Delayed radio flares from a tidal disruption event

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Radio observations of tidal disruption events (TDEs)—when a star is tidally disrupted by a supermassive black hole (SMBH)—provide a unique laboratory for studying outflows in the vicinity of SMBHs and their connection to accretion onto the supermassive black hole. Radio emission has been detected in only a handful of TDEs so far. Here we report the detection of delayed radio flares from an optically discovered TDE. Our prompt radio observations of the TDE ASASSN-15oi showed no radio emission until the detection of a flare six months later, followed by a second and brighter flare years later. We find that the standard scenario, in which an outflow is launched briefly after the stellar disruption, is unable to explain the combined temporal and spectral properties of the delayed flare. We suggest that the flare is due to the delayed ejection of an outflow, perhaps following a transition in accretion states. Our discovery motivates observations of TDEs at various timescales and highlights a need for new models.

Synoptic time-domain surveys have been increasingly fruitful in discovering nearby tidal disruption events (TDEs) over the past several years. These transient events, which are interpreted as stars being tidally disrupted by supermassive black holes (SMBHs), may provide a window into many diverse astrophysical questions. Uncovering dormant SMBHs is only one of the revelations made through these events. The complex physical process of the accretion of matter onto a SMBH is another. The nature of TDEs and their emission mechanisms are still puzzling. For example, what generates the ultraviolet (UV) and optical emission? Is it a process related to accretion or maybe internal shocks in streams of stellar debris? Does an accretion disk form around the SMBH, and if so, when and in which geometry? Panchromatic studies of a growing number of events hold the key to unlocking many of the remaining open questions.

An example is the progress made in recent years by uncovering two potentially distinct sub-classes of TDEs: (1) thermal TDEs, discovered via their optical/UV emission, and (2) relativistic events such as Swift J1644+57 (refs. 7–9), which exhibit high-energy non-thermal emission. Until recently, thermal TDEs were not seen to exhibit strong radio emission, but this changed with the discovery of a prompt radio signal10,11 from the nearby event ASASSN-14li (ref. 12). The weak radio emission has been interpreted as originating from a sub-relativistic shockwave launched into the SMBH circumnuclear material (CNM), driven by either outflows from an accretion disk12 or by the unbound stellar debris travelling away from the central SMBH13,14 (another plausible explanation is that the outflow is a jet that slowed down15). On the other hand, Swift J1644+57 exhibited a strong radio afterglow15,16, orders of magnitude more luminous than the emission in ASASSN-14li, originating from a relativistic jet that is viewed on-axis.

The field of TDE radio observations has seen further developments in recent years. Very long baseline radio observations of an infrared (IR) transient that is considered to be a TDE candidate (Arp 299B-AT1), revealed a radio jet17. Moreover, a recent radio transient, discovered independently of detection at other wavelengths, is also attributed to a TDE18. A recent excitement is the discovery of a coincident neutrino with an optically discovered TDE19, AT2019DSG, which also exhibits radio emission similar to that of ASASSN-14li. These past discoveries represent other pieces of the puzzle, which will hopefully allow a coherent picture of the overall physical processes in play to be built.

In search of similar radio emission from other nearby TDEs, we carried out radio (6–22 GHz) observations using the Karl Jansky Very Large Array (VLA) telescope and, recently, the Arcminute Microkelvin Imager (AMI) telescope of a number of optically discovered TDE candidates at various timescales from early to late times (A. Horesh et al., manuscript in preparation). Although most of the observations resulted in null detections, a single event—named ASASSN-15oi—revealed a delayed radio flare, months after its optical discovery, followed by (even more surprisingly) a second flare years later.

ASASSN-15oi was discovered in optical wavelengths by the All-Sky Automated Survey for SuperNovae (ASASSN20) on 2015 August 14 (ref. 21) at a distance of 216 Mpc. At the time of discovery it had an optical magnitude of $V \approx 16.2$, whereas previously it was not detected on 2015 July 26 down to $V \lesssim 17.2$, suggesting that it was discovered relatively young. An optical spectrum obtained by the PESSTO collaboration22 on 2015 August 20 provided the initial classification of ASASSN-15oi as a TDE23. Multiple groups then launched panchromatic monitoring campaigns. In the optical, additional spectroscopy of ASASSN-15oi confirmed the initial classification of the event as a TDE21 and showed a rapid spectral evolution (compared with other optically discovered TDEs). A search for high-energy emission by the Neil Gehrels Swift Observatory initially showed no significant emission24. However, deeper X-ray observations revealed what first seemed to be a non-varying weak X-ray source that later increased in flux25,26. In the radio, we launched a monitoring campaign using the VLA.

