativistic speeds $\sim 0.995 c$, but after a distance of less than $\sim 10^{17}$ cm (corresponding to ~ 760 days after the burst) it has already decelerated significantly

to $\sim 0.22 c$, in agreement with expectations for TDE-driven jets (6). The apparent speed of the jet indicated by the VLBI observations, together with the non-detection of the counterjet, constrains the jet viewing angle, θ_{obs} , to be within a narrow range: 25° - 35° (7). If the jet had been launched by a pre-existing AGN, its viewing angle with respect to our line-of-sight should have been close to 90° , as the AGN torus is seen almost edge-on (11), and a counterjet should have also been detected (7). However, a radio jet associated with a TDE does not necessarily have to be perpendicular to the pre-existing AGN accretion disc (17). We therefore identify the observed radio jet as being launched by a TDE. No direct imaging has previously shown an expanding jet in a TDE, and its likely presence has been inferred based on unresolved radio observations only in the cases of ASASSN-14li (18, 19), IGR J12580+0134 (20), and Swift J164449.3+573451 (hereafter Sw J1644+57) (21). Our VLBI observations show a resolved, expanding radio jet in a TDE, in accordance with theoretical expectations (6).

The intrinsic (i.e., beaming-corrected) kinetic energy of the jet required to reproduce the radio light curves (Fig. 2) is $(1.8 \pm 0.9) \times 10^{51}$ erg (7), similar to the case of the relativistic TDE Sw J1644+57 (16). The rise of the radio emission at high frequencies in less than about 200 days and the significant delay of the lower-frequency radio emission (7) implies the existence of substantial external absorption, consistent with the jet being embedded in the very dense nuclear medium of the AGN, which has a constant thermal electron number density $\sim 4 \times 10^4 \text{ cm}^{-3}$ up to a distance 6.3×10^{17} cm from the central engine (7).

Observations from the ground and the *Spitzer* Space Telescope show that the IR SED of Arp 299-B AT1 and its evolution from 2005 until 2016 can be explained by a single blackbody component (Fig. 3). The blackbody radius expands from 0.04 pc to 0.13 pc between May 2005 and Jan. 2012 while its temperature cools from ~ 1050 K to ~ 750 K. The size, temperature and peak luminosity ($6 \times 10^{43} \text{ erg s}^{-1}$) of the IR emitting region agrees well with both theoretical predictions and observations of thermal emission from warm dust surrounding TDEs (22, 23). Therefore, the IR SED and its evolution are consistent with absorption and reradiation of the UV and optical light from Arp 299-B AT1 by local dust.

We modeled the IR SED of the pre- and post-outburst (734 days after the first IR detection) components of Arp 299-B1 using radiative transfer models for the emission from a starburst within the galaxy, and from a dusty torus, as predicted by the standard unified model for AGN, including also the effect of dust in the polar regions of the torus (Fig. 4) (24). The model luminosities of the starburst and AGN dusty torus components remain constant within the uncertainties, whereas the luminosity of the polar dust component is found

to increase by a factor of ~ 15 after the outburst, and the corresponding polar dust temperature increases from 500 to 900 K. Therefore, the observed IR SED of Arp 299-B AT1 can be most plausibly explained by reradiation by optically thick dust clouds in the polar regions of the torus, which suffer from a relatively low foreground extinction within Arp 299-B1 (7).

Integrating the luminosity of Arp 299-B AT1 over the period 2005–2016 (Fig. 3) yields a total radiated energy of about 1.5×10^{52} erg. However, a significant fraction of the total energy emitted by the transient can be expected to be scattered, absorbed, and reradiated at substantially longer IR wavelengths by the dusty torus. We estimate that the fraction of energy that heated the polar dust was in the range 23%–78% (7). Thus the total radiated energy of Arp 299-B AT1 was $(1.9\text{--}6.5) \times 10^{52}$ erg, which requires a disruption of a star with a mass of about 1.9–6.5 solar masses (M_{\odot}), assuming a standard accreted fraction and radiative efficiency (7). Stars in this mass range can be disrupted by the $\sim 2 \times 10^7 M_{\odot}$ SMBH in Arp 299-B1 (10, 25). The kinetic energy of the jet is expected to be about 1% of the total energy (6), which agrees well with our estimated kinetic energy for the radio jet of Arp 299-B AT1 (7).

