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Radio jets from stellar tidal disruptions

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ABSTRACT

A star that passes too close to a massive black hole will be torn apart by tidal forces. The flare of photons emitted during the accretion of the stellar debris is predicted to be observable, and candidates of such events have been observed at optical to X-ray frequencies. If a fraction of the accreted material is fed into a jet, tidal flares should be detectable at radio frequencies too, thus comprising a new class of rare radio transients. Using the well-established scaling between accretion power and jet luminosity and basic synchrotron theory, we construct an empirically rooted model to predict the jet luminosity for a time-dependent accretion rate. We apply this model to stellar tidal disruptions and predict the snapshot rate of these events. For a small angle between the observer and the jet, our model reproduces the observed radio flux of the tidal flare candidate GRB 110328A. We find that future radio surveys will be able to test whether the majority of tidal disruptions are accompanied by a jet.

Key words: accretion – black hole physics – galaxies: jets – radio continuum: galaxies.

1 INTRODUCTION

When a star wanders too close to the massive black hole at the centre of its galaxy, it will be tidally disrupted by the gravity of the hole (Hills 1975). After the disruption, about half of stellar mass remains bound (e.g. Rees 1988; Evans & Kochanek 1989) and an electromagnetic flare is produced as the debris falls back on to the black hole. Theoretical efforts to predict this emission have focused predominately on the accretion of the bound stellar debris (e.g. Rees 1988; Loeb & Ulmer 1997; Ulmer 1999; Bogdanović et al. 2004) and the contribution from a super-Eddington outflow (Strubbe & Quataert 2009, 2011; Lodato & Rossi 2011).

The electromagnetic flare from a stellar tidal disruption event (TDE) may be our only tool to probe dormant black holes, e.g. the Galactic Centre black hole (Melia & Falcke 2001), beyond the local Universe and could allow a much-anticipated study of black hole demographics as a function of galaxy type and cosmic time. Individual TDEs are also interesting since the sudden increase of accretion rate after the disruption, from zero to super-Eddington in a few months or even hours, is much more rapid than the time-scale of normal accretion on to supermassive black holes.

A number of (candidate) TDEs have been identified in X-ray (Bade, Komossa & Dahlem 1996; Komossa & Bade 1999; Komossa & Greiner 1999; Esquej et al. 2008) – for a review see Komossa (2002) – UV (Gezari et al. 2006, 2008, 2009) and optical surveys (van Velzen et al. 2010b; Drake et al. 2011; Cenko et al. 2011). Based on the optical luminosity of observed TDEs, one can predict that near-future synoptic surveys, such as LSST (Ivezić et al. 2008), should detect thousands of such events per year (Gezari et al. 2009; van Velzen et al. 2010b).

Follow-up observations of candidate TDEs at radio frequencies are important to identify these events, as was realized when the first X-ray candidates were detected (Komossa 2002). However, blind radio variability surveys also have the potential to *discover* TDEs. The rapid increase of sky coverage and sensitivity of variability surveys at both high and low frequencies promises an exciting future for this field.

Recently, Giannios & Metzger (2011) proposed a model for the radio emission from TDEs, based on the interaction of the jet with the interstellar medium (ISM); Bower (2011) compared their predictions to upper limits of existing radio surveys for transients. The present work is an extension of the approach outlined in van Velzen, Falcke & Farrar (2010a), where we use the well-established jet–disc symbiosis model to calculate a time-dependent jet model for TDEs. We will only consider the emission from the compact core of the jet; interactions with the surrounding medium may enhance the jet luminosity in some cases, but here we aim to obtain a conservative model and we therefore consider solely the internal jet emission.

In Section 2, we present our time-dependent jet model. In Section 3, we discuss the light curves produced by our model and compare them to radio observations of candidate TDEs such as GRB 110328A. We predict the snapshot rate of jets from TDE in Section 4 and compare this rate to the sensitivity of current and future radio transient surveys.