Discovery of a delayed radio flare

Our radio campaign began on 2015 August 22, 8 days after the optical discovery. Our initial observation, performed at both 5 GHz and 22 GHz, resulted in null detections with $\sigma$ limits of $\sim 33\mu$Jy ($1.8 \times 10^{27}$ erg s$^{-1}$ Hz$^{-1}$) and $\sim 60\mu$Jy ($3.3 \times 10^{27}$ erg s$^{-1}$ Hz$^{-1}$), respectively. Despite the non-detections, we continued to observe the source, motivated by some theoretical models that suggest a delay between the TDE optical flare and the formation of the accretion...
The peculiar evolution of the delayed radio flare

Our follow-up campaign (which includes six additional observing epochs since the radio discovery) reveals an unusually evolving radio spectrum (the full spectral evolution is presented in Extended Data Fig. 2). During the first 2 weeks after the initial detection of the radio emission, the peak frequency slowly evolved, from $\nu_p = 9.6 \pm 0.9$ GHz to $\nu_p = 8.6 \pm 0.4$ GHz (see ‘Radio observations’ in the Methods), while the peak flux density simultaneously dropped by ~25%. In contrast, at later times, the radio flare evolved quickly. As seen in Fig. 2, the peak frequency of the radio emission decreased to <3 GHz only 2 months after radio discovery.

Another oddity is the shape of the radio spectrum. In general, the radio spectral peak ($\nu_p$) observed in transient phenomena is due to either the minimum energy of the emitting electrons (in which case the flux density at $\nu < \nu_p$ is $F_\nu \propto \nu^{\alpha_s}$) or absorption (usually due to synchrotron self-absorption (SSA) and thus the flux density at $\nu < \nu_p$ is $F_\nu \propto \nu^{-\alpha_s}$, as seen in most radio supernovae, for example). Neither of these two cases is observed in ASASSN-15oi. Instead, our data show that the flux density, $F_\nu \propto \nu^{\alpha}$, has a power law of $\alpha \approx 1$ (in contrast to both ASASSN-14li (ref. 10) and Swift J1644+57 (ref. 10) in which $\alpha \approx 5/2$). Although this differs from the spectral shape of standard SSA (from a homogeneous CNM shockwave) models, it may be explained by a more complex model in which the SSA originates from an inhomogeneous source (see ‘Spectral modelling of the radio emission’ in the Methods). This spectral index is also typical of radio emission originating from some quiescent gigahertz-peaked spectrum (GPS) sources30, which are considered to be young active galactic nuclei (AGNs), but do not exhibit flares on the timescales observed here (see ‘Spectral modelling of the radio emission’ in the Methods and Extended Data Fig. 3). The spectral index of the optically thin synchrotron emission above the peak ($F_\nu > \nu^p \propto \nu^{\alpha_n}$), is a function of the energy index ($p$) of the energy distribution ($N_\nu \propto \nu^{-p}$) of the emitting electrons ($N_\nu \propto \nu^{-1}$). For ASASSN-15oi, the spectral index is initially in the range $-2 \leq \alpha_n \leq -1$, which is steeper than the spectral index observed in both Swift J1644+57 and ASASSN-14li. Later, when the peak flux density decreased to below 3 GHz, the optically thin spectrum became shallower ($\alpha_n \gtrsim -0.6$; which is also shallower compared with ASASSN-14li and Swift J1644+57).

The nature of the delayed radio flare

The delayed radio emission we observe from the TDE ASASSN-15oi, its properties and evolution raise several key questions. Can the late-time radio emission and the earlier null detections be reconciled under a standard CNM shockwave model? If so, does it originate in a relativistic jet, such as observed in Swift J1644+57 or perhaps an off-axis jet that became visible only at late times? Or does it point to a sub-relativistic shockwave (driven by accretion disk outflows or stellar debris), such as the one observed in disk12,27,28. We observed ASASSN-15oi twice more on 2015 September 6 ($\Delta t = 23$ days, where $\Delta t$ is the time since optical discovery) and November 12 ($\Delta t = 90$ days); observations that also resulted in null detections, until the discovery of significant radio emission on 2016 February 12 ($\Delta t = 182$ days; Fig. 1 and Extended Data Fig. 1), with an approximate flux density of $\sim 1,300 \,\mu Jy \, (7.3 \times 10^3 \,\text{erg s}^{-1} \,\text{Hz}^{-1})$ at a peak frequency of $\sim 9.6$ GHz. Once ASASSN-15oi was detected in the radio, we embarked on a follow-up observing campaign, carrying out observations in multiple radio frequencies to characterize the properties of the broadband radio spectrum and its evolution.

