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Radio Properties of Tidal Disruption Events

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Abstract Radio observations of tidal disruption events (TDEs) probe material ejected by the disruption of stars by supermassive black holes (SMBHs), uniquely tracing the formation and evolution of jets and outflows, revealing details of the disruption hydrodynamics, and illuminating the environments around previously-dormant SMBHs. To date, observations reveal a surprisingly diverse population. A small fraction of TDEs (at most a few percent) have been observed to produce radio-luminous mildly relativistic jets. The remainder of the population are radio quiet, producing less luminous jets, non-relativistic outflows or, possibly, no radio emission at all. Here, we review the radio observations that have been made of TDEs to date and discuss possible explanations for their properties, focusing on detected sources and, in particular, on the two best-studied events: Sw J1644+57 and ASASSN-14li. We also discuss what we have learned about the host galaxies of TDEs from radio observations and review constraints on the rates of bright and faint radio outflows in TDEs. Upcoming X-ray, optical, near-IR, and radio surveys will greatly expand the sample of TDEs, and technologi-

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cal advances open the exciting possibility of discovering a sample of TDEs in the radio band unbiased by host galaxy extinction.

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1 Introduction

Radio observations have been used over the past several decades to detect and characterize outflows in extragalactic transient phenomena. These outflows can appear in different forms having a wide range of energies and velocities, ranging from narrow ultra-relativistic jets (as in gamma-ray bursts; GRBs) to sub-relativistic spherical ejecta (as in core-collapse supernovae; SNe). Some famous examples in which radio observations provided key diagnostics of the type of outflows and helped reveal the nature of the transient phenomena in question include: the associated relativistic outflow in the SN 1998bw, the first SN found to be associated with a GRB (Galama et al. 1999; Kulkarni et al. 1998); SN 2009bb, a SN with a relativistic outflow that lacks γ-ray emission (Soderberg et al. 2010); the discovery of both relativistic and sub-relativistic outflows in TDEs (Bloom et al. 2011; Levan et al. 2011; Zauderer et al. 2011; Alexander et al. 2016; van Velzen et al. 2016) and the characterization of the complex structure of the relativistic outflow in the first discovered neutron star merger GW170817 (Alexander et al. 2017b, 2018; Hallinan et al. 2017; Kim et al. 2017; Corsi et al. 2018; Dobie et al. 2018; Margutti et al. 2018; Mooley et al. 2018a,b,c; Resmi et al. 2018; Troja et al. 2018; Ghirlanda et al. 2019; Hajela et al. 2019).

It is now a common practice to perform radio observations of almost any transient phenomena discovered, especially nearby ones, as the radio emission is quite weak if the outflow is sub-relativistic. The radio observations provide key diagnostics such as calorimetry, outflow velocity, magnetic field strength, and the density of the immediate environments surrounding the transient (e.g. Chevalier 1982, 1998, Frail et al. 2000, Barniol Duran et al. 2013). In some cases these crucial pieces of information are not accessible via other wavelengths. Additionally, Very Long Baseline Interferometry (VLBI) radio observations can achieve higher resolution than available at any other wavelength, directly resolving the structure of jets and outflows for nearby events (e.g. Taylor et al. 2004, 2005, Pihlström et al. 2007, Romero-Cañizales et al. 2016, Mattila et al. 2018, Mooley et al. 2018c).

Radio observations of TDEs have revealed extremely diverse radio properties (Fig. 1). This diversity and its implications are the subject of this review. We begin with an overview of the general synchrotron mechanism for producing radio emission (Sect. 2; see also Roth et al. (2020, this issue)). To illustrate the range of radio properties observed to date, we then present a detailed discussion of the two best-studied radio TDEs, Sw J1644+57 and ASASSN-14li, and briefly discuss the other TDEs with detected radio emission (Sect. 3). We then discuss what we have learned about TDE host galaxies and TDEs' immediate environments from radio observations (Sect. 4). We finish with a discussion of occurrence rates of jets and outflows in TDEs and prospects for the future (Sect. 5).

2 Radio Emission Basics

When a fast (either relativistic or sub-relativistic) outflow interacts with the circumstellar (interstellar) medium (CSM/ISM), it drives a shockwave into that medium. As the shockwave plows through the CSM/ISM, it accelerates free electrons to relativistic velocities and enhances magnetic fields. As a result, synchrotron emission ensues. This is the basic mechanism responsible for the radio emission in all types of transients mentioned above (e.g., Chevalier 1982, 1998; Weiler et al. 2002; Granot and Sari 2002; Chevalier and Fransson 2006; Giannios and Metzger 2011; Barniol Duran et al. 2013), including TDEs. In most cases, synchrotron from the external shock between the expanding outflow and the surrounding medium dominates the observed emission, but sometimes synchrotron produced by internal shocks in the jet is also significant (e.g. in the compact cores of AGN jets, and possibly in some TDEs; see Sect. 3.2.3 and Pasham and van Velzen 2018). Roth et al. (2020, this issue) provide additional theoretical discussion of synchrotron emission in the context of TDEs; here, we review the aspects most relevant for radio observations.

The properties of the observed synchrotron emission depend on the physical properties of the system such as the CSM/ISM density, the velocity of the outflow driving the shockwave, the electron energy distribution, the total energy carried by the outflow, and other microphysical parameters such as the fractions of shockwave energy deposited in the electrons and the magnetic field, respectively. The resulting shape of the synchrotron radio spectrum is in general a multiple broken power-law, which can be fully described by its break frequencies and an overall normalization factor (e.g. Granot and Sari 2002).[1] In particular, radio observations reveal the peak of the synchrotron emission spectrum, which for TDEs is typically where the emission transitions from optically thick ($F_\nu \propto \nu^{5/2}$ at low frequencies) to optically thin ($F_\nu \propto \nu^{-(p-1)/2}$ at higher frequencies). Relativistic bulk motion of the emitting region also affects the observed luminosity of the source, due to Doppler boosting effects. In particular, a source with a simple power-law spectrum $F_\nu \propto \nu^{-\alpha}$ that emits isotropically with flux density F_0 in its rest frame, moving relativistically with Lorentz factor $\Gamma \equiv 1/\sqrt{1-\beta^2}$ at an angle θ to the observer's line of sight, will be observed to have a flux density F enhanced by an amount $\delta^{2+\alpha} < F/F_0 < \delta^{3+\alpha}$ (Condon and Ransom 2016). Here, $\delta \equiv [\Gamma(1-\beta\cos\theta)]^{-1}$ is the Doppler factor of the source. For nearly on-axis jets, the Doppler boosting can be quite large, while the flux from off-axis jets will initially be relativistically beamed away from the observer, and the jet may not become observable until it decelerates and becomes non-relativistic. This explains why on-axis relativistic jets have higher observed peak luminosities than off-axis jets or sub-relativistic sources, and thus why on-axis jetted synchrotron sources (e.g. GRBs, radio-loud TDEs) – although rarer than non-relativistic sources (e.g. SNe, some radio-quiet TDEs) – can be detected to much higher redshifts.

If the full synchrotron spectrum is observed and all of the break frequencies are measured (which typically requires coordinated radio, optical, and X-ray observations with dense temporal sampling), then all of the physical parameters listed above can be uniquely determined. If, as is often the case in TDEs, the optical and X-ray emission are dominated by other processes (see Roth et al. (2020, this issue)), then radio and millimeter observations may provide the only constraints on the synchrotron spectrum and some break frequencies will not be observable, so some parameter degeneracies may persist. In such cases, we can make the simplifying assumption that the energy in the synchrotron-emitting outflow is in equipartition between the electrons and the magnetic field (e.g. Scott and Readhead 1977, Chevalier 1998; Barniol Duran et al. 2013). By reducing the number of free parameters, this allows us

[1] We make several simplifying assumptions, most importantly that the magnetic field is constant over the emitting region, and that all electrons are accelerated into a single power-law distribution of energies, $N_e(E) \propto E^{-p}$ for $E > E_0$ (E_0 is typically taken to be $\gtrsim$ the electron rest mass energy). This is typically the case for single impulsive events like GRBs and TDE jets, but is not always true. For example, the compact jet cores of AGN typically have flat spectra because we are observing a superposition of many different synchrotron components.