In addition to Arp 299-B AT1, the only other TDE candidates (although with debated nature) to have an observed radiated energy on the order of 10^{52} erg are ASASSN-15lh (26, 27) and possibly transients similar to PS1-10adi (28). The high energy of ASASSN-15lh was originally proposed to be the result of an energetic SN (26), but was later explained as a tidal disruption by a high mass ($7.6 \times 10^8 M_{\odot}$), rapidly rotating black hole (27). In the case of PS1-10adi the large radiated energy was proposed to arise from the interaction of either an expanding TDE, or SN ejecta, with the dense medium in the nuclear environment (28). Arp 299-B AT1 was most plausibly the result of the disruption of a star more massive than about $2 M_{\odot}$ in a very dense medium. The soft x-ray photons produced by the event were efficiently reprocessed into UV and optical photons by the dense gas, and further to IR wavelengths by dust in the nuclear environment. Efficient reprocessing of the energy might thus resolve the outstanding problem of observed luminosities of optically detected TDEs being generally lower than predicted (29).

The case of Arp 299-B AT1 suggests that recently formed massive stars are being accreted onto the SMBH in such environments, resulting in TDEs injecting large amounts of energy into their surroundings. However, events similar to Arp 299-B AT1 may remain hidden within dusty and dense environments, and would not be detectable by optical, UV or soft x-ray observations. The recent discovery of another TDE candidate in the nucleus of the luminous infrared galaxy IRAS F01004-2237 (30) yields further support for an enhanced rate

of TDEs in such galaxies, which could be missed due to dust extinction. Such TDEs from relatively massive, newly formed stars might provide a large radiative feedback, especially at higher redshifts where galaxy mergers and LIRGs are more common (31).

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60142, 80105, 90031, 90157, 10086, 11076), from the EVN data archive at <http://archive.jive.nl/scripts/listarch.php> (proposal IDs EP063, EP068, EP075, EP087, GP053), the NRAO data archive at <https://archive.nrao.edu/archive/advquery.jsp> (proposal IDs: BPU027, BP202, AC0749), the NOT data archive at <http://www.not.iac.es/archive/>, the Gemini Observatory Archive at <https://archive.gemini.edu/searchform> (programs: GN-2008B-Q-32, GN-2009A-Q-12, GN-2009B-Q-23, GN-2010A-Q-40, GN-2011A-Q-48 and GN-2011B-Q-73), the Hubble Legacy Archive at <https://hla.stsci.edu/hlview.html>, the Chandra Data Archive at <http://cxc.harvard.edu/cda/> (OBSIDs 1641, 6227, 15077 and 15619), the XMM-Newton Science Archive at <http://nxsa.esac.esa.int/nxsa-web/> (ObsId 0679381101), the Isaac Newton Group Archive at <http://casu.asi.cam.ac.uk/casuadc/ingarch/query>, and the United Kingdom Infrared Telescope Archive at http://casu.asi.cam.ac.uk/casuclient/ukirt_arch/. The radiative transfer models are part of the CYGNUS project with the model grids available at <http://ahpc.euc.ac.cy/index.php/resources/cygnus>. The results of the hydrodynamic and radiative simulations used for modeling the radio light curves, and the data and Python code used to produce Fig. 2A and fig. S6 are available at <https://www.uv.es/mimica/doc>. The Python code used for determining the allowed values for the viewing angle of the radio jet and producing fig. S7 is available at <https://github.com/mapereztorres/rad-trans-theta>. Full details of all data and software used in this paper are given in the supplementary materials.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/cgi/content/full/science.aao4669/DC1