The position of ASASSN-15oi was recently observed separately from our follow-up observing campaign as part of the Very Large Array Sky Survey (VLASS30). Inspection of the quick-look images (produced by the National Radio Astronomy Observatory (NRAO)) reveals a rebrightening of the radio emission at 3 GHz on 2019 July 01 (almost 4 years after the initial optical discovery), to a flux density level of $\sim 8,000 \,\mu Jy \, (4.4 \times 10^3 \,\text{erg s}^{-1} \,\text{Hz}^{-1})$.

ASASSN-14li? Does a delayed radio detection require a delayed outflow formation?

To address these questions, first we tested the standard dynamical models that have been used to explain the radio emission from TDEs11–14. In these models, a single shockwave (either relativistic or sub-relativistic) is launched into the CNM around the time of optical discovery. Both the optically thick and optically thin emission have a power-law temporal evolution with a range of values for the power-law indexes (depending on the properties of the shockwave; see ‘Temporal evolution of the radio emission’ in the Methods). The steep rise of the observed radio emission from non-detection on $\Delta t = 90$ days to detection on $\Delta t = 182$ days requires that the temporal evolution of the flux density is steeper than $F_\nu \propto t$. In the analytical models that we explore, the fastest increase in the rate of the emission occurs in the relativistic jet case. When an on-axis relativistic jet is interacting with CNM profiles in the range between a constant density $\rho$ and $\rho_{\text{CNM}} \propto r^{-2/3}$ (which is the steepest density
to have a power-law temporal evolution \(F_t \propto t^\beta\) with a predicted power-law index of \(-1 \geq \beta \geq -3\). However, here we saw a varying, steep temporal evolution, where the temporal power law reaches a value \(\beta \leq -3\) (Extended Data Fig. 4).

A possible solution to explain the initial radio null detections could be unbound material from the TDE initially travelling in a cavity around the SMBH, before suddenly reaching an extended high-density CNM structure. However, once the outflow enters the high-density extended CNM structure, the radio emission from the shockwave should follow a spectral evolution similar to ASASSN-14li (or Swift J1644+57), in contrast to what we observed (Fig. 2 and Extended Data Fig. 4), making this scenario less plausible. A scenario in which an outflow from the TDE suddenly encounters a spatially thin, confined, dense CNM shell or filament, producing a brief late-time flare, is also unlikely. In this latter case, the radio flux density is expected to decrease extremely rapidly after peak \(F_t \propto t^{-\beta}\), once the outflow crosses the filament\(^{49}\), but such a steep decline was not observed here. One may also consider the possibility that an outflow was launched only at late times due to delayed accretion of bound stellar debris (as suggested by some studies\(^{27}\)). But again in this case, once the outflow is launched into the CNM, the resulting radio emission should have spectral and temporal properties according to the standard model discussed above, in contrast to the data presented here. It is possible, however, that some delayed activity (accretion) is in play, but involves processes that are not included in standard TDE models at present.

The rebrightening of the radio emission on July 2019 may be the most recent evidence against the scenarios we examined above. A secondary flare with an increase in emission by a factor of \(>20\), years after the onset of the TDE, is not expected in any of the above scenarios. Even when considering a radio rebrightening in a structured jet model\(^{30,31}\), none of these models predict a rebrightening of the flux density by more than an order of magnitude over a timescale as long as observed here. Moreover, explaining a rebrightening at late times with a structured jet that has been launched early on requires that the initially observed delayed late-time emission is explained by this outflow as well. However, as we have shown, it cannot. A secondary flare years after the onset of the TDE is therefore not expected in any of the above scenarios. One possibility is that the rebrightening is driven by the same process responsible for theinitial delayed flare we detected. We may also consider the possibility of a recurring TDE flare due to repeated partial disruptions of a star\(^{40,41}\). Another possible explanation is that the TDE occurred around a binary SMBH system. In such a scenario, the accretion rate may be more variable with multiple peaks that could appear several years after the initial disruption\(^{41}\). Still, none of these proposed theoretical explanations offer clear predictions for late-time radio emission that can be tested against our measurements. Unfortunately, further information about the 2019 rebrightening event is also limited (K. Alexander et al., manuscript in preparation).