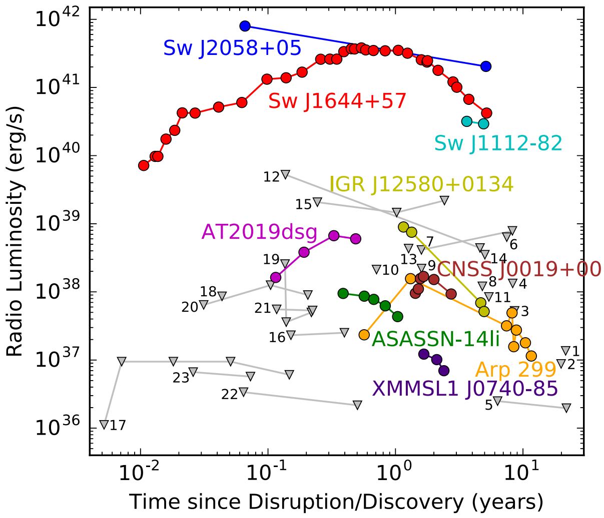

Fig. 1 Literature TDE radio observations. To date, nine TDEs have published radio detections: Sw J1644+57, Sw J2058+05, Sw J1112-82, IGR J12580+0134, ASASSN-14li, XMMSL1 J0740-85, Arp 299-B AT1, CNSS J0019+00, and AT2019dsg (colored circles; see Table 1 and references therein). Although most of the detected TDEs were observed at multiple frequencies, for simplicity we show only a single frequency for each event (8.4 GHz for Arp 299-B AT1 and AT2019dsg, 5 GHz for all others). An additional 23 events have published upper limits (gray triangles; a key to the labels is given in the first column of Table 2). When a non-detected TDE was observed at multiple frequencies on the same date, we show only the most constraining limit. All upper limits are 3σ

to estimate the physical size of the emitting region, the kinetic energy of the outflow, and other physical properties (the outflow velocity, the ambient density, the average magnetic field strength, etc.) even if only part of the synchrotron spectrum is observed (preferably including the peak). The energy thus obtained is a lower bound on the total energy, which can be much larger if the source is not exactly in equipartition, while the size of the emitting region is more robust. Multi-frequency radio observations are preferred for this technique, to constrain the peak frequency and flux density of the radio emission and their temporal evolution. Calculating the size evolution of the emitting region allows us to infer when the outflow was launched (assuming that the radio emission traces the leading edge of the outflow, as expected for external shock models). This is an important constraint for modeling TDEs, for which the time of disruption may not be known precisely (e.g. Zauderer et al. 2011, Alexander et al. 2016). For extremely nearby events, the size evolution of the outflow may also be measured directly using VLBI observations (e.g. Mattila et al. 2018).

3 Radio-Detected TDEs: Probes of Accretion and Outflow Physics

To date, several dozen TDEs have been observed in the radio, revealing a large diversity in their radio properties (Fig. 1). In particular, a few percent of TDEs are radio loud, exhibiting luminous radio emission detectable for years post-disruption, while the rest are radio quiet, with detections or upper limits constraining their radio emission to be orders of magnitude fainter than the radio-loud events. For the purpose of this review, we define a "radio-loud TDE" to have a peak radio luminosity $\nu L_\nu > 10^{40}$ erg s^{-1} and a "radio-quiet TDE" to have

Table 1 TDEs with published radio detections

Name	Redshift	Discovery method	Peak radio luminosity ($\mathrm{erg\,s^{-1}}$)	Proposed origin(s) of radio emission (see text)	Reference(s) for radio data
Sw J1644+57	0.354	γ-rays	4×10^{41}	on-axis initially relativistic jet	Zauderer et al. (2011, 2013); Berger et al. (2012); Wiersema et al. (2012); Yang et al. (2016); Eftekhari et al. (2018)
Sw J2058+05	1.1853	γ-rays	8×10^{41}	on-axis initially relativistic jet	Cenko et al. (2012); Pasham et al. (2015); Brown et al. (2017)
Sw J1112−82	0.8901	γ-rays	3×10^{40}	on-axis initially relativistic jet	Brown et al. (2017)
IGR 12580+0134*	0.00411	X-rays	9×10^{38}	off-axis initially relativistic jet	Irwin et al. (2015); Yuan et al. (2016); Perlman et al. (2017)
AT2019dsg	0.051	optical	7×10^{38}	outflow (collimation and max velocity uncertain)	Stein et al. (2020)
Arp 299-B AT1*	0.010411	near-IR	2×10^{38}	off-axis jet	Mattila et al. (2018)
CNSS J0019+00*	0.018	radio	2×10^{38}	non-relativistic outflow	Anderson et al. (2019)
ASASSN-14li*	0.0206	optical	9×10^{37}	non-relativistic outflow, internal shocks in on-axis jet, or unbound debris	Alexander et al. (2016); van Velzen et al. (2016); Romero-Cañizales et al. (2016); Bright et al. (2018)
XMMSL1 J0740-85	0.0173	X-rays	1×10^{37}	outflow (collimation and max velocity uncertain)	Saxton et al. (2017); Alexander et al. (2017a)

*Host galaxy exhibited weak to significant AGN activity prior to the onset of the TDE

$\nu L_\nu < 10^{40}$ erg s^{-1}. We list the nine TDEs with published radio detections in Table 1, in order of decreasing peak radio luminosity. While we generally assume that both radio-loud and radio-quiet TDEs are powered by the disruption of a star, the parameters of the disruption could be different. Radio-loud TDEs also exhibit bright high-energy emission and are discussed in more detail by Zauderer et al. (2020, this issue). Their unique properties are generally attributed to the fact that they launch very energetic relativistic jets viewed on-axis, while other TDEs either launch jets viewed off-axis or do not launch energetic jets. (Off-axis jets will have a much fainter peak luminosity than on-axis jets because the radio emission is suppressed at early times by Doppler beaming, as discussed above.) Differences in parameters such as circumnuclear density, magnetic field strength or configuration, black hole spin, and disruption geometry may also contribute to the observed wide range of TDE radio luminosities (e.g. Giannios and Metzger 2011, van Velzen et al. 2011b, 2013, Krolik et al. 2016, Generozov et al. 2017, Yalinewich et al. 2019). The impact of host galaxy environment on TDE properties is discussed further in Sect. 4 and in French et al. (2020, this issue).

In contrast, radio-quiet TDEs are generally (but not always) discovered in the X-ray, optical, or UV (see Saxton et al. (2020, this issue) and van Velzen et al. (2020a, this issue)). Optical and X-ray-discovered TDEs are also called thermal TDEs because their optical, UV, and X-ray emission generally can be well-modeled as a blackbody peaking in the UV or soft X-ray. Only a handful of thermal TDEs have radio detections, but this may be partially an observational bias. Many TDEs received radio follow up that would have been too sparse or too shallow to reveal low-luminosity outflows similar to those seen in radio-detected sources (Fig. 1, gray triangles), and about half of known TDEs have not been observed in the radio at all. While the current data cannot rule out the hypothesis that radio emission with a peak luminosity $\sim 10^{38}$ erg s^{-1} may be common in radio-quiet TDEs, deep upper limits for several recent events (e.g. Blagorodnova et al. 2017, van Velzen et al. 2019, Saxton et al. 2019) hint that there may be additional diversity within this class. We have compiled a list of all published radio non-detections of TDEs available in the literature, presented in Table 2. Below, we discuss the physical insights derived from radio observations of the two best-studied radio-detected TDEs to date: the radio-loud Sw J1644+57 and the radio-quiet ASASSN-14li. We also briefly summarize the properties of other TDEs detected in the radio.

3.1 Sw J1644+57: A Relativistic Jet

Sw J1644+57 was discovered by the Neil Gehrels Swift Observatory on 28 March 2011 as an unusual γ-ray and X-ray transient coincident with the nucleus of a galaxy at redshift $z = 0.354$ (Bloom et al. 2011; Burrows et al. 2011; Levan et al. 2011; Zauderer et al. 2011). Associated radio emission was discovered within 24 hours, initiating an extensive radio observing campaign spanning $1 - 345$ GHz (Zauderer et al. 2011; Bloom et al. 2011; Levan et al. 2011; Berger et al. 2012; Wiersema et al. 2012; Zauderer et al. 2013; Yang et al. 2016; Eftekhari et al. 2018).[2] The full radio dataset includes observations extending to ≈ 2000 days post-discovery and the source continues to be detected in multi-frequency observations. Here, we focus on the radio properties of Sw J1644+57; for more discussion of this source and other TDEs with high-energy emission, see Zauderer et al. (2020, this issue).

The radio observations of Sw J1644+57 capture the peak of the synchrotron emission. The peak frequency, ν_p, decreases with time, while the peak flux density $F_{\nu,p}$ remains approximately constant (within a factor ~ 3) for ~ 400 days and then decreases (Eftekhari

[2] Sw J1644+57 was also observed at 149 MHz by LOFAR, but the resulting non-detection is not constraining (Cendes et al. 2014).