Materials and Methods

Figs. S1 to S7

Tables S1 to S8

References (33–99)

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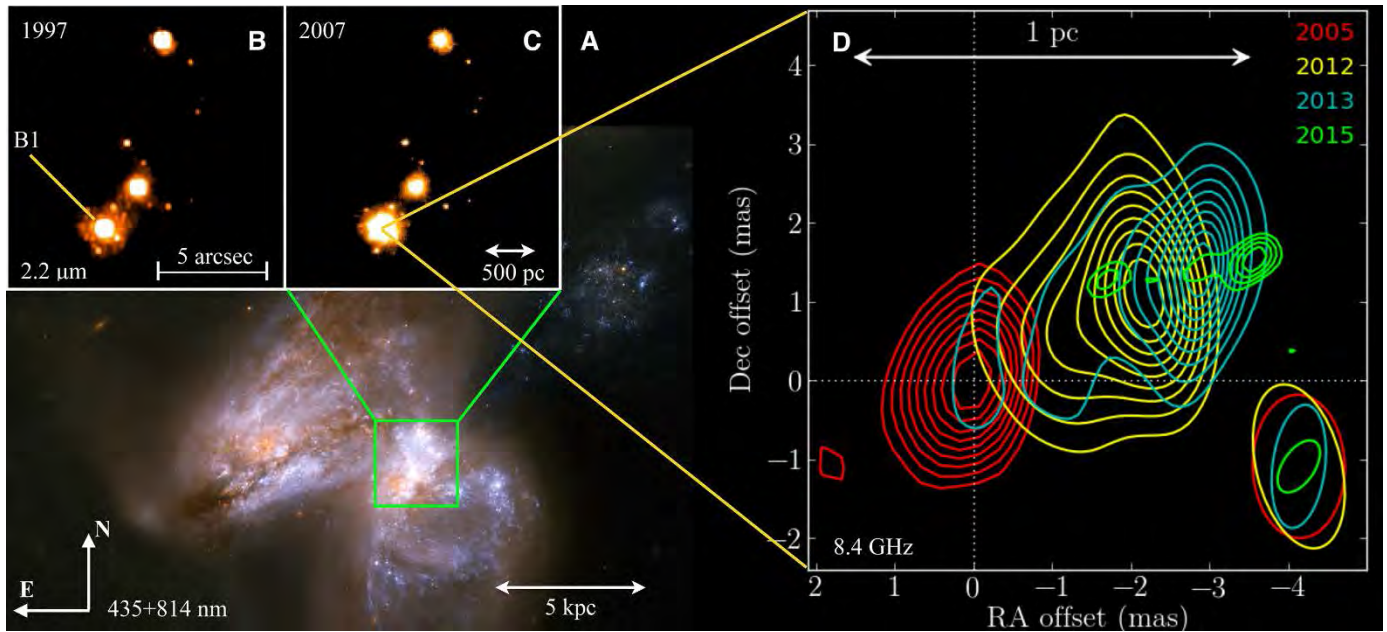


Fig. 1. The transient Arp 299-B AT1 and its host galaxy Arp 299. (A) A color-composite optical image from the Hubble Space Telescope (*HST*), with high resolution, 12.5×13 arcsecond size near-infrared $2.2 \mu\text{m}$ images [insets (B) and (C)] showing the brightening of the B1 nucleus (7). (D) The evolution of the radio morphology as imaged with Very Long Baseline Interferometry (VLBI) at 8.4 GHz (7×7 milliarcsecond region centered at the 8.4 GHz peak position in 2005, RA = 11h28m30.9875529s, Dec = $58^\circ 33' 40''.783601$ (J2000.0), indicated by the dotted lines). The VLBI images are aligned with an astrometric precision better than $50 \mu\text{as}$. The initially unresolved radio source develops into a resolved jet structure a few years after the explosion, with the center of the radio emission moving westward with time (7). The radio beam size for each epoch is indicated in the lower-right corner.