Late-time UV and optical observations show no signature of any renewed activity or a secondary flare during the first year after the optical discovery of ASASSN-15oi (ref. \(^{25}\)). UV emission is still detected from the TDE after the time when we discovered the delayed radio flare (with observations ongoing up to a year after optical discovery), and is consistent with a simple power-law decline of the UV emission detected at early times. A series of optical spectra taken starting at \(\Delta t = 301\) days and up to \(\Delta t = 455\) days shows that the broad emission lines, which are typical of TDEs and detected early on, have diminished, and no new emission lines are present\(^{26}\).

We now compare the evolution of the X-ray emission with that of the radio emission (Fig. 3). The X-ray emission, which was detected early on, slowly and steadily rose with time and peaked (after an increase in flux by a factor of \(\sim 10\)) about a year after the optical discovery\(^{25,26}\). A direct comparison with the evolution of the radio
emission was somewhat limited by a gap in the X-ray data during the time of the first late-time radio detection and the subsequent follow-up radio observations. It is clear that the radio emission did not increase in parallel with the X-ray emission (Fig. 3), as the radio emission faded away at ≤200 days, while the X-ray emission was still rising. Interestingly enough, the X-ray emission after the gap in X-ray observations increased beyond 1% of the Eddington luminosity ($L_{\text{Edd}}$), and its thermal (soft) component became brighter\(^{26}\). This behaviour is usually observed in X-ray binaries (XRBs), but although this transition is observed at a level of ~1% $L_{\text{Edd}}$ when radio emission is detected. The X-ray data are presented as blue circles\(^{25}\) (error bars show 1σ). The radio data are at a frequency of 13 GHz (red squares; uncertainties are the image noise and flux calibration uncertainty added in quadrature as defined in Supplementary Table 1). Averaged early radio 3σ non-detections up to 90 days after optical discovery are represented by red arrows.

![Fig. 3](image-url) | Comparison of the temporal evolution of the X-ray luminosity with the optically thin radio luminosity in ASASSN-15oi. The X-ray emission (left y axis) is detected soon after the occurrence of the TDE, whereas the radio emission (right y axis) begins later. Unfortunately, no X-ray data are available when the radio emission was initially detected. The X-ray luminosity, however, increases to a level of ~1% $L_{\text{Edd}}$ when radio emission is detected. The X-ray data are presented as blue circles\(^{25}\) (error bars show 1σ). The radio data are at a frequency of 13 GHz (red squares; uncertainties are the image noise and flux calibration uncertainty added in quadrature as defined in Supplementary Table 1). Averaged early radio 3σ non-detections up to 90 days after optical discovery are represented by red arrows.

When the accretion rate increases and fresh material with a high Lorentz factor is injected into an existing jet\(^{26}\), it occurs on average at higher Eddington luminosities (~10–30%)\(^{46–48}\). A possible explanation for this behaviour in XRBs is that this transition occurs when the accretion rate increases and fresh material with a high Lorentz factor is injected into an existing jet\(^{26}\). Following this stage in XRBs, a radio flare is observed\(^{46}\). We also note that combined X-ray observations during June–August 2019, the period in which a rebrightening of the radio emission was detected in VLASS, show that the X-ray flux slightly increased, after declining, to a flux level of $8.07 \pm 1.1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. This translates to only 0.4% of the Eddington luminosity (lower than the X-ray luminosity increase to 1% $L_{\text{Edd}}$ around the time of the initial delayed radio flare we observed). However, these recent X-ray data are limited and averaged over several months (see 'A comparison between the X-ray and radio emission temporal evolution' in the Methods), thus making their interpretation difficult.

Radio emission with a similar spectral shape to the one we observe in ASASSN-15oi and similar temporal behaviour (in contrast to the one in GPS sources), has been observed in some AGN or blazar radio flares (but is not necessarily typical of the whole AGN/blazar flare population). In September 2011, a radio flare from M81 exhibited an inverted radio spectrum with a peak frequency of ~10 GHz. The flare radio flux density slowly decreased on a timescale of weeks with the spectral peak frequency roughly staying the same until a second flare was observed\(^{46}\). In another case, a year-long radio flare from the blazar CTA 102 had a complex temporal and spectral behaviour\(^{46}\). The late-time evolution phase of this radio flare also shows similar characteristics to those observed in ASASSN-15oi (Fig. 2). In general, these AGN/blazar radio flares have been partially explained by the shock-in-jet model\(^{46}\) in which a shock propagates in an existing radio jet leading to what seems to be a flare. However, a phase in which the radio peak frequency does not vary while the peak flux density decreases, as observed in both the M81 and the CTA 102 flares, is not captured by this model.