Table 2 Published radio upper limits of TDEs

Fig. 1 label	Name	Redshift	MJD (d)	Δt[1] (yr)	Frequency (GHz)	3σ upper limit (μJy)	Reference
1	RXJ1624+7554	0.06	56082.342	21.6	3.0	51	Bower et al. (2013)
2	RXJ1242-1119	0.046	56085.027	19.9	3.0	54	Bower et al. (2013)
3	SDSSJ1323+48	0.08	56082.301	8.6	3.0	102	Bower et al. (2013)
4	SDSSJ1311-01	0.156	56085.040	8.3	3.0	57	Bower et al. (2013)
5	NGC 5905	0.012	50390.786	6.3	8.46	90	Komossa (2002)
5	NGC 5905	0.012	56082.328	21.9	3.0	200	Bower et al. (2013)
6	GALEX-D1-9	0.326	55955.988	7.46	5.0	27	van Velzen et al. (2013)
7	GALEX-D3-13[2]	0.3698	53478.312	1.26	1.4	45	Bower (2011)
7	GALEX-D3-13	0.3698	55955.498	8.05	5.0	24	van Velzen et al. (2013)
8	D23H-1	0.186	55955.938	4.8	4.3	24	van Velzen et al. (2013)
9	PTF10iya	0.224	55955.479	1.6	5.0	24	van Velzen et al. (2013)
10	PS1-10jh	0.170	55649.348	0.71	5.0	45	van Velzen et al. (2013)
11	SDSS-TDE1	0.136	55955.942	5.4	5.0	30	van Velzen et al. (2013)
12	SDSS-TDE2	0.252	54407.071	0.137	8.4	255	van Velzen et al. (2011a)
12	SDSS-TDE2	0.252	55955.935	4.6	5.0	36	van Velzen et al. (2013)
13	SDSSJ1201+30	0.146	55819.767	1.267	8.3	108	Saxton et al. (2012)
13	SDSSJ1201+30	0.146	55819.779	1.267	4.8	135	Saxton et al. (2012)
13	SDSSJ1201+30	0.146	55819.788	1.267	1.4	201	Saxton et al. (2012)
14	PTF09axc	0.1146	56836.221	4.953	6.1	150	Arcavi et al. (2014)
14	PTF09axc	0.1146	56836.233	4.953	3.5	330	Arcavi et al. (2014)

Table 2 (*Continued*)

Fig. 1 label	Name	Redshift	MJD (d)	Δt[1] (yr)	Frequency (GHz)	3σ upper limit (μJy)	Reference
15	PS1-11af	0.4046	55649.053	0.186	4.9	51	Chornock et al. (2014)
15	PS1-11af	0.4046	55933.409	0.965	5.875	30	Chornock et al. (2014)
15	PS1-11af	0.4046	56443.992	2.363	5.875	45	Chornock et al. (2014)
16	PS16dtm	0.0804	57653.227	0.00610	21.8	57	Blanchard et al. (2017)
16	PS16dtm	0.0804	57653.250	0.00616	6.0	23	Blanchard et al. (2017)
16	PS16dtm	0.0804	57743.136	0.252	21.8	51	Blanchard et al. (2017)
16	PS16dtm	0.0804	57743.159	0.252	6.0	25	Blanchard et al. (2017)
17	iPTF16fnl	0.016328	57631.281	−0.00224	22	52[3]	Blagorodnova et al. (2017)
17	iPTF16fnl	0.016328	57631.293	−0.00221	6.1	34[3]	Blagorodnova et al. (2017)
17	iPTF16fnl	0.016328	57632	−0.000274	15	117	Blagorodnova et al. (2017)
17	iPTF16fnl	0.016328	57636	0.0107	15	117	Blagorodnova et al. (2017)
17	iPTF16fnl	0.016328	57648	0.0435	15	117	Blagorodnova et al. (2017)
17	iPTF16fnl	0.016328	57683	0.139	15	75	Blagorodnova et al. (2017)
18	iPTF15af	0.07897	57053.215	−0.0659	22	108	Blagorodnova et al. (2019)
18	iPTF15af	0.07897	57053.225	−0.0659	6.1	84	Blagorodnova et al. (2019)
19	AT2018zr	0.071	58205.883	0.0344	16	120	van Velzen et al. (2019)
19	AT2018zr	0.071	58207.170	0.0379	10	27	van Velzen et al. (2019)
19	AT2018zr	0.071	58236.154	0.117	10	37.5	van Velzen et al. (2019)
20	AT 2018fyk	0.059	58380.677	0.0313	18.95	38	Wevers et al. (2019)
20	AT 2018fyk	0.059	58407.490	0.1048	18.95	74	Wevers et al. (2019)
20	AT 2018fyk	0.059	58444.289	0.2055	18.95	53	Wevers et al. (2019)
21	AT 2017eqx	0.1089	57948.465	0.0736	21.7	80	Nicholl et al. (2019)
21	AT 2017eqx	0.1089	57948.477	0.0736	6.0	27	Nicholl et al. (2019)

Table 2 (*Continued*)

Fig. 1 label	Name	Redshift	MJD (d)	Δt^{1} (yr)	Frequency (GHz)	3σ upper limit (μJy)	Reference
21	AT 2017eqx	0.1089	57987.240	0.180	21.7	76	Nicholl et al. (2019)
21	AT 2017eqx	0.1089	57987.252	0.180	6.0	26	Nicholl et al. (2019)
22	XMMSL2_J1446+68	0.029	57646.155	0.0643	21.7	85	Saxton et al. (2019)
22	XMMSL2_J1446+68	0.029	57646.167	0.0643	6.0	28	Saxton et al. (2019)
22	XMMSL2_J1446+68	0.029	57806.511	0.503	21.7	84	Saxton et al. (2019)
22	XMMSL2_J1446+68	0.029	57806.524	0.503	6.0	18	Saxton et al. (2019)
23	ASASSN-18pg	0.017392	58319.454	−0.06611	18.95	50	Holoien et al. (2020)
23	ASASSN-18pg	0.017392	58336.617	−0.01912	18.95	43	Holoien et al. (2020)

[1]Time relative to peak bolometric luminosity, given in the observer frame. For events with sparse multi-wavelength coverage, we list the time relative to maximum light in a single optical or X-ray observing band

[2]Based on serendipitous observations of the TDE field co-added by Bower (2011) (note: Bower 2011 reports the observation dates as 2003 Dec 2, 2005 Apr 18, and 2005 Jun 20. However, the VLA data archive records no observations within 1 degree of the TDE coordinates on Jun 20, so it is likely that one or more of the observations of the field collected under the same observing program between 2005 May 14 - 2005 Jun 7 were used instead. We use the MJD of the 2005 Apr 18 observation to compute Δt for this observation)

[3]Based on a re-reduction of the data by KDA

et al. 2018). This behavior is consistent with synchrotron emission from an initially mildly relativistic ($\Gamma \approx 3$), collimated jet that expands and slowly decelerates (Zauderer et al. 2011; Berger et al. 2012; Zauderer et al. 2013; Eftekhari et al. 2018). The jet launch date inferred from the radio observations is consistent with the onset of the high-energy emission (Zauderer et al. 2011). For equipartition models and other models where the energy carried by electrons and the energy in magnetic fields remain constant fractions of the total energy, the total energy must increase by an order of magnitude from $30-250$ days. This could be explained by structured ejecta, in which slower-moving material catches up to the head of the jet as it decelerates and begins contributing to the emission at later times (e.g. Berger et al. 2012, Mimica et al. 2015). An alternate possibility is that the energy distribution varies in time; e.g. most energy is initially carried by the magnetic field, and at later times shifts to being carried by the electrons (Barniol Duran and Piran 2013). In this case, it is possible for the total energy in the jet to remain constant. However, more recent work sees no evidence for such time variations (Eftekhari et al. 2018).

The electrons producing the radio emission in Sw J1644+57 are in the slow cooling regime, but at higher frequencies a cooling break in the synchrotron spectrum is expected (e.g. Granot and Sari 2002). The location of this break provides an additional constraint on the synchrotron model, breaking parameter degeneracies and removing the need to assume equipartition. The optical data alone cannot precisely constrain the position of the cooling break, as they are affected by a large but uncertain amount of host extinction (Levan et al. 2016). Until 500 days, the X-rays are dominated by emission from the base of the jet (Zauderer et al. 2011; Berger et al. 2012; Zauderer et al. 2013), rather than by the same synchrotron component producing the radio emission. At 500 days, the X-ray luminosity drops precipitously as the jet shuts off, and the residual X-rays are consistent with an extension of the radio emission spectrum (Zauderer et al. 2013). The post-500 days X-ray data, together with the optical observations, allow constraints on both the cooling break frequency and the amount of host extinction (Eftekhari et al. 2018). This reveals a magnetic field lower than the equipartition value, and correspondingly increases the total energy in the jet by a factor of 3 to $E \sim 4 \times 10^{51}$ erg (Eftekhari et al. 2018).