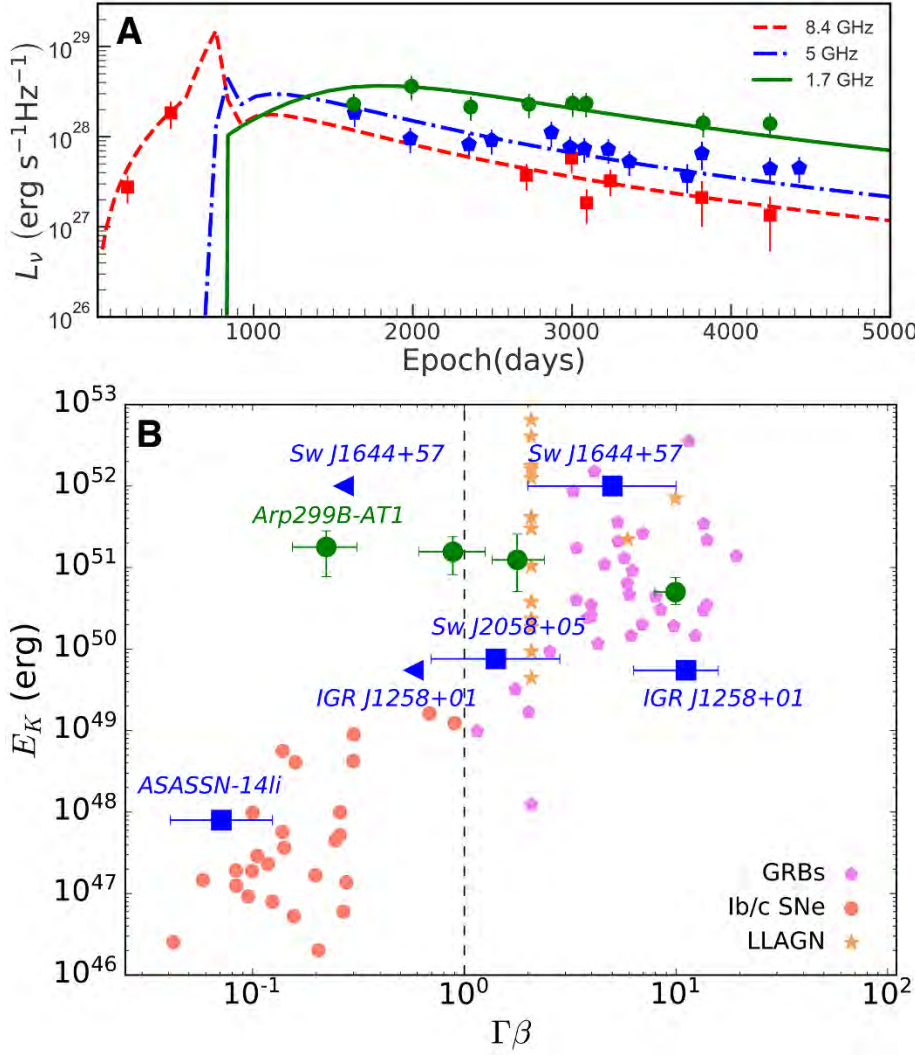


Fig. 2. Radio properties of Arp 299-B AT1. (A) Radio luminosity evolution of Arp 299-B AT1 at 1.7 (circles), 5.0 (pentagons) and 8.4 GHz (squares) spanning more than 12.1 years of observations, along with modeled radio light curves, using hydrodynamic and radiative simulations for a tidal disruption event (TDE) launched jet (16). The day zero corresponds to 2004 Dec. 21.6. (B) Intrinsic (beaming-corrected) jet kinetic energy, E_K , versus outflow speed ($\Gamma\beta$, where $\Gamma = (1-\beta^2)^{-1/2}$ is the bulk Lorentz factor of the outflow and $\beta = v/c$), from radio observations of gamma-ray bursts (GRB), supernovae (SNe), low-luminosity active galactic nuclei (LLAGN), and TDEs (4, 16, 19–21, 32). The large circles show, from right to left, the inferred loci for Arp 299-B AT1 at four different epochs in the observer's frame: just after the jet is launched by the TDE, and ~ 1 , ~ 12 , and ~ 760 days thereafter. For the LLAGN sample, we have assumed a constant jet kinetic power over 10 years. The triangles indicate upper limits for the expansion speed of IGR J1258+01 (20) and Sw J1644+57 (21).