Nonetheless, it is possible that there is a radio weak quiescent jet associated with the SMBH of ASASSN-15oi that is shocked by a delayed injection of energy by the TDE. Such pre-existing weak quiescent radio emission, which suggests a non-TDE related activity of the SMBH, has been found in ASASSN-14li\(^{46}\) at a level that is too faint for detection at the distance of ASASSN-15oi.

It has been suggested that emission in both XRBs and AGNs is dominated by a weak non-thermal jet when the accretion rate is considerably sub-Eddington (the accretion becomes radiatively inefficient)\(^{46}\). A phase transition in accretion occurs when the accretion rate increases above a critical threshold, at which point the emission in the X-ray becomes disk dominated and a high-velocity outflow is launched (sometimes observed as spatially discrete knot ejections\(^{46–48}\)) resulting in a radio flare. It is therefore possible that such a phase transition occurred in ASASSN-15oi, resulting in the delayed launch of an outflow that led to rapidly rising radio emission at late times. However, what triggers this phase transition, how this transition and the outflow launching coupled to it depend on the nature and properties of the relevant phenomena (for example, TDE versus XRB) and what the typical signatures of this transition in TDEs are (for example, will all TDEs exhibit an increase of their X-ray emission above a certain threshold characterized by some percentage of their Eddington luminosity?) remain open questions.

The details of what follows any transition in the accretion phase are also unclear. Recall that, once detected, we observed an initially slowly evolving inverted spectrum but the spectral peak frequency rapidly evolved shortly after. It is possible that the termination of the slow spectral evolution phase marks the point at which the shock reached the edge of a pre-existing jet and that the emission that follows is of the slowly cooling jet. Testing this scenario and answering any other open questions may become possible with the discovery of additional events like ASASSN-15oi.

Yet another open question relates to how common such late-time flares (due to a delayed outflow ejection) are in TDEs. There is one other case of a possible late-time radio flare in the IR TDE AR299B-AT1 (ref. \(^{1}\)). In that case, a single-frequency (8.4 GHz) radio observation, taken 12 days after the first possible indication of an increase in the IR flux, resulted in a null detection. The next observation, carried out just 48 days later, detected increasingly bright radio emission. The full set of radio measurements (spanning thousands of days) of AR299B-AT1 is consistent with a relativistic jet launched briefly after the stellar disruption. The late-time radio spectrum, which is consistent with originating from an electron energy distribution of $N_e \propto E^{-3}$, was also slowly evolving, in agreement with the predictions of known models\(^{12}\), but in contrast to the evolution observed in ASASSN-15oi.

It is possible that the delayed launch of an outflow, as observed here, has been missed in other TDEs due to limited observational coverage. First, in several past TDEs there is a substantial gap between the time of disruption and the time at which the first radio observation was carried out (for example, the disruption time in the case of ASASSN-14li is poorly constrained). Thus even if radio emission is detected initially in such cases, the exact time at which the outflow was launched with respect to disruption is unknown. Moreover, radio observations in most cases—whether radio emission is detected or not—are curtailed after several months, leaving any flaring event that occurs later undetected. The peculiar delayed flares we discovered in ASASSN-15oi on timescales of months and years thus motivate carefully planned observational campaigns of TDEs from early times until very late times.
Conclusions
Our radio observing campaign of the optically discovered TDE ASASSN-15oi since discovery to over a year later revealed a delayed radio flare with odd spectral and temporal properties. A second, even more luminous radio flare has been detected in VLASS observations. The various models that we explore here, which have been proposed to explain the radio emission originating from TDEs, are unable to explain the combined properties of the observed radio emission. Specifically, it seems that such a delayed bright radio flare following an extended period of null radio detections requires some sort of an outflow to be launched at late times (into a possibly inhomogeneous CNM; Methods), suggesting a delayed onset of enhanced accretion. Some of the properties of the emission have similarities to XRBs and to AGN/blazar radio flares, thus raising the possibility that a transition in the accretion phase state (which has been proposed as an explanation of these latter flares) is also at play in TDEs. The details of this process, which has not previously been observed in TDEs, and what triggers it are yet to be discovered. Understanding this process requires that we first better characterize it. Our discovery thus motivates late-time radio campaigns of TDEs that will hopefully identify additional delayed flares. These could help us to study the process responsible for triggering delayed enhanced accretion, the subsequent outflow launching and the emission that accompanies it, thus helping to unveil the nature of this new puzzling phenomenon in TDEs.