3.2 ASASSN-14li: A Thermal TDE with Radio Emission

ASASSN-14li was discovered by the All Sky Automated Survey for SuperNovae (ASAS-SN) on 22 November 2014, coincident with the center of the $z = 0.0206$ galaxy PGC043234 (luminosity distance $d_L \approx 90$ Mpc). It was subsequently detected across the electromagnetic spectrum (Miller et al. 2015, Holoien et al. 2016, van Velzen et al. 2016, Alexander et al. 2016, Jiang et al. 2016; Romero-Cañizales et al. 2016; Bright et al. 2018). Unlike many TDEs, it exhibited both optical and X-ray variability, along with declining radio emission and an infrared echo. ASASSN-14li has the best-studied radio emission of all thermal TDEs and has become a poster child for this class. Below, we summarize several different models that have been proposed to explain its radio emission, which is $\sim 10^3$ times less luminous than Sw J1644+57's.

3.2.1 Non-Relativistic Wind

Alexander et al. (2016) modeled ASASSN-14li's radio emission as synchrotron radiation arising from the external shock between outflowing material from the TDE and the surrounding circumnuclear medium. In this model, the peak of the radio spectral energy distribution (SED) corresponds to the synchrotron self absorption frequency, which depends on the density and the properties of the outflow. Assuming that the energy contained in the outflow is always in equipartition between the electrons and the magnetic field (and that emission from a single region dominates the radio SED at all frequencies) allows the energy and radius of the emitting region to be computed independently in each multi-frequency radio epoch (e.g. Barniol Duran et al. 2013). Thus, no dynamical assumptions are required and the derived physical properties of the emitting region don't depend on any specific launching mechanism for the outflow.

In the case of ASASSN-14li, multi-frequency radio observations with the Karl G. Jansky Very Large Array (VLA) were found to be consistent with an outflow with a constant equipartition energy of $\sim 10^{48}$ erg expanding at a constant velocity $0.04-0.12c$ (Alexander et al. 2016). (There is a mild degeneracy between the energy/velocity and the assumed opening angle of the outflow, with a spherical outflow moving slower than a conical one.) This method also revealed a steep circumnuclear density profile proportional to $r^{-2.5}$ (Sect. 4). These properties are consistent with expectations for a wind produced during a phase of super-Eddington accretion (Strubbe and Quataert 2009). Alexander et al. (2016) showed that the launch time of ASASSN-14li's outflow roughly coincided with the time when the accretion rate first exceeded Eddington (independently estimated from the optical, UV, and X-ray light curves), providing additional support for this picture. In this scenario, only TDEs in which the peak accretion rate exceeds the Eddington limit would produce radio emission. Alternately, recent simulations suggest that a similar outflow could also be launched by the self-intersection of the bound debris stream, expected due to relativistic apsidal precession (Lu and Bonnerot 2020). Such collision-induced outflows could produce radio emission with a wide range of peak luminosities and timescales.

3.2.2 Unbound Tidal Debris Stream

Approximately half of the stellar debris from a TDE will ultimately accrete onto the SMBH, while the rest is unbound (Rees 1988). A second possibility is that ASASSN-14li's radio emission is produced by the interaction between the unbound debris and the circumnuclear medium. In this case, synchrotron radiation is emitted in the bow shock that forms along the leading edge of the debris stream, and the emitting region is expected to expand at a velocity $\sim 0.2c$ (Krolik et al. 2016). Krolik et al. (2016) performed a similar equipartition analysis to Alexander et al. (2016) and reached similar conclusions about the velocity and energetics of the radio-emitting material in ASASSN-14li, roughly consistent with this picture. Only a tiny fraction of the unbound debris is required to produce the observed radio luminosity, consistent with a model in which the bulk of the unbound debris has not yet decelerated on the timescale of the observations.

An important prediction of this model is that all TDEs should generate radio emission from this process, with no dependence on the peak accretion rate. However, the brightness of the emission will depend on both the ambient density and the cross-section of the debris stream (which may be quite small for some observer viewing angles). Some theoretical studies suggest that in most disruptions the debris stream should remain self-gravitating until large radii (e.g. Guillochon et al. 2016, Steinberg et al. 2019); in this case, the stream may be too narrow to produce detectable radio emission. However, for disrupted stars on deeply plunging orbits, the unbound debris fan may be more dispersed (Strubbe and Quataert 2009; Yalinewich et al. 2019) and more luminous emission similar to that seen in ASASSN-14li may be possible. As only a small amount of mass is required to produce the observed radio emission in ASASSN-14li (Krolik et al. 2016; Yalinewich et al. 2019), only a small fraction of the ejecta need not be self-gravitating. Recent work by Piran et al. (in prep) suggests that in most TDEs, radio emission from the bow shock generated by the fastest unbound debris should be marginally detectable, with a peak flux density of a few μJy for a TDE at the distance of ASASSN-14li (~ 90 Mpc).

3.2.3 Jet

A third possibility to explain the radio flare of ASASSN-14li is emission from a (sub-)relativistic jet. Such jets can have two modes of emission. External emission is powered by a forward shock that the jet drives into the surrounding medium (in AGN jets these shocks power the so-called hotspots). The external mode of emission is akin to the wind and unbound-debris models discussed above. However jets can also produce synchrotron emission without interaction with a surrounding medium. This internal emission mechanism is powered by shocks inside the jet (in AGN jets, internal emission is responsible for the compact, flat-spectrum radio cores).

The first model that was proposed for radio emission of ASASSN-14li was external (i.e., shock-driven) emission from a relativistic jet (van Velzen et al. 2016). This model could explain the 16 GHz light curve, but the multi-frequency radio observations (Alexander et al. 2016) that appeared later challenged this interpretation. Romero-Cañizales et al. (2016) also suggested the possibility of a relativistic jet in ASASSN-14li, based on VLBI observations that showed two separate components of radio emission separated by ~ 2 pc (implying superluminal motion from a nearly on-axis relativistic jet with $\Gamma \gtrsim 7$). However, jets with similarly high Lorentz factors typically have much higher brightness temperatures, so they conclude that the second emission component is more likely unrelated to the TDE (Sect. 4.2).

An improvement to the jet model for ASASSN-14li is presented in Pasham and van Velzen (2018), who updated the original internal emission mechanism for TDE jets (van Velzen et al. 2011b) to include adiabatic cooling. In this model the jet consists of a superposition of synchrotron-emitting regions in a conical geometry, each with their own equipartition magnetic field. Applying this model to the observed synchrotron SEDs yield a measurement of the scaling of the equipartition magnetic field with the radius in the jet, which was found to be $B \propto R^{-1.02\pm0.05}$. This is remarkably close to the predicted power-law index of -1 for a freely expanding jet that is powered by an internal emission mechanism (Blandford and Königl 1979; Falcke and Biermann 1995).

The strongest evidence against an external emission mechanism for the radio properties of ASASSN-14li is the detection of a cross-correlation between the X-ray and radio light curves (Pasham and van Velzen 2018); the radio lags the X-rays by about 12 days (see van Velzen et al. (2020b, this issue) for details of the cross-correlation). Establishing this correlation requires a coupling between the X-ray emitting disk and the source of the radio photons. This coupling is not expected in any of the proposed external emission mechanisms (disk-wind, streams shocks, or jet hotspots) because these are all impulsive: the radio emission is governed by the evolution of the shock, which decouples from the accretion disk. However in an internal jet model, this coupling is naturally expected (and is observed for jets from active black holes; Falcke and Biermann 1995, Marscher et al. 2002). The observed 12 day lag is consistent with the time that is required for the 16 GHz radio emission to become optically thin to synchrotron self absorption.

3.3 Other Detected Sources

At the time of writing, seven other TDEs with radio detections have been reported in the literature (Fig. 1). Two of these sources, Sw J2058+05 and Sw J1112-82, were discovered in archival searches of Swift data and have similar γ-ray, X-ray, and radio properties to Sw J1644+57 (Cenko et al. 2012; Pasham et al. 2015; Brown et al. 2015, 2017). Like Sw J1644+57, they likely launched energetic relativistic jets viewed on-axis. For a more complete discussion of these sources, see Zauderer et al. (2020, this issue).