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2 TIME-DEPENDENT JET MODEL

There is already quite a range of time-dependent models for radio jets in supermassive black holes in the literature (e.g. Chiaberge & Ghisellini 1999; Gupta, Böttcher & Dermer 2006), but they typically only address relatively small changes or focus on a subclass of AGN. A major question remains: how jets evolve as a function of time when accretion suddenly sets in and increases by many orders of magnitude? There is an increasing consensus that accretion discs and jets are intrinsically coupled and are best understood as a symbiotic system. Evidence that jets are ubiquitous to accretion comes from the 'Fundamental Plane of black holes', which provides a universal scaling law for the non-thermal emission of black holes over all mass scales (Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2004). We thus proceed under the hypothesis that all accreting massive objects, including TDEs, launch a jet, but, as discussed later, take potential radio-loud/radio-quiet switches at high accretion rates into account.

In this section, we will first generalize the jet–disc symbiosis model of Falcke & Biermann (1995, hereafter FB95) to a time-dependent accretion rate, and we then apply this model to TDEs.

2.1 Basic jet model

The essence of jet–disc symbiosis is power unification: $Q_\mathrm{j} = q_\mathrm{j} L_\mathrm{d} \propto q_\mathrm{j} \dot{M}$, the jet power ($Q_\mathrm{j}$) is some fraction ($q_\mathrm{j}$) of the disc luminosity (L_d), which is a linear function of the accretion rate ($\dot{M}$). If we assume equipartition between the energy in relativistic particles and the magnetic field, the synchrotron emissivity follows from the accretion rate: $\epsilon_\mathrm{syn} \propto B^{3.5} \propto (q_\mathrm{j}\dot{M})^{1.75} z^{-3.5}$, with z the distance to the origin of the jet (FB95, equation 19). We obtain the synchrotron luminosity of the jet (L_ν) by integrating the emissivity over the jet volume, a cylindrical symmetric cone,

$$L_\nu = C_\mathrm{eq} \int_{z_\mathrm{ssa}}^{\infty} \mathrm{d}z\, z^2 \epsilon_\mathrm{syn}(z, \nu/\delta) \propto (q_\mathrm{j} L_\mathrm{d})^{17/12} \qquad (1)$$

(FB95, equations 52 and 56). Here δ is the Doppler factor of the jet and ν is the observed frequency. The lower limit of integration, $z_\mathrm{ssa}(\nu/\delta)$, is the distance where the jet becomes optically thin to synchrotron self-absorption. The normalization (C_eq) is the conversion factor between jet power and jet luminosity, which can be estimated using equipartition arguments or obtained by observations.

The great success of jet–disc symbiosis is that the observed properties of all accreting black holes with radio-loud jets can be fitted with $q_\mathrm{j} = 0.2 \equiv q_\mathrm{loud}$ and a single value of the normalization (C_eq) of equation (1) (Falcke, Malkan & Biermann 1995; Körding, Jester & Fender 2008). In this work, we will fix C_eq using the empirical normalization found by Körding et al. (2008) for efficient accretion, $L_\mathrm{d} = 0.1c^2\dot{M}$, and we will use a jet Lorentz factor $\gamma_\mathrm{j} = 5$ (Falcke et al. 1995) throughout.

The 'classic' jet model (equation 1) is derived for a constant accretion rate; to use this model for a time-dependent accretion rate, $\dot{M}(t)$, we have to consider three things: (i) the non-zero time delay of photons emitted at different locations in jet, (ii) $z_\mathrm{ssa}(t)$ will set the time-scale of the emission and (iii) the emissivity becomes a function of time. The latter of these changes is trivial to apply because at the base of the jet, the relation between the synchrotron emissivity and accretion rate is given by the standard jet–disc model and all that one has to do is to propagate ϵ_syn forward in time using $z(t) = t\beta_\mathrm{j}c$. To account for (ii), we use $\tau \propto z\kappa_\mathrm{syn}/\sin(i) = 1$, where κ_syn is the synchrotron emission coefficient, to find

$$z_\mathrm{ssa} = 1\,\mathrm{pc}\; f \frac{\mathrm{GHz}}{\nu/\delta} \left(\frac{q_\mathrm{j}(t)}{0.2} \frac{L_\mathrm{d}(t)}{10^{45}\,\mathrm{erg\,s^{-1}}} \right)^{2/3} \left(\frac{\beta_j}{\sin(i/30^\circ)} \frac{5}{\gamma_j} \right)^{1/3}, \qquad (2)$$

(FB95, equation 52), where $f \sim 1$ is a factor that depends on the details of equipartition. We perform a check on the latter using observations of NGC 4258 at 22 GHz showing the base of the jet at a minimum distance of 0.012 pc from the dynamical centre of the accretion disc (Herrnstein et al. 1997); using $i_\mathrm{obs} = 83^\circ$ and $\gamma_\mathrm{j} = 3$ (Yuan et al. 2002) at the base of the jet and $\dot{M} = 0.01\,\mathrm{M_\odot\,yr^{-1}}$ (Gammie, Narayan & Blandford 1999), we obtain $f \approx 0.5$.