Methods
Radio observations. We observed the field of ASASSN-15oi with the VLA on 2015 August 22, September 06 and November 12, and on 2016 February 12, under a Swift-VLA joint programme (SB 4220). Later observations were performed on the $X$ and $K$ bands (6 GHz and 22 GHz, respectively) as a director discretionary time programme (16A-422). The four initial observations were performed in only the $X$ and $K$ bands (6 GHz and 22 GHz, respectively) as a detection experiment in search of radio emission. Once radio emission was detected in the fourth observation (Extended Data Fig. 1), the follow-up observations were conducted in a wide range of bands from the $S$ band (3 GHz) to the $K$ band, as needed, to characterize and capture the evolution of the broadband radio spectrum (Extended Data Fig. 2).

We calibrated the radio data using the automated VLA calibration pipeline available in the Common Astronomy Software Applications (CASA) package. Flux density calibration was conducted using 3C84, whereas 2040-2007 was used as a gain calibrator. Images of the ASASSN-15oi field were produced using the CASA task CLEAN. In images where ASASSN-15oi was detected, the source flux density was measured using the CASA task IMFIT, and the image root mean square was calculated using the CASA task IMSTAT. We also added a flux density calibration for the AGN component to the SSA models, the AGN spectral index of $\alpha = 0.7$ is in agreement with the flux density measurements.

Spectral modelling of the radio emission. Below we attempt to model the observed broadband radio spectra of ASASSN-15oi at the individual observing epochs where a peak in the flux density was observed, but without modelling the temporal evolution. Theoretical models predict that radio emission in TDEs originates from a forward shockwave (either relativistic or sub-relativistic) travelling in the surrounding environment. This shockwave accelerates free electrons that gyrate in the shockwave-enhanced magnetic field and thus emit synchrotron radiation. Therefore, we first modelled the individual single-epoch broadband radio spectra that we observed according to a SSA spectral emission model. We then successfully accounted for the radio emission observed in both Swift J1644+57 and ASASSN-14li (refs. [1644+57, 14li]).

In the SSA emission model, the radio spectrum exhibits a peak below which the emission is self-absorbed and thus optically thick, and above which the emission is optically thin. The optically thick emission can be described as

$$F_{\nu} \propto \frac{\pi R^2}{D^2} \frac{\nu^{-1/2}}{1 - \tau_{e}},$$

whereas the optically thin emission is described by

$$F_{\nu} \propto \frac{4\pi R^2}{D^2} \frac{\nu^{1/2}}{\beta} \frac{B_{\nu}(\nu^{\beta}/2)}{(1 - \nu^{\beta/2})^{1/2}},$$

where $R$ is the radius of the radio-emitting shell, $D$ is the distance to the TDE, $f_{\nu}$ is the emission filling factor and $B_{\nu}$ is the magnetic field strength. The energy density of the magnetic field is a fraction $\epsilon_B$ of the energy density of the shocked CNM. Thus, the magnetic field strength also depends on the square root of the CNM density (and its profile).

Our SSA best-fit models of each of the ASASSN-15oi radio spectra, separately, in which a radio peak is evident, are presented in Extended Data Fig. 3. As shown in Extended Data Fig. 3, the SSA models poorly account for the observed radio spectra (with reduced $\chi^2$ values of $\chi^2 > 8$ at times $\Delta t = 190, 197$ days). This is no surprise, as the optically thick spectral index of the SSA model is at $\alpha = 5/2$, while examination of the data suggests a spectral index of $\alpha \approx 1$. A shallower spectral index of the optically thick emission is expected if only internal free–free absorption (FFA) is the dominant absorption mechanism instead of SSA, although still steeper than the observed $\alpha = 1$ spectral index. In this internal FFA model, the flux density is

$$F_{\nu} \propto F_{\nu,\text{un}} \left( 1 - \frac{\nu^{\beta}}{\tau_{e}} \right),$$

where $F_{\nu,\text{un}}$ is the unabsorbed synchrotron emission and $\tau_{e}$ is the FFA optical depth. The results of the FFA modelling are presented in Extended Data Fig. 3. While the internal FFA models better account for the observed radio spectra than the SSA model ($\chi^2 > 2.5$), they still significantly deviate from the observations. A solution may be found by reverting to the SSA model, but this time, instead of assuming a homogeneous CNM environment, we will assume an inhomogeneous one.