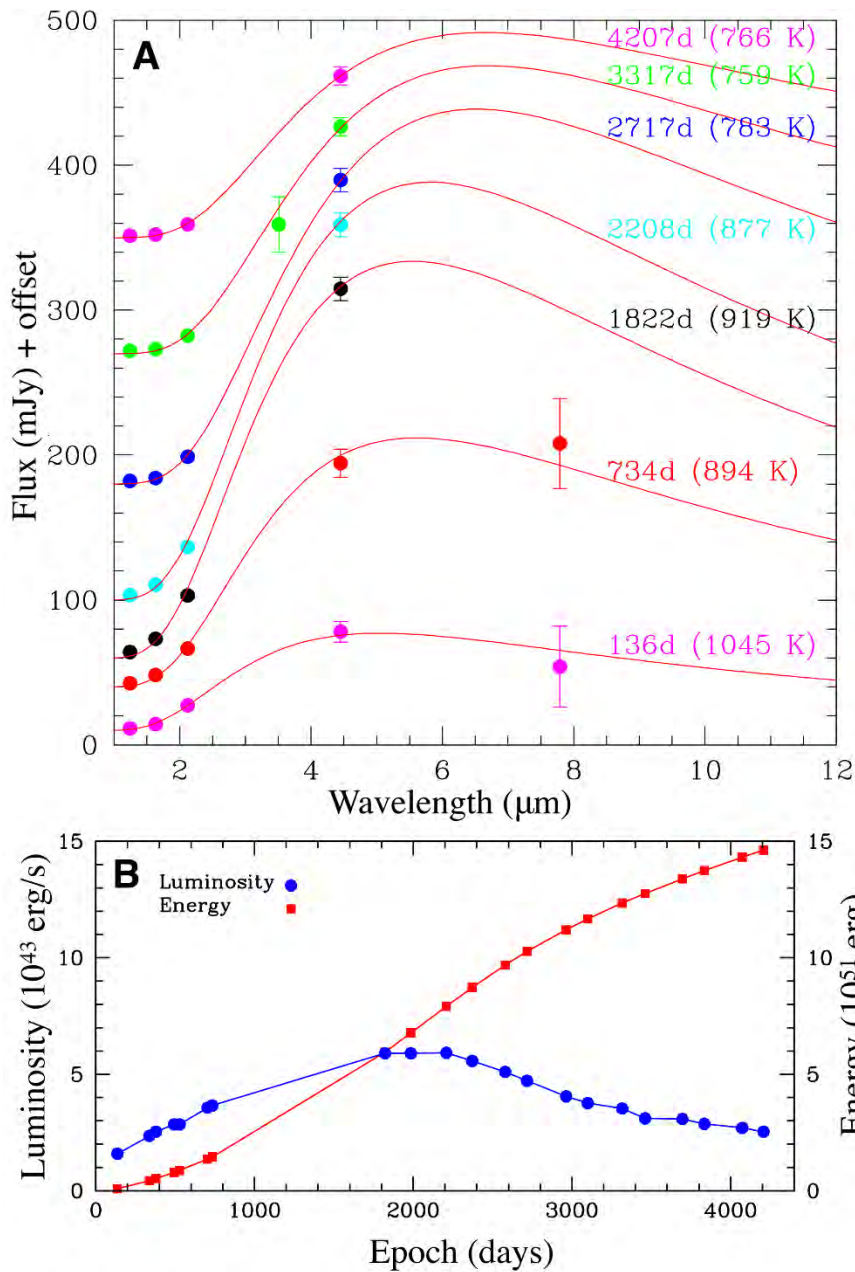


Fig. 3. Infrared properties of Arp 299-B AT1. (A) Evolution of the observed infrared spectral energy distribution (points) shown together with blackbody fits between 136 and 4207 days after the first infrared detection on 2004 Dec. 21.6 (7). Over this period the blackbody temperature decreased from about 1050 to 750 K while the blackbody radius increased from 0.04 to 0.13 pc. (B) The evolution of the integrated blackbody luminosity (blue circles) and cumulative radiated energy (red squares). The observed radiated energy by day 4207 was about 1.5×10^{52} erg.

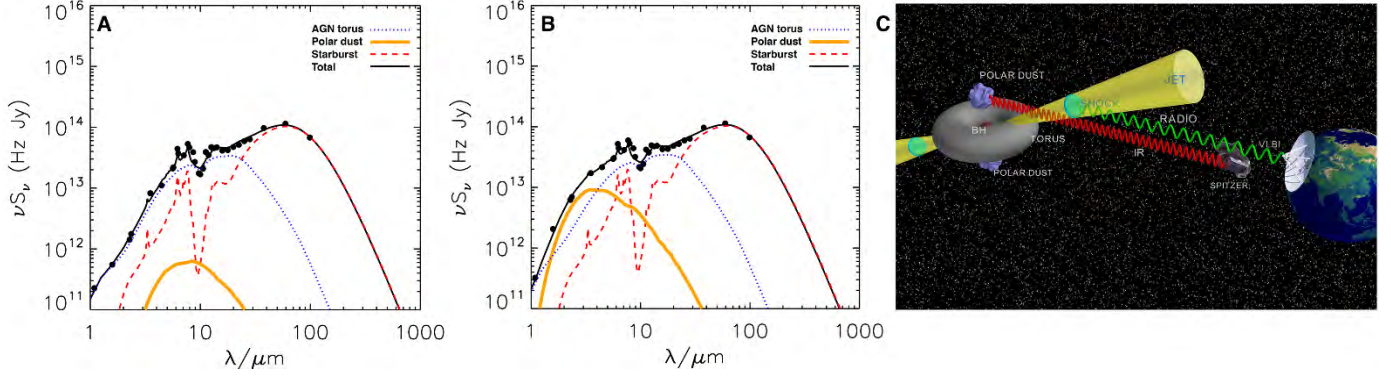


Fig. 4. Model for the observed properties of Arp 299-B AT1. Best-fit models for the spectral energy distribution of the Arp 299 nucleus B at (A) pre-outburst (A) and (B) post-outburst (734 days after the first mid-infrared detection). The models include a starburst component (dashed line), an active galactic nucleus (AGN) dusty torus (dotted line), and a polar dust component (thick solid line) (7). The sum of these components is shown as a thin solid line. In (B) most of the model parameters were fixed, while the temperature of the polar dust varied from 500 K in the pre-outburst case to 900 K in the post-outburst case. This yields a covering factor of the polar dust of 23%-78%, implying that the total radiated energy is $\sim(1.9\text{-}6.5) \times 10^{52}$ erg. (C) Schematic diagram (not to scale) showing the geometry of the emitting and absorbing regions (7). The tidal disruption event generates prominent x-ray, ultraviolet and optical emission. However, the direct line-of-sight to the central black hole is obscured by the dusty torus, which is opaque from soft x-rays to infrared wavelengths. The polar dust reradiates in the infrared a fraction of the total energy emitted by the event. The transient radio emission originates from a relativistic jet launched by the tidal disruption of a star.