We can now modify the integral of equation (1) to obtain our time-dependent jet model,

$$L_\nu(t) = C_\mathrm{eq}\delta^2 \int_0^{z_\mathrm{dec}} \mathrm{d}z\, z^2 \epsilon_\mathrm{syn}(t_\mathrm{r}, z, \nu/\delta)\Theta_\mathrm{ssa}(t_\mathrm{r}, z, \nu/\delta). \qquad (3)$$

Here $\Theta_\mathrm{ssa}(t, z, \nu)$ is a step function that enforces a crude radiative transfer: it is zero for $z < z_\mathrm{ssa}(t)$ and unity for $z > z_\mathrm{ssa}(t)$. The retarded time, t_r, is introduced to ensure that we integrate using only the photons that will arrive simultaneously at the observer, $t_\mathrm{r}(t, z) = t - z\cos(i)\,c^{-1}$, with i the angle between the jet and observer, in the rest frame of the jet. Note that for observed angles $\cos(i_\mathrm{obs}) < \beta_j$, we have $t_\mathrm{r} > t$; the photons from the middle of the jet arrive simultaneously with photons emitted further ahead, i.e. the jet appears to be seen from behind in the observer frame (e.g. Jester 2008). The upper limit of integration, z_dec, is the radius where the jet will slow down significantly because the initial jet energy equals the energy of the shocked matter swept up by the jet (e.g. Piran 2004): $z_\mathrm{dec} \propto (E_\mathrm{j}/n\gamma_\mathrm{j}^2)^{1/3}$, with $E_\mathrm{j} \propto \int q_\mathrm{j}\dot{M}\,\mathrm{d}t$ and n the ISM number density. In the following section, we discus $q_\mathrm{j}(t)$ and $\dot{M}(t)$ for TDEs and give the physical scale of z_dec.

2.2 Accretion states of TDE

To apply the time-dependent jet–disc symbiosis model (equation 3) to TDE, we need the accretion rate as a function of time and black hole mass. We first consider the time it takes for most of the stellar debris to return to the pericentre (R_p) after the disruption, $t_\mathrm{fallback} \sim 0.1(M_\mathrm{BH}/10^6\,\mathrm{M_\odot})^{1/2}(R_\mathrm{p}/R_\mathrm{t})^3$ yr for a solar-type star (e.g. Ulmer 1999, equation 3), R_t is the tidal disruption radius. After this time, the material falls back on to the black hole at a rate, $\dot{M}_\mathrm{fallback} \approx 1/3\, M_*/t_\mathrm{fallback}(t/t_\mathrm{fallback})^{-5/3}$ (Rees 1988), where M_* is the mass of the star. We will use $\dot{M}_\mathrm{fallback}$ with $R_\mathrm{p} = R_\mathrm{t}$ for the accretion rate on to the black hole that can be fed into the jet. For $M_\mathrm{BH} <$ few $\times\ 10^7\,\mathrm{M_\odot}$, the fallback rate will (greatly) exceed the Eddington rate for some time, but we will conservatively assume that $\dot{M}(t) = \dot{M}_\mathrm{Edd}$ during this time; we use an exponential rise to the peak accretion rate for $t < t_\mathrm{fallback}$. Our results are not sensitive to potential deviations from the canonical $t^{-5/3}$ scaling of the fallback rate (e.g. Lodato, King & Pringle 2009), because most of the energy is injected into the jet during the super-Eddington phase, where $\dot{M}$ is capped at $\dot{M}_\mathrm{Edd}$.