Inhomogeneities in the CNM can be modelled as inhomogeneities of the magnetic field and will result in an SSA spectrum with a broader peak and a shallower spectral index. This explanation was also used recently to describe a shallow optically thick radio emission in a stripped envelope supernova. We follow this model (which is an extension of the SSA model but one that is parameterized with a distribution of magnetic fields, $P(B) \propto B^{-\gamma}$, instead of a single magnetic field). This model thus adds two degrees of freedom: the range of magnetic field strengths and the power-law index ($\gamma$) of the magnetic field distribution. The best-fit results of this model are presented in Extended Data Fig. 3. We find that the inhomogeneous SSA model provide a better spectral fit ($\chi^2 < 0.8$) than the previous models. It is important to note that finding a separate good spectral fit to each of the individual observed spectra does not mean that we have found a dynamical single scenario that can explain the combined full observed dataset, as we explain below, when attempting a temporal modelling.

At this point, it is worth mentioning that the observed radio spectrum of ASASSN-15oi is reminiscent of GPS sources. These radio sources have a spectrum with a peak frequency in the low gigahertz range, as their name suggests. They are powerful, compact ($\lesssim 1$ kpc) radio sources, some of which exhibit a morphology of two sided symmetric sources when resolved with high-angular-resolution observations, and are believed to be young AGN radio jets. On a long timescale, GPS sources can exhibit strong variability up to an order of a magnitude in the radio. However, the complex spectral variations observed here, over a short timescale of 2 months, are atypical of GPS sources. Still, considering that the radio spectral shape of GPS sources is attributed to inhomogeneities and the resemblance of ASASSN-15oi to that of ASASSN-15oi strengthens the conclusion that the radio emission from ASASSN-15oi may originate from a complex CNM environment. Despite the poor fit by a simple SSA model, assuming that the peak flux density is the result of SSA, we use the peak flux density and frequency to roughly estimate the shockwave radius by

$$R_{p} = 4.0 \times 10^{14} \left( \frac{\nu}{\text{GHz}} \right)^{-1/3} \left( \frac{\nu}{190 \text{GHz}} \right)^{1/3} \left( \frac{B_{\nu}}{10^{19} \text{Gauss}} \right)^{1/3} \text{cm},$$

where $\nu_c$ and $\nu_g$ are the fractions of shockwave energy deposited into accelerating free electrons and enhancing the magnetic field, respectively. We adopt standard equipartition value of $\epsilon_B = \epsilon_e = 10^{-4}$.

The radius of the radio-emitting region when we first detected it (2016 February 12, $\Delta t = 182$ days), is estimated at $R \approx 4 \times 10^{-3}$ cm, which implies that an outflow was launched at optical discovery) a shockwave velocity of $25,000 \text{ km s}^{-1}$ (only slightly higher than the velocity expected for the unbound stellar debris). Note, however, that if a jet (or an outflow) is launched later, then the velocity estimate will be higher. We also find that the radius of the radio-emitting region remains roughly the same over a two-week period (when evaluated on 2016 February 20 and 27; $\Delta t = 190$ and 197 days, respectively, following the initial radio evaluation on $\Delta t = 182$ days). Following this period, the estimated radius makes a big jump to $R \approx 1.1 \times 10^{-3}$ cm in only 6 days. The above radius estimates (as well as the velocity estimates) should become lower limits if the emission originates from an inhomogeneous source (as discussed above).
Temporal evolution of the radio emission. The temporal evolution of the observed radio emission can be compared with main theoretical predictions. We first address the analytical predictions for an on-axis relativistic jet and a sub-relativistic outflow in the case of an off-axis relativistic jet the optically thick emission is expected to rise as $t^{(p+2)/(p+4)}$, where $p$ is the power-law index of the CNM density profile ($\rho_{\text{CNM}} \propto r^{-p}$). Adopting the steepest density profiles in some TDEs of $\rho_{\text{CNM}} \propto r^{-3}$ (which is steeper than the usual wind-like CNM profile used in most numerical simulations), we obtain $F \propto t^{3}$. In the sub-relativistic case, the optically thick emission evolves as $F \propto t^{p+2}/(p+4)$, which is shallower than the relativistic case. We also found that attempting to model the full observed data (including the observed non-detections) with a sub-relativistic spherical outflow model fails. Adopting, therefore, the steepest relation $F \propto t^3$ (of the relativistic case), the optically thick emission detected on 2016 February 12 can be evolved back in time to 2015 November 12, resulting in a predicted flux density level of 0.15 mJy in the C band, well above the detection threshold of our observation at that time (a 3σ limit of 60 mJy). As shown in Extended Data Fig. 4, the jump in flux density from non-detection to detection requires a temporal power law slightly steeper than $t^3$, which requires a CNM density profile with a power law steeper than $k = 2.8$. However, note that while this model predicts that the optically thick emission is rising, in fact, upon detection it is declining. The optically thin emission, on the other hand, is expected to be declining according to $F \propto t^3$ or $F \propto t^{p+2}/(p+4)$ in either the relativistic jet or the sub-relativistic outflow scenario, respectively. The steepest decline in this case for a $k = 2.5$ is $t^{-1}$, while the observed emission decline rate becomes steeper than this.