As jets in the most energetic TDEs are thought to be narrowly collimated, we expect that most jetted TDEs will be viewed off-axis. In this case, the radio emission is suppressed at early times due to relativistic beaming effects, but will appear similar to on-axis jetted events after the jet decelerates (Granot et al. 2002; van Velzen et al. 2013). However, by this point, the radio emission evolves very slowly – so it may be difficult to identify the transient nature of off-axis TDEs (Eftekhari et al. 2018). To date, two additional radio TDEs, IGR J12580+0134 and Arp 299-B AT1, have been proposed to exhibit off-axis jets (Lei et al. 2016; Mattila et al. 2018). IGR J12580+0134's radio emission was discovered serendipitously in a survey of nearby galaxies (Irwin et al. 2015), and was connected to a hard X-ray flare interpreted as a TDE that occurred in the same galaxy one year prior (Nikołajuk and Walter 2013). Its peak radio luminosity is intermediate between Sw J1644+57's and ASASSN-14li's (Fig. 1). This event occurred in a known AGN, so it is possible that the radio emission is associated with another type of AGN flaring event – nevertheless, late-time radio follow up observations show that the radio flux density has decreased by a factor $\gtrsim 10$ over five years (Perlman et al. 2017), which is extreme for typical AGN flares (Hovatta et al. 2008; Nieppola et al. 2009).

In contrast, Arp 299-B AT1 was discovered as a bright flare in the near-IR, and was luminous and long-lasting in both the IR and radio (Mattila et al. 2018). It exhibits no variability at shorter wavelengths due to extremely high host galaxy extinction (Mattila et al. 2018). Its host, Arp 299, consists of two merging galaxies, potentially resulting in a temporarily enhanced TDE rate; the nucleus in which the flare occurred is also a Compton-thick AGN with an almost edge-on torus. It has been observed extensively in the radio with VLBI, directly imaging a resolved jet in a TDE for the first time (Mattila et al. 2018). These observations initially show only a single emerging jet with no corresponding counterjet, allowing a constraint on the viewing angle ($25 - 35°$). This implies that the TDE accretion disk is not aligned with the pre-existing AGN torus. It is possible that many TDEs occur in galaxy nuclei with similarly high levels of extinction, and are currently being missed by the optical and X-ray surveys that have yielded most TDE discoveries to date.

The remaining three radio-quiet TDEs also likely launched outflows, but these outflows may be quasi-spherical rather than collimated jets. XMMSL1 J0740-85 was discovered during the XMM Newton Slew Survey (Saxton et al. 2008) on 2014 April 1 as a bright X-ray transient (Saxton et al. 2017). Its X-ray spectrum contained both thermal and non-thermal components, placing it in between the jetted Swift events and TDEs not detected in γ-rays. XMMSL1 J0740-85 exhibited little to no variability in the optical and modest variability in the UV (Saxton et al. 2017). At late times ($\gtrsim 600$ days after discovery), weak, fading radio emission was observed (Alexander et al. 2017a). The origin of this radio emission is ambiguous: it is consistent with either a decelerated jet or an always non-relativistic outflow. In either model, the energy contained in the outflowing material is much less than the energy of Sw J1644+57's jet.

Further deep radio observations of TDEs are needed to determine whether weak radio emission like that seen in XMMSL1 J0740-85 and ASASSN-14li is common (Sect. 5), and to determine the physical conditions that lead to jet formation in a small subset of TDEs. Such efforts are already proving fruitful. For example, the most recently reported optical TDE with a radio detection, AT2019dsg (Stein et al. 2020), has a similar luminosity to

ASASSN-14li, but unlike ASASSN-14li it shows a linear increase of the equipartition energy with time, possibly suggesting that the outflow or jet in this source receives a constant injection of power at its origin.

Future radio facilities will have the capabilities to carry out blind searches for radio transients, and may discover many events that would have been missed by optical and X-ray surveys. Radio emission is not affected by extinction, so a uniform sample of TDEs discovered in the radio will provide an independent estimate of the TDE rate (Sect. 5.3). The final radio-detected TDE, CNSS J0019+00, was discovered in a blind search for radio transients in the SDSS Stripe 82 region, illustrating the promise of this technique (Mooley et al. 2016; Anderson et al. 2019). This TDE was in a Seyfert 2 galaxy and was localized to within 1 pc of the galaxy nucleus by VLBI observations. CNSS J0019+00's luminosity and duration make it more similar to other radio-quiet TDEs than to supernovae or AGN flares (although a reactivated AGN cannot be completely ruled out; Anderson et al. 2019). Similar to ASASSN-14li and XMMSL1 J0740-85, CNSS J0019+00's radio emission can be well-modeled as a sub-relativistic spherical outflow with an energy $\sim 10^{49}$ erg, expanding at a velocity $\sim 0.05c$ (Anderson et al. 2019).

4 Host Properties and Constraints on Nuclear Environments from Radio Observations

Radio observations of TDEs also reveal useful information about the properties of their host galaxies. The immediate vicinity of the SMBH can be probed via the interaction between outflowing debris from the TDE and the circumnuclear medium, while VLBI observations may reveal structures in the circumnuclear environment at larger scales. Processes such as star formation and AGN activity may also produce radio emission in the vicinity of the TDE; these additional sources of emission must be properly accounted for when interpreting radio observations carried out during the flare. Due to the long cooling time, relic lobes of AGN activity prior to the TDE can generate (near) nuclear radio emission that lingers for $\sim$Gyr. Additionally, AGN can exhibit radio variability on timescales ranging from hours to decades, including flares with typical timescales of a few years (Hovatta et al. 2008; Nieppola et al. 2009). The amplitude of such flares is typically much smaller than the level of variability seen during radio-detected TDEs, but more observations are needed to properly locate radio TDEs within the broader framework of SMBH accretion.

Surveying large areas of the radio sky at high resolution is time-consuming and data-intensive; until recently, only shallow extragalactic source catalogs existed for the vast majority of the radio sky. Thus, meaningful constraints on the pre-flare radio emission from TDE hosts has so far only been possible for the nearest events. This situation has started to change with the advent of the VLA Sky Survey (VLASS), which will image the entire sky north of declination -40° with a combined limiting rms of 69 μJy, and with the deployment of ASKAP and MeerKAT in the southern hemisphere, building towards the extremely sensitive Square Kilometer Array (SKA). In this section, we summarize the progress that has been made so far using radio observations to study the nuclear environments in which TDEs occur.

4.1 Density Constraints

When radio emission is produced in an external shock between a transient outflow and the surrounding medium, then we can also use radio observations of TDEs to infer the ambient

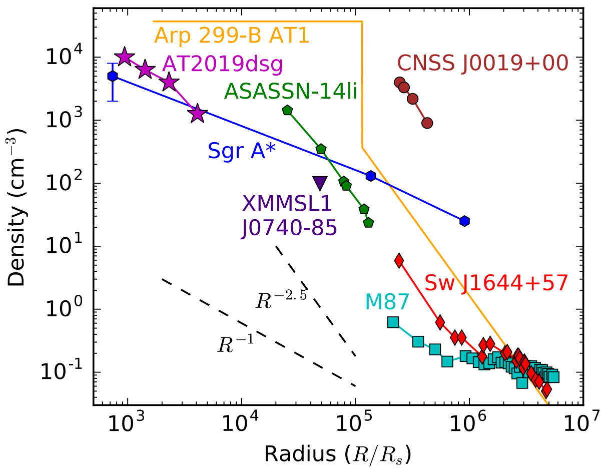

Fig. 2 The circumnuclear density profiles of TDE host galaxies inferred from their radio observations, with the distance from each SMBH given in units of its Schwarzschild radius. The normalization of the profiles for ASASSN-14li (Alexander et al. 2016), XMMSL1 J0740-85 (Alexander et al. 2017a), and AT2019dsg (Stein et al. 2020) depends on the geometry of the outflows, which is not well constrained by the data; here, we assume spherical outflows. The density profile for Sw J1644+57 is taken from the analysis by Eftekhari et al. (2018), the profile for Arp 299-B AT1 is taken from Mattila et al. (2018), and the profile for CNSS J0019+00 is taken from Anderson et al. (2019). Shown for comparison are measurements of the density profile around two other well-studied SMBHs: the nearby and more massive M87 (Russell et al. 2015), and Sagittarius A* (Baganoff et al. 2003; Gillessen et al. 2019). Sgr A* has a much shallower density profile ($\rho \propto r^{-1}$) than ASASSN-14li's SMBH ($\rho \propto r^{-2.5}$) at comparable distance scales. We also show sample r^{-1} and $r^{-2.5}$ profiles to guide the eye (black dashed lines)

density surrounding the supermassive black hole at parsec or even sub-parsec scales (e.g. Alexander et al. 2016, Krolik et al. 2016, Eftekhari et al. 2018; Mattila et al. 2018, Anderson et al. 2019, Stein et al. 2020). As the outflow expands, independent measurements of the density at different epochs can be used to construct a density profile of the circumnuclear gas. (The dust distribution at comparable distances can be indirectly probed via the detection of infrared dust echoes; see van Velzen et al. (2020b, this issue) and references therein.) Such constraints are extremely valuable, as these scales are not directly resolvable at any wavelength with current facilities at the distance of most TDE hosts.