With the accretion rate given by the theory of tidal disruptions, we only have to provide one more ingredient to produce radio light curves for these events: the fraction of accretion power that is fed into the jet. Jets from active supermassive black holes can be radio loud or radio quiet (Kellermann et al. 1989), which appears to be at odds with jet–disc symbiosis. However, detailed observations have shown that nearly all radio-quiet AGN do show some radio emission which can be interpreted as originating from the core of a relativistic jet (Brunthaler et al. 2000; Falcke 2001). Indeed radio-quiet jets can also be accommodated by equation (1) by reducing $C_{\rm eq}$ or $q_{\rm j}$ with a factor of $\sim 10^2$ with respect to radio-loud systems.

If we assume that the physics behind launching the jet and producing the synchrotron emission is no different for TDE and 'normal' active black holes, we are left to answer the following question: *is a TDE jet radio loud or radio quiet?* Observations of accreting stellar mass black holes (i.e. X-ray binaries) can help answer this question since they are variable on time-scales down to minutes (Belloni et al. 2005) and they can serve as examples for AGN (McHardy et al. 2006; Chatterjee et al. 2011).

When X-ray binaries experience a burst of accretion, they follow a pre-defined track in the hardness–intensity diagram (Belloni et al. 2005) corresponding to distinct accretion states with associated jet properties (Fender, Belloni & Gallo 2004). In the quiescent mode (the hard state) and during the onset of the burst, jets in X-ray binaries are radio loud, while in the high-accretion mode (the soft state) they are radio quiet.

The sudden enhancement of the accretion rate during a TDE may move it through the different modes of accretion in two ways: directly into the radio-quiet soft state, or into the soft state via the radio-loud burst state. Alternatively, the jet from a TDE may behave like a radio-loud quasar at all times. We therefore consider three different scenarios for the fraction of accretion energy that is fed into the jet:

$$q_{\rm j} = \begin{cases} q_{\rm loud} & \text{all times} \quad \text{(a)} \\ q_{\rm loud}/10^2 & \dot{M}(t) > 2\ \text{per cent}\ \dot{M}_{\rm Edd} \quad \text{(b)} \\ q_{\rm loud} & t < t_{\rm fallback} \quad \text{(c)} \end{cases} \qquad (4)$$

where each scenario reverts to the preceding one if the condition on t or $\dot{M}$ is not true (e.g. $q_{\rm j} = q_{\rm loud} = 0.2$ if $\dot{M} < 2$ per cent $\dot{M}_{\rm Edd}$ in all three scenarios). In scenario (b), the jet becomes radio loud only when the accretion drops below <2 per cent $\dot{M}_{\rm Edd}$ (Maccarone 2003), while in scenario (c) the systems make a full loop trough all accretion modes, starting with a radio-loud burst during the onset of the accretion. We consider (a) the most optimistic scenario, (b) the most pessimistic scenario and (c) the most likely scenario. The two orders of magnitude difference in $q_{\rm j}$ between scenarios (a) and (b) can also be taken to reflect our uncertainty on the coupling between jet power and accretion during the super-Eddington phase of the disruption.

With $q_{\rm j}$ and $\dot{M}$ at hand, we can now calculate, $z_{\rm dec}$, the radius where the jet will slow down significantly, which is the upper limit of the integral over jet volume (equation 3). For $M_{\rm BH} = 10^7\,{\rm M}_\odot$ and scenario (a) (equation 4), using a jet opening angle of 7° (FB95) and an ISM density of 1 proton $\rm cm^{-3}$, we obtain $z_{\rm dec} = 3.5$ pc. Comparing this to $z_{\rm ssa}$ (equation 2), this implies a significant suppression of the luminosity for observers looking at $\nu < 500\,$MHz because $z_{\rm dec} < z_{\rm ssa}(\nu)$. However, this suppression is less relevant at lower $M_{\rm BH}$ or $q_{\rm j}$, since $z_{\rm dec} \propto (q_{\rm j} L_{\rm d})^{1/3}$, while $z_{\rm ssa} \propto (q_{\rm j} L_{\rm d})^{2/3}$. Clearly, the density distribution within a few parsec from the black hole varies between galaxies: each TDE jet will face a different deceleration radius. In elliptical galaxies, $z_{\rm dec}$ is likely to be larger by at least a factor of 10 with respect to the value adopted in this work, due to the low gas density in these galaxies (e.g. Biermann & Kronberg 1983). On the other hand, $z_{\rm dec}$ can decrease if the jet runs into a high-density clump of matter, which will enhance the luminosity, as seen in an exemplary way in the radio-intermediate quasar III Zw 2 (Brunthaler et al. 2000). For galaxies where $z_{\rm dec} < 0.1$ pc, the external emission as modelled by Giannios & Metzger (2011) dominates over emission from the core of the jet at all relevant frequencies. Discriminating between core and external emission for individual TDE jets may be possible using the time delay between the radio emission and the time of disruption.