We next turned to examine numerical emission models for off-axis relativistic jets. For that purpose, we use the publicly available (https://cosmo.nyu.edu/afterglowlibrary/boxfit2011.html) BoxFit code36. In this scenario, a steep rise in the radio emission (steeper than the time of the third null detection observation. The observed decline rate of the emission after the discovery is also steeper than that expected from standard theoretical models.

A comparison between the X-ray and radio emission temporal evolution. The X-ray luminosity of ASASSN-15oi (ref. 39) is shown in Fig. 3 in units of the Eddington luminosity. We estimated the Eddington luminosity using the black hole mass estimate of $\sim10^{6}$ $M_{\odot}$ (ref. 28). As seen in Extended Data Fig. 3, the X-ray emission is limited by the X-ray detection threshold of the telescope at the time we discovered the radio flare, then the radio emission should have been detectable at the time of the third null detection observation. The observed decline rate of the radio emission after the discovery is also steeper than that expected from standard theoretical models.

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Author contributions
A.H. led the radio observing campaign, the data analysis and modelling, the interpretation and the manuscript preparation. S.B.C and I.A. contributed to the interpretation of the results and to the manuscript preparation.

Competing interests
The authors declare no competing interests.

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Extended Data Fig. 1 | VLA K-band images of the position of the optical TDE candidate ASASSN-15oi, before and after radio detection. The left panel (a) presents the third VLA image we obtained of this field 3 months after optical discovery on 2015 Nov 12, still showing a null-detection. The right panel (b) presents the image from our forth VLA observation on 2016 Feb 12 which reveals a delayed radio flare, 6 months after optical discovery. The synthesized beam size is shown as a white ellipse at the bottom left corner of the images. The flux density scale is identical in both images.
Extended Data Fig. 2 | The full observed broadband spectral evolution of the delayed radio flare from ASASSN-15oi. Each of the radio broadband spectra is from a different observing epoch, starting from the initial detection of the delayed flare on 182 days and up to 576 days after optical discovery. Data from each epoch is represented by a different marker shape and color as noted in the legend (a dashed line connecting the data has been added for convenience). The error bars represent the image noise and flux calibration error added in quadrature (see Supplementary Table 1).
Extended Data Fig. 3 | Best fit single-epoch spectral models of the radio flare. Observing epochs at Δt=182, 190, 197 days are represented in purple, yellow and red, respectively. The broadband spectrum in each single epoch was fitted independently, thus not including any modeling of the temporal evolution. The errors of the data modeled here include the flux density calibration error and image noise added in quadrature. The left panel (a) presents the best-fit homogeneous SSA model. The middle panel (b) shows the best-fit models of the radio flare spectra using the internal free-free absorption model. The right panel (c) is the best-fit models using the inhomogeneous SSA model. Out of the three models that we try here, the latter model is the best match to the spectral data presented in this figure (see details in Methods).
Extended Data Fig. 4 | Comparison of the temporal evolution of the observed optically thin radio emission with different rising and declining power-law functions. The presented radio emission is at a frequency of 15 GHz (black solid line and markers). The various power-law functions for both the rise of the emission (since the last non-detection) and its decline are presented as dashed curves (representing various predictions, see details in Methods). The black triangle represents a 3σ non-detection limit (based on the average between the 22 GHz and 6 GHz limits).