The shape of the ambient circumnuclear density profile directly probes the history of accretion onto the SMBH in the TDE host galaxy and the circumnuclear environment. Spherically symmetric accretion results in a Bondi profile, $\rho \propto r^{-3/2}$ (Bondi 1952), while adding the effects of mass loss from massive stars produces a shallower profile (e.g. Quataert 2004, Generozov et al. 2017). A recent compilation of density measurements for Sagittarius A* reveals a density profile $\rho \propto r^{-1}$ over four orders of magnitude in distance,[3] consistent with this picture (Gillessen et al. 2019 and references therein). We compare these results with the density measurements inferred for TDE host galaxies in Fig. 2. AT2019dsg's density profile is similar to Sgr A*'s (Stein et al. 2020), while Sw J1644+57's host galaxy exhibits a Bondi-like profile at $\gtrsim 0.7$ pc (Eftekhari et al. 2018). In contrast, ASASSN-14li's and CNSS J0019+00's host galaxies exhibit a steeper profile, $\rho \propto r^{-2.5}$ (Alexander et al. 2016,

[3] We note that the available observations only sparsely sample Sgr A*'s density profile, so in principle deviations from r^{-1} over a narrower range of radii could be present.

Krolik et al. 2016; Anderson et al. 2019).[4] Arp 299-B AT1's radio emission can be best fit with a dense torus extending to 6.75×10^{17} cm, with a similarly steep $r^{-2.5}$ density profile at larger radii (Mattila et al. 2018). Such a steep profile is not expected for spherically symmetric accretion, but appears in some models of super-Eddington accretion flows (e.g. ZEBRAs; Coughlin and Begelman 2014). This may indicate that the circumnuclear environments of ASASSN-14li's, Arp 299-B AT1's, and CNSS J0019+00's host galaxies have been shaped by previous episodes of accretion onto their SMBHs. This is consistent with multi-wavelength evidence of at least a low level of AGN activity in these galaxies that predates the TDE outburst (Alexander et al. 2016; Romero-Cañizales et al. 2016; Mattila et al. 2018; Anderson et al. 2019).

4.2 Radio Evidence for AGN Activity and Complex Nuclear Environments

Interestingly, of the six published radio-quiet TDEs with detected low-luminosity radio emission, only two (XMMSL1 J0740-85 and AT2019dsg) occurred in host galaxies that showed no signs of recent or ongoing AGN activity (Table 1). This may indicate that AGN produce environmental conditions particularly favorable for the production of detectable radio emission in TDEs, but it also raises the question of possible contamination. While this is a valid concern (as noted in Sect. 3.3, AGN flares cannot be completely ruled out as an explanation for two or three of the radio-quiet TDEs discussed here), the past two decades of increasingly detailed observations have also allowed us to build up a set of multi-wavelength characteristics that differentiate AGN variability from true TDEs. The multi-wavelength properties that distinguish TDEs from "imposters" such as nuclear SNe or AGN flares are discussed in detail in Zabludoff et al. (2020, this issue). For some events whose optical and X-ray properties are ambiguous, the radio properties of the transient and its host galaxy may help to clarify its nature, as AGN variability is typically much less extreme at radio wavelengths compared to other parts of the electromagnetic spectrum (e.g. Hovatta et al. 2008, Nieppola et al. 2009).

Pre-flare radio observations of a TDE's host galaxy provide important context for interpreting radio observations collected during the TDE (e.g., Alexander et al. 2016; van Velzen et al. 2016; Romero-Cañizales et al. 2016; Mattila et al. 2018; Anderson et al. 2019). For example, ASASSN-14li's host galaxy was detected in two archival radio surveys $15 - 20$ years prior to the discovery of the TDE. Optical spectra of the host galaxy reveal a level of ongoing star formation an order of magnitude too low to explain the archival radio emission, so the best explanation for the archival detections is that ASASSN-14li's host galaxy hosts a weak AGN (Alexander et al. 2016; van Velzen et al. 2016). Long-term monitoring of ASASSN-14li's radio emission revealed a plateau starting ~ 1 year after discovery, indicating that the transient component of the emission has faded, and we are now viewing only the quiescent component (Bright et al. 2018).

The spectral index of the baseline radio emission in the host galaxy of ASASSN-14li is steep ($\alpha \approx -1$), suggesting that the emission is due to a "relic" population of electrons that was accelerated up to a few Gyr prior to the TDE. Integral field spectroscopy supports this evidence for recent, but not on-going, AGN activity in the host galaxy of ASASSN-14li

[4] We note that this result is only valid for models in which the radio emission arises from an external (forward) shock (Sects. 3.2.1 and 3.2.2). In the model presented by Pasham and van Velzen (2018) (Sect. 3.2.3), the radio emission arises internal to the jet and thus does not provide any information about the density profile of the external medium. However, because the data prefer a freely-expanding jet, Pasham and van Velzen (2018) infer that the external density must be low.

(Prieto et al. 2016). VLASS observations of new TDEs will help determine whether similar low levels of AGN activity are common in TDE host galaxies.

A more detailed picture of the nuclear environment may also be obtained via extremely high resolution VLBI observations. VLBI observations at early times can help pinpoint the nuclear position of the transient, confirming or ruling out a TDE origin. This is especially useful for more distant events, like Sw J1644+57 (Zauderer et al. 2011). Observations at later times can also constrain the velocity and orientation of the jet relative to the observer's line of sight (as Yang et al. 2016 do for Sw J1644+57), and can even directly resolve the jet for nearby events (as Mattila et al. 2018 do for Arp 299-B AT1).

VLBI observations of nearby events additionally reveal that many TDEs occur in complex nuclear environments. In two events, ASASSN-14li and IGR 12580+0134, VLBI observations taken after the discovery of each transient revealed multiple emission components in the nuclear vicinity, some of which were at least marginally resolved (Romero-Cañizales et al. 2016; Perlman et al. 2017). In both cases, these secondary components would require superluminal motion if associated with the TDE; more likely they are related to previous episodes of accretion activity. In the case of ASASSN-14li, it is also possible that the two observed radio components may correspond to the two components of a binary black hole (Romero-Cañizales et al. 2016). Additionally, Mattila et al. (2018) observed multiple compact radio sources in the nuclear vicinity (within a few parsecs) of Arp 299-B AT1 in pre-TDE VLBI imaging. This is not surprising, given that its host galaxy both contains an AGN and has an exceptionally high core-collapse supernova rate.

5 Upper Limits and Occurrence Rates

5.1 Radio Follow-up Observations

In 2011, the year when Sw J1644+57 was discovered, very few TDEs had received radio follow-up observations (exceptions are NGC 5905, Komossa 2002, and SDSS-TDE2, van Velzen et al. 2011a). This lack of data allowed for the exciting possibility of TDE unification via orientation, akin to the successful unification model of AGN (Bloom et al. 2011). The hope was that every TDE produces a relativistic jet, with Sw J1644+57 being the first discovered on-axis example of this new class of transient jets from SMBHs (e.g. Giannios and Metzger 2011). The first hint that this unified model of thermal and relativistic TDEs is not correct was presented by Bower (2011), who found no detections in archival radio observations available for a small number of TDEs (see Table 2). The first targeted follow-up observations of thermal TDEs were obtained using the VLA (Bower et al. 2013; van Velzen et al. 2013) and also yielded no detections.

To obtain an estimate of the off-axis radio flux of an event similar to Sw J1644+57, van Velzen et al. (2013) used the observed radio light of this source and adopted a constant late-time bulk Lorentz factor of 2; this Lorentz factor was inferred from the late-time radio light curve of Sw J1644+57 (Berger et al. 2012). Even with this conservative assumption, the radio upper limits obtained in 2013 could be used to rule out a unified model in which all thermal TDEs produce jets similar to Sw J1644+57 (van Velzen et al. 2013). A few years later, a more physical prediction of the off-axis radio luminosity of jet similar to Sw J166+57 was presented by Mimica et al. (2015). These authors tuned a hydrodynamical simulation of a fallback-powered jet interacting with a circumnuclear medium to obtain an excellent match to the observed light curve of Sw J1644+57. This simulation includes the deceleration of the jet, finding that the late-time radio emission becomes isotropic after about 3 years. At this point the luminosity at 10 GHz is predicted to be $\sim 10^{40}$ erg s^{-1}, which is larger than almost all upper limits that have been obtained. We can thus conclude that jets similar to Sw J1644+57 are rare; at the time of writing, 27 thermal TDEs (see Saxton et al. (2020, this issue) and van Velzen et al. (2020a, this issue)) have received radio follow-up, yet none show evidence for jets as powerful as Sw J1644+57.