3 RADIO LIGHT CURVES

In Fig. 1, we show the radio light curves that result from applying the jet–disc symbiosis to TDEs. For the scenario in which the jet is always radio loud (equation 4, scenario a), one can see most clearly how the opacity sets the time-scale of the emission. Since $z_{\rm ssa} \propto \nu^{-1}$ (equation 2), the jet is visible at earlier times and at higher luminosity for higher frequencies. The sudden drop in luminosity after about 20 years is caused by our fixed upper limit of equation 3 ($z_{\rm dec}$): we stop following the jet beyond this point because the aim of this work is to predict the internal jet emission. Connecting the internal and external emission in a single model will be the subject of future work. At $\nu = 200$ MHz, we see a plateau of constant luminosity which is caused by the photons produced after the super-Eddington phase. For a given black hole mass, the duration of the radio flare is maximal if viewed along the critical angle, $i_{\rm obs} = \arccos(\beta_{\rm j})$; within this angle, the time-scale is shorter because most photons arrive nearly simultaneously at the detector, while at larger viewing angles, the frequency in the rest frame of the jet (ν/δ) increases, making the jet visible at earlier times.

In Fig. 2, we show follow-up radio observations that have been obtained for some candidate TDEs. The upper limits on the radio luminosity are consistent with our most optimistic prediction for the jet luminosity, except for the candidate in NGC 5905 which is only consistent with scenarios (b) and (c). We note that observations of similar depth obtained today, ~5 years after the flare, should yield a detection. Finally, we consider the recently discovered GRB 110328A/Swift J164449.3+573451, which may be an example of a strongly beamed TDE (e.g. Bloom et al. 2011; Levan et al. 2011; Zauderer et al. 2011); indeed, for $i_{\rm obs} < 10^\circ$ and $M_{\rm BH} = 10^6\,{\rm M}_\odot$ our model with scenario (a) yields the observed VLBA radio flux (Levan et al. 2011) of this transient. If we conservatively assume that the first *Swift* detection marks the start of the disruption, our model requires $i_{\rm obs} < 1^\circ$ to explain the few days delay between gamma-ray and radio photons; this angle constraint becomes less stringent if the high-energy photons originate from the jet.

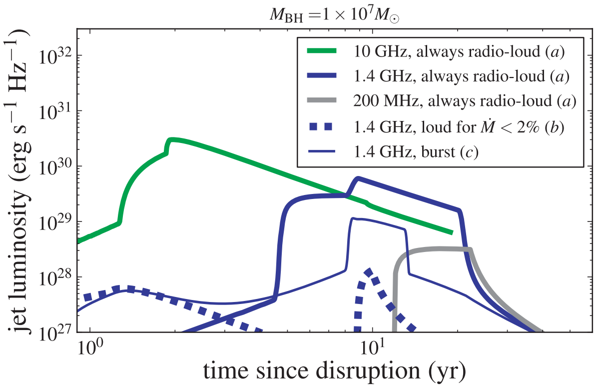

Figure 1. Light curves for synchrotron emission for jets from TDEs for $i_{\rm obs} = 30^\circ$, $M_{\rm BH} = 10^7\,{\rm M}_\odot$ and three different scenarios of coupling between accretion and jet power [(a), (b) and (c) in the legend refer to equation 4]. For the 'always radio-loud' scenario, we show three different frequencies (thick solid lines). The highest frequencies are visible at the earliest times and at highest luminosity because $z_{\rm ssa} \propto \nu^{-1}$ (equation 2). For the 'burst' scenario (thin line), we see a strong luminosity increase corresponding to the radio-loud part of the jet during the start of the accretion; as expected, this peak coincides with the peak of scenario (a).