A direct comparison of radio upper limits for known TDEs to off-axis light curves based on Sw J1644+57 has one caveat. Beside the jet power, the radio light curve depends on the circumnuclear medium. The effect of this second parameter was studied by Generozov et al. (2017), who considered a wide range of nuclear densities (as motivated by a physical model for gas supply from stellar winds; Generozov et al. 2015) to obtain an upper limit to the jet power for TDEs with radio follow-up observations. For nearly all thermal TDEs studied by Generozov et al. (2017), the upper limit to the total jet energy is an order of magnitude lower than the total of Sw J1644+57. This conclusion is consistent with the work of Mattila et al. (2018), who find that the radio transient Arp 299-B AT1 is an off-axis jet with a similar energy as Sw J1644+57. While Arp 299-B AT1 was detected in a nearby galaxy, even at the higher redshift of most thermal TDEs ($z \sim 0.1$), the isotropic radio emission of this source would exceed most of the published upper limits (Table 2). If events like Arp 299-B AT1 are common, many more should have been detected in our current follow-up observations of thermal TDEs found in blind optical/X-ray surveys, thus confirming that powerful jets following a TDE are rare.

In 2014, ASASSN-14li (Sect. 3.2) was discovered and we learned that thermal TDEs can be accompanied by a low energy radio flare ($E \sim 10^{47-48}$ erg, compared to $E \sim 4 \times 10^{51}$ erg for Sw J1644+57). At the time of its discovery, the radio luminosity of ASASSN-14li was lower than any of the upper limits obtained within one year of peak (mainly thanks to the low redshift of ASASSN-14li). Furthermore, since the radio emission was observed to fade quickly, the late-time follow-up observations of previous TDEs were also not sensitive enough to catch a radio flare similar to ASASSN-14li. Most models for the origin of the radio emission from ASASSN-14li suggested this emission could be (or should be) common to all thermal TDEs (see Sect. 3.2), which renewed the interest in rapid and sensitive radio follow-up of new TDEs.

At the time of writing, ASASSN-14li is one of two optically selected TDEs (see Table 1 of van Velzen et al. (2020a, this issue)) with published radio detections. Unlike many optical TDEs, ASASSN-14li also has bright X-ray emission, as do at least three of the other five detected radio-quiet TDEs. (Arp 299-B AT1's X-ray emission, if present, would have been masked by the large column density towards the TDE, as the AGN in Arp 299-B is Compton thick (Ptak et al. 2015), while CNSS J0019+00 was not observed in the X-ray at early times.) The first upper limits that rule out a radio flare similar to ASASSN-14li were obtained for the optical TDE iPTF-16fnl (Blagorodnova et al. 2017). However the low optical and X-ray luminosity of iPTF-16fnl ($L_X \sim 10^{37}$ erg s^{-1}), plus the rapid decay rate of its optical light curve make this source an outlier in the class of thermal TDEs—although we note that these faint TDEs dominate the volumetric rate (van Velzen 2018). The radio non-detection for iPTF-16fnl could be explained by its low luminosity. More recently, van Velzen et al. (2019) presented rapid and sensitive radio follow-up observations for optical TDE PS18kh/AT2018zr (Holoien et al. 2019) that also rule out a radio flare similar to ASASSN-14li. The optical properties of AT2018zr are similar to ASASSN-14li, and like ASASSN-14li AT2018zr also showed a soft, thermal X-ray spectrum (van Velzen et al. 2019). However the X-ray luminosity of AT2018zr is two orders of magnitude lower than ASASSN-14li's. The recent X-ray TDE XMMSL2 J1446+68 also shows no radio emission down to deep limits, suggesting that bright X-ray emission alone is not sufficient to produce detectable radio emission (Saxton et al. 2019).

In summary, at this point we can conclude that $\sim$ year-long radio flares with a peak luminosity $\sim 10^{38}$ erg s^{-1} are not common to *all* thermal TDEs. Of the six sources that have been studied with sufficient sensitivity, only ASASSN-14li and XMMSL1 0740-85 showed this feature. Somewhat brighter (peak luminosity $\sim$few 10^{38} erg s^{-1}), longer-lasting radio flares similar to Arp 299-B AT1 or IGR J12580+0134 are also not ubiquitous. If this trend is confirmed in a larger sample size, models that predict all TDEs should exhibit some level of radio emission will be disfavored (e.g. Sect. 3.2.2). While as yet there is no unifying physical characteristic that distinguishes the radio-detected thermal TDEs from those without faint radio emission, ongoing observing campaigns with the world's most sensitive radio and mm telescopes are expected to greatly expand the number of TDEs with radio detections and/or deep limits, allowing us to discriminate among the models presented in Sect. 3.2.

5.2 Rate of Sw J1644+57-Like Relativistic Jets

While the fraction of TDEs producing faint ASASSN-14li-like radio emission is still poorly constrained, existing observations do allow us to constrain the rate of radio-loud TDEs. Based on the first 10 years of *Swift*/BAT monitoring, the observed rate of events similar to Sw J1644+57 is $\sim 10^{-2}$ Gpc^{-3}yr^{-1} (Metzger et al. 2015).[5] Applying a correction for the Doppler boosting of the X-rays of $f_{\rm beam} \sim 100$ (van Velzen et al. 2018) we find $\dot{N}_{\rm J1644} \sim 1$ Gpc^{-3}yr^{-1}.

To estimate the expected fraction of observed TDEs with jets similar to Sw J166+57 we consider the ratio of the beaming-corrected rate to the rate of thermal TDEs,

$$f_{\rm J1644} \equiv \dot{N}_{\rm J1644}/\dot{N}_{\rm thermal}. \tag{1}$$

Since the volumetric rate of thermal TDEs depends on the flare's luminosity (van Velzen 2018), and most surveys are biased to the brighter events, we adopt $\dot{N}_{\rm thermal} = 10^{-4.3}$ galaxy^{-1} yr^{-1} $= 5 \times 10^{-5}$ galaxy^{-1} yr^{-1}. This rate is consistent with the observational TDE rates reported for several recent optical surveys (SDSS: $3^{+5}_{-3} \times 10^{-5}$ galaxy^{-1} yr^{-1}, van Velzen and Farrar 2014; ASAS-SN: $4.1^{+12.9}_{-1.9} \times 10^{-5}$ galaxy^{-1} yr^{-1}, Holoien et al. 2016; iPTF: $1.7^{+2.9}_{-1.3} \times 10^{-4}$ galaxy^{-1} yr^{-1}, Hung et al. 2018; see also the detailed discussion by van Velzen et al. (2020a, this issue)). The density of galaxies that can produce detectable TDEs is $\sim 10^{-2.4}$ Mpc^{-3} (for $h = 0.7$; see van Velzen and Farrar 2014), and we thus obtain $\dot{N}_{\rm thermal} \sim 10^{2.3}$ Gpc^{-3} yr^{-1}.

These two estimates of the rate imply $f_{\rm J1644} \sim 10^{-2.3}(f_{\rm beam}/100)$. One caveat to this estimate relates to the redshift evolution of the disruption rate; the jetted TDEs are found at higher redshift ($z \sim 1$) compared to the thermal TDEs ($z \sim 0.1$) and the redshift evolution of the TDE rate is unknown (depending on the loss-cone feeding mechanism the rate could both increase or decrease with redshift, see Stone et al. (2020, this issue)). At the time of writing, at least 29 TDEs have received radio follow-up observations that rule out a jet similar to Sw J1644+57 (Table 2, plus the six TDEs with faint radio detections). This lack of bright sources is consistent with our estimate of $f_{\rm J1644}$. Unless we underestimated the beaming factor, we should expect powerful jets in at most 1% of thermal TDEs. Constraints on the beaming factor can be obtained by measuring the isotropic rate of events similar to Sw J1644+57 using blind radio surveys.

[5] assuming all TDEs that launch radio-loud jets also produce bright γ-ray emission when viewed on-axis.