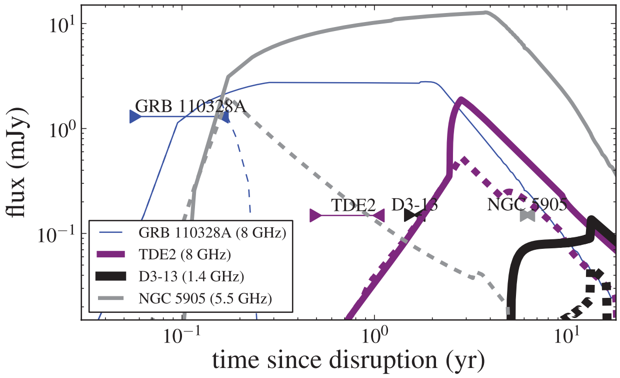

Figure 2. The predicted flux for TDE2 $M_{\rm BH} \sim 5 \times 10^7$ M$_\odot$ (van Velzen et al. 2010b), D3-13, $M_{\rm BH} \sim 2 \times 10^7$ M$_\odot$ (Gezari et al. 2008), the X-ray flare from NGC 5905, $M_{\rm BH} \sim 2 \times 10^5$ M$_\odot$ (Komossa & Bade 1999) and GRB 110328, assuming $M_{\rm BH} \sim 1 \times 10^6$ M$_\odot$. We show our most optimistic model (a) (solid line) and the more realistic 'burst model' (c) (dashed line). We use $i_{\rm obs} = 30°$ for the first three candidates and show the 3σ upper limits at $\nu = 8$ GHz (van Velzen et al. 2010b), $\nu = 1.4$ GHz (Bower 2011) and $\nu = 8$ GHz (Komossa 2002) from the last radio observations. For GRB 110328, we use $i_{\rm obs} = 1°$, and we show the VLBA detection at 8.4 GHz (Levan et al. 2011). The triangles pointing right and left correspond to the lower and upper limit on the time of disruption, respectively.

4 SNAPSHOT RATE

Using the model presented in Section 2, we can predict how many jets are visible above a certain flux limit ($F_{\rm lim}$) at any moment in time,

$$N(F_{\rm lim}, \nu) = (4\pi)^{-1} \dot{N}_{\rm tde} \int {\rm d}\Omega_{\rm obs} \int {\rm d}z\, 4\pi d_{\rm C}^2(z) \times \int {\rm d}M_{\rm BH}\, \phi_{\rm BH}\, \tau_{\rm eff}(L_\nu, d_{\rm L}(z), F_{\rm lim}) \,. \qquad (5)$$

Here $d_{\rm C}(z)$ and $d_{\rm L}(z)$ are the comoving and luminosity distance,[1] respectively, and $\phi_{\rm BH}$ is the black hole mass function. The integration over viewing angles, ${\rm d}\Omega_{\rm obs}$, accounts for the effects of Doppler boosting. Finally, our jet model enters via $\tau_{\rm eff}(L_\nu(M_{\rm BH}, i_{\rm obs}), d_{\rm L}, F_{\rm lim})$ or the 'effective time' given by the part of the light curve that obeys $L_\nu(t)/(4\pi d_{\rm L}^2) > F_{\rm lim}$. We also consider the model by Giannios & Metzger (2011) using their equation (8), with fiducial parameters.

We use the local black hole mass function of Marconi et al. (2004) for $\phi_{\rm BH}$ and a TDE rate per black hole of $\dot{N}_{\rm tde} = 10^{-5}\,{\rm yr}^{-1}$ which is based on the observed rate per galaxy from SDSS observations ($3 \times 10^{-5}\,{\rm yr}^{-1}$; van Velzen et al. 2010b) and *ROSAT* observations ($9 \times 10^{-6}\,{\rm yr}^{-1}$; Donley et al. 2002). At the lowest flux limit we consider, $F_{\rm lim} = 0.05$ mJy and $\tau_{\rm eff}(z) \times d_{\rm C}^2$ peaks at $z = 0.5$, so we are not sensitive to cosmological evolution of $\phi_{\rm BH}$ or $\dot{N}_{\rm TDE}$. Since L_ν peaks at $M_{\rm BH} \sim 5 \times 10^7$ M$_\odot$ and $\phi(M_{\rm BH})$ flattens towards low black hole mass, equation (5) is not sensitive to the upper or lower boundaries of the integration over black hole mass.