5.3 Blind Searches

Radio emission from TDEs has so far been detected primarily via follow-up observations (as TDEs have been discovered at other wavelengths, e.g., X-ray, UV, and optical). The sample of radio TDEs thus obtained is inevitably observationally biased, as the subset of TDEs chosen for radio follow up to date has not been uniformly selected. Direct discovery of TDEs in the radio can be achieved by blind searches in radio data. Several such searches have been conducted either by using archival data or by carrying out specifically designed time-domain radio surveys (e.g., Frail et al. 1994, Carilli et al. 2003, Bower et al. 2007, Croft et al. 2011, Ofek et al. 2011, Frail et al. 2012, Hodge et al. 2013, Mooley et al. 2016).[6] A blind search in the radio is more challenging compared, for example, to optical surveys, as the field of view of radio interferometers is much narrower and the typical sensitivity of radio facilities enables detection of radio emission from thermal TDEs only from nearby events. With time, the capabilities of numerous facilities have been upgraded, thus enabling wider and more sensitive blind searches.

Compared with theoretical expectations, most of the blind searches have not been wide and/or deep enough to discover TDEs. However, the upgrade of the VLA over the last decade has opened a window for performing effective blind surveys in which TDEs can be expected to be discovered. One such survey is the Caltech-NRAO Stripe 82 Survey (CNSS; Mooley et al. 2016). This survey was designed to cover the full $270\,\mathrm{deg}^2$ of the SDSS Stripe 82 area over multiple timescales in the $2-4$ GHz band with high spatial resolution (~ 3") and achieved a per-epoch sensitivity of ~ 80 μJy (Mooley et al. 2016). In five epochs spread over two years, one TDE was discovered, CNSS J0019+00 (Anderson et al. 2019). This implies that the rate of TDEs with radio emission brighter than 0.5 mJy is $1.8^{+5.4}_{-1.6} \times 10^{-3}$ deg^{-2} (Anderson et al. 2019). This corresponds to a volumetric rate of ~ 10 Gpc^{-3} yr^{-1} for radio TDEs with the same peak luminosity as CNSS J0019+00.

At face value, comparing this rate to the results presented above implies that TDEs with low-luminosity radio outflows similar to CNSS J0019+00 or ASASSN-14li are ~ 10 times more common than Sw J1644+57-like radio-loud TDEs, and comprise $\sim 10\%$ of thermal TDEs (Anderson et al. 2019). However, a direct comparison is not trivial due to remaining uncertainties in the TDE occurrence rate and its redshift evolution, the fraction of TDEs missed by optical/X-ray surveys, and the radio luminosity function of thermal TDEs. Additionally, identifying off-axis jetted TDEs as transient sources may be challenging because their radio emission evolves very slowly; during the 1.5 yr of the CNSS pilot survey, the 3 GHz flux density of a Sw J1644+57-like off-axis jet may not have changed sufficiently to be flagged as a variable source (Eftekhari et al. 2018). Radio surveys with more widely-separated epochs may be better suited to detect slow synchrotron transients like off-axis jetted TDEs (Metzger et al. 2015).

On the other hand, if most TDEs are thermal events that produce mostly weak radio emission, as implied by the rate from the CNSS, then a wider survey with the same sensitivity as the CNSS may be more effective to blindly detect TDEs. In fact, such a survey, the VLA Sky Survey (VLASS), has begun at the time of writing this book. The VLASS is an all sky survey that will be carried out using the VLA over the next several years. VLASS is using a drift scan technique that allows fast mapping of the sky (Mooley et al. 2019). Each piece of survey sky is expected to be observed three times during the project with each epoch separated by $\sim 18-24$ months. According to current estimates, tens of TDEs will be discovered

[6] A more complete list of radio transient surveys and additional details can be found at http://www.tauceti.caltech.edu/kunal/radio-transient-surveys/index.html.

in VLASS (Metzger et al. 2015, van Velzen et al. 2018; Anderson et al. 2019). However, this estimate is highly dependent on the true TDE rates and the TDE luminosity function, as already discussed above.

In the southern hemisphere, the best current facilities for wide-field radio transient searches are the Australian Square-Kilometre-Array Pathfinder (ASKAP; Johnston et al. 2008) and MeerKAT (Jonas 2016; Camilo et al. 2018). ASKAP utilizes a new phased array feed receiver design that effectively gives it an instantaneous field of view much larger than the VLA's (~ 30 deg^2 versus 0.25 deg^2), making it well-suited for targeted follow up of poorly-localized transients (including gravitational wave events, as recently demonstrated by Dobie et al. 2019) or for wide-field blind transient detection surveys. Several such surveys are already planned or underway (Murphy et al. 2013; Heywood et al. 2016; Hobbs et al. 2016; Bhandari et al. 2018). The largest of these is VAST (the ASKAP survey for Variables and Slow Transients), which includes a wide-field component (VAST-Wide) that will survey 10,000 deg^2 day^{-1} over a two-year period with an RMS sensitivity of 0.5 mJy. VAST-Wide is predicted to discover up to a dozen TDEs per year (van Velzen et al. 2011b; Murphy et al. 2013). MeerKAT, located in South Africa, has a smaller but still impressive field of view ($\sim 1°$ at 1.4 GHz; Driessen et al. 2020) and has achieved sub-microjansky noise in its deepest observations to date (Mauch et al. 2020). Transient science has been designated as one of the key early science priorities for MeerKAT under the ThunderKAT Large Survey Project (Fender et al. 2017), which recently published its first blind detection of a radio transient (Driessen et al. 2020).

Both ASKAP and MeerKAT are currently limited to observing frequencies ≤ 1.4 GHz, and therefore using them to blindly discover TDEs involves many of the same challenges as discovering TDEs in the CNSS and VLASS (including the slow evolution of radio TDEs at low frequencies, and the challenge of distinguishing TDEs from background variable AGN). However, both ASKAP and MeerKAT are precursors to the Square Kilometer Array (SKA; Dewdney et al. 2009), which is expected to include high-frequency sensitivity up to at least 15 GHz.[7] Radio observations with future facilities such as the SKA and the next generation VLA (ngVLA)[8] are expected to produce larger samples of TDEs (hundreds per year) that are also more distant at higher redshifts (Metzger et al. 2015; Donnarumma et al. 2015; van Velzen et al. 2018).

6 Conclusions

Radio observations of TDEs provide unique information about these rare events that cannot be gleaned from observations at other wavelengths. In particular, they probe fast-moving material ejected from the system, in contrast to the generally thermal emission seen in the optical, UV, and X-rays. Radio observations have shown that a small subset of TDEs produce relativistic jets, while a larger fraction may produce less energetic outflows. The physical conditions required for jet production and the diversity of sub-parsec scale nuclear gas profiles around SHBMs in TDE hosts will be revealed by increasing the sample size of radio-detected TDEs. Given the broad range in observed TDE radio luminosities, we suggest that

[7] https://astronomers.skatelescope.org.

[8] While the ngVLA has a much smaller field of view than the SKA under the current design, its exquisite sensitivity at high frequencies will make it a key tool for the follow up and discovery of TDEs. Additionally, its milliarcsecond resolution will be very interesting for VLBI observations of nearby events (van Velzen et al. 2018).

radio follow up of new events should optimally probe radio luminosities $\nu F_\nu \leq 10^{37}\ \mathrm{erg\,s^{-1}}$, as many existing upper limits are too shallow to detect outflows similar to those observed in e.g. ASASSN-14li. Furthermore, with the advent of ALMA, it is now possible to probe even less energetic outflows, which are expected to reach higher peak luminosities in the millimeter than in the centimeter bands probed by the VLA (Yuan et al. 2016).

The increased TDE discovery rate promised by new sensitive, wide-field optical surveys like ZTF is already being realized (van Velzen et al. 2019). Simultaneously, new and upcoming radio surveys may soon provide the first population of TDEs discovered in the radio band (Murphy et al. 2013, Metzger et al. 2015, Fender et al. 2017, Anderson et al. 2019). Within the next five years, we will have placed strong constraints on the rate of weak radio outflows in TDEs, and may discover further extremes in an already diverse radio TDE population. The sample of radio TDEs will continue to grow in the era of LSST plus SKA (Donnarumma et al. 2015) — although we note that the slow evolution of the radio light curve in low-frequency observations (1.4 GHz) will present a major challenge for TDE identification (Donnarumma and Rossi 2015). A time-domain survey at higher frequencies ($\gtrsim 5$ GHz) with the ngVLA (van Velzen et al. 2018) or SKA band 5 would be the ultimate discovery machine for radio-emitting TDEs, finding as many as $\sim 10^2$ jetted TDEs per year.

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