In Fig. 3, we show the snapshot rate for the three different scenarios we consider (equation 4) and three different frequencies. At higher frequencies, the jets are brighter and thus visible out to a larger volume, while at lower frequencies the duration is longer. These competing effects also imply that any uncertainty on $z_{\rm ssa}$ (equation 2) has limited influence on the predicted snapshot rate.

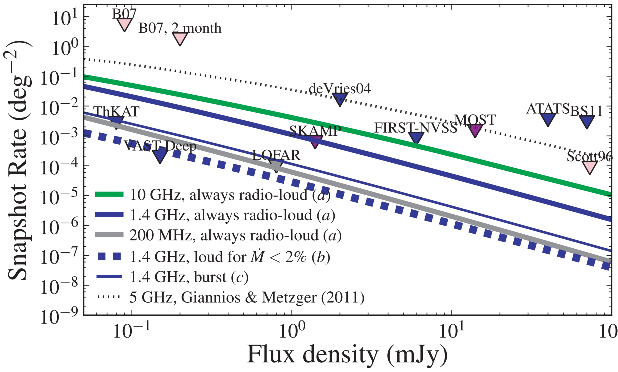

Figure 3. The snapshot rate of TDE jets. We show 2σ upper limits from Scott (1996) and Bower et al. (2007, B07) at 5 GHz; Levinson et al. (2002), Gal-Yam et al. (2006, FIRST-NVSS), de Vries et al. (2004), ATAS (Croft et al. 2010) and Bower & Saul (2011, BS11) at 1.4 GHz; and MOST (Bannister et al. 2011) at 843 MHz. We also show the limits that can be obtained if no candidates are detected in (near) future variability surveys. We refer to Ofek et al. (2011) for an overview of radio variability surveys.

We also compare our predicted snapshot rate to observed upper limits on the rate of extragalactic radio transients. For surveys with detected transients, we use the classification by Bower (2011) to limit these radio transients to potential TDE jets only.

The current radio transient surveys are not sensitive or large enough to test our prediction of the snapshot rate. This changes, however, when we consider the potential of near-future projects. For LOFAR,[2] we use 0.25 mJy for the thermal rms obtained at 180 MHz in a survey that will cover 2π sr in about 3 months We also consider SKAMP,[3] ThunderKAT, which is part of MeerKAT[4] and the VAST project, which is part of ASKAP.[5] Using three times the rms for the detection threshold, we find that for the optimistic scenario (equation 4, sequence a), the SKAMP and LOFAR surveys should contain about two jets from TDEs. The VAST project is sensitive enough to test even the most conservative scenario (b).

5 SUMMARY AND CONCLUSION

We have presented a time-dependent jet–disc symbiosis model that yields a conservative and robust estimate of the radio luminosity of the compact jet that likely accompanies stellar TDEs. This model is consistent with current constraints of the radio properties of TDE candidates and naturally predicts the observed radio flux of the newly discovered GRB 110328A. Based on our predicted snapshot rate, we conclude that future radio surveys will be able to test whether the majority of tidal disruptions are indeed accompanied by a relativistic jet.

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[1] We adopt a standard cosmology with $H_0 = 72\,{\rm km\,s^{-1}\,Mpc^{-1}}$, $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$.

[2] www.lofar.org

[3] www.physics.usyd.edu.au/sifa/Main/SKAMP

[4] www.ska.ac.za/meerkat

[5] www.csiro.au/science/ASKAP

REFERENCES

Bade N., Komossa S., Dahlem M., 1996, A&A, 309, L35
Bannister K. W. et al., 2011, MNRAS, 412, 634
Belloni T. et al., 2005, A&A, 440, 207
Biermann P., Kronberg P. P., 1983, ApJ, 268, L69
Bloom J. S. et al., 2011, Sci, 333, 203
Bogdanović T. et al., 2004, ApJ, 610, 707
Bower G. C., 2011, ApJ, 732, L12
Bower G. C., Saul D., 2011, ApJ, 728, L14
Bower G. C. et al., 2007, ApJ, 666, 346
Brunthaler A. et al., 2000, A&A, 357, L45
Cenko S. B. et al., 2011, MNRAS, submitted (arXiv:1103.0779)
Chatterjee R. et al., 2011, ApJ, 734
Chiaberge M., Ghisellini G., 1999, MNRAS, 306, 551
Croft S. et al., 2010, ApJ, 719, 45
de Vries W. H. et al., 2004, AJ, 127, 2565
Donley J. L. et al., 2002, AJ, 124, 1308
Drake A. J. et al., 2011, ApJ, 735, 106
Esquej P. et al., 2008, A&A, 489, 543
Evans C. R., Kochanek C. S., 1989, ApJ, 346, L13
Falcke H., 2001, in Schielicke R. E., ed., Reviews in Modern Astronomy 14: Dynamic Stability and Instabilities in the Universe. Astronomische Gesellschaft, Hamburg, Germany, p. 15
Falcke H., Biermann P. L., 1995, A&A, 293, 665 (FB95)
Falcke H., Malkan M. A., Biermann P. L., 1995, A&A, 298, 375
Falcke H., Körding E., Markoff S., 2004, A&A, 414, 895
Fender R. P., Belloni T. M., Gallo E., 2004, MNRAS, 355, 1105
Gal-Yam A. et al., 2006, ApJ, 639, 331
Gammie C. F., Narayan R., Blandford R., 1999, ApJ, 516, 177
Gezari S. et al., 2006, ApJ, 653, L25
Gezari S. et al., 2008, ApJ, 676, 944
Gezari S. et al., 2009, ApJ, 698, 1367
Giannios D., Metzger B. D., 2011, MNRAS, in press (arXiv:1102.1429)
Gupta S., Böttcher M., Dermer C. D., 2006, ApJ, 644, 409
Herrnstein J. R. et al., 1997, ApJ, 475, L17
Hills J. G., 1975, Nat, 254, 295
Ivezić Z. et al., 2008, preprint (arXiv:0805.2366)
Jester S., 2008, MNRAS, 389, 1507
Kellermann K. I. et al., 1989, AJ, 98, 1195
Komossa S., 2002, in Gilfanov M., Sunyeav R., Churazov E., eds, Lighthouses of the Universe. Springer, Berlin, p. 436
Komossa S., Bade N., 1999, A&A, 343, 775
Komossa S., Greiner J., 1999, A&A, 349, L45
Körding E. G., Jester S., Fender R., 2008, MNRAS, 383, 277
Levan A. J. et al., 2011, Sci, 333, 199
Levinson A. et al., 2002, ApJ, 576, 923
Lodato G., Rossi E. M., 2011, MNRAS, 410, 359
Lodato G., King A. R., Pringle J. E., 2009, MNRAS, 392, 332
Loeb A., Ulmer A., 1997, ApJ, 489, 573
Maccarone T. J., 2003, A&A, 409, 697
McHardy I. M. et al., 2006, Nat, 444, 730
Marconi A. et al., 2004, MNRAS, 351, 169
Melia F., Falcke H., 2001, ARA&A, 39, 309
Merloni A., Heinz S., di Matteo T., 2003, MNRAS, 345, 1057
Ofek E. O. et al., 2011, ApJ, submitted (arXiv:1103.3010)
Piran T., 2004, Rev. Modern Phys., 76, 1143
Rees M. J., 1988, Nat, 333, 523
Scott W. K., 1996, PhD thesis, Univ. British Columbia
Strubbe L. E., Quataert E., 2009, MNRAS, 400, 2070
Strubbe L. E., Quataert E., 2011, MNRAS, 415, 168
Ulmer A., 1999, ApJ, 514, 180
van Velzen S., Falcke H. D. E., Farrar G. R., 2010a, ISKAF2010 Science Meeting, A New Golden Age for Radio Astronomy. ISKAF, the Netherlands, p. 86
van Velzen S. et al., 2010b, ApJ, submitted (arXiv:1009.1627)
Yuan F. et al., 2002, A&A, 391, 139
Zauderer B. A. et al., 2011, Nat, submitted (arXiv:1106.3568)

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