Predictions for the Observational Properties of Tidal Disruption Events: Super-Eddington Outflow & Accretion Disk

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Emission from Tidal Disruption Events

Having an idea about rate of gas falling back to the black hole $\dot{M}_{\text{fallback}}$ ...

What are the accretion physics and radiative processes that tell us what we’re likely to observe?
Emission from Tidal Disruption Events

Having an idea about rate of gas falling back to the black hole $\dot{M}_{\text{fallback}}$ …

What are the accretion physics and radiative processes that tell us what we’re likely to observe?

Not as simple as $\nu L_\nu \propto \dot{M}_{\text{fallback}}$ … !

• What observing band?
• What radiative processes? In thermal equilibrium?
• What are temperature and area of emitting region?

Focus on optical/UV emission, for recent/upcoming transient surveys (GALEX, Palomar Transient Factory, Pan-STARRS, LSST)
The Bound Material: Fallback

\[ \dot{M}_{\text{fallback}} \sim \frac{M_*}{t_{\text{fallback}}} \left( \frac{t}{t_{\text{fallback}}} \right)^{-5/3} \]

Eddington rate:

Radiation pressure (produced by accretion) balances Gravity (from the black hole)

Gravity vs. Radiation

Proton

\[ M_{\text{BH}} = 10^6 M_\odot \]

\[ R_p = R_T \]

super-Eddington fallback rate

sub-Eddington fallback rate
The Bound Material: Fallback

$$\dot{M}_{\text{fallback}} \sim \frac{M_*}{t_{\text{fallback}}} \left( \frac{t}{t_{\text{fallback}}} \right)^{-5/3}$$

As fallback rate declines with time, 2 Phases of Evolution:

1. **Super-Eddington fallback**:  \( \dot{M}_{\text{fallback}} \gg \dot{M}_{\text{Edd}} \)
   Physics is uncertain, but likely advective disk + powerful outflows
   \( \sim \text{weeks - months} \)

2. **Sub-Eddington fallback**:  \( \dot{M}_{\text{fallback}} \lesssim \dot{M}_{\text{Edd}} \)
   Thin accretion disk
   \( \sim \text{months - year} \)

\( M_{\text{BH}} = 10^6 M_\odot \)
\( R_p = R_T \)

e.g., Evans & Kochanek (1989), Cannizzo et al. (1990), Ramirez-Ruiz & Rosswog (2009), Lodato et al. (2009), Guillochon & Ramirez-Ruiz (2012)
The Bound Material: Fallback

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   Thin accretion disk

\[ M_{\text{BH}} = 10^6 M_\odot \]

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The Bound Material: Accretion disk

- debris shocks and circularizes
- forms steady accretion disk in time $t_{\text{visc}} \ll t_{\text{fallback}}$
- disk is optically thick
- supported by radiation pressure

Solve equations for disk structure:

- debris shocks and circularizes
- forms steady accretion disk in time $t_{\text{visc}} \ll t_{\text{fallback}}$

Blackbody temperature

Super-Eddington fallback rate
$t_{\text{photon diff}} > t_{\text{advect}}$
emission $\sim$ capped at $L_{\text{edd}}$

Sub-Eddington fallback rate
$t_{\text{photon diff}} < t_{\text{advect}}$
emission declines with time
The Bound Material: Accretion disk

- multicolor blackbody
  peaks at $\sim 100$ eV $\sim 100$ Å

- while $\dot{M}_{\text{fallback}} > \dot{M}_{\text{Edd}}$, disk luminosity is constant at $L_{\text{Edd}}$

- once $\dot{M}_{\text{fallback}} < \dot{M}_{\text{Edd}}$, disk cools and fades
  
  $L_{\text{bol}} \propto T^4 \propto \dot{M}_{\text{fallback}} \propto t^{-5/3}$
  
  $L_{\text{optical}} \propto T \propto \dot{M}_{\text{fallback}}^{1/4} \propto t^{-5/12}$

- faint emission lines from photoionized surface of unbound debris

- fairly modest optical emission

Strubbe & Quataert (2009)
The Bound Material: Fallback

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   Physics is uncertain, but likely advective disk + powerful outflows (+ jet?)

2. **Sub-Eddington fallback**: \( \dot{M}_{\text{fallback}} \lesssim \dot{M}_{\text{Edd}} \)

   Thin accretion disk

\[
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\( \dot{M}_{\text{fallback}} \sim \frac{M_*}{t_{\text{fallback}}} \left( \frac{t}{t_{\text{fallback}}} \right)^{-5/3} \)

\( \dot{M}_{\text{fallback}} \approx \dot{M}_{\text{Edd}} \) ~weeks - months

\( \dot{M}_{\text{fallback}} \lesssim \dot{M}_{\text{Edd}} \) ~months - year

\( M_{BH} = 10^6 M_{\odot} \)

\( R_p = R_T \)

\( \text{e.g., Loeb & Ulmer (1997), Ayal et al. (2000)} \)

\( \text{see also Lodato & Rossi (2011)} \)
The Bound Material: Super-Eddington Fallback Phase

- High fallback rate → High density at pericenter

- Electron scattering traps photons. Matter is so dense that most photons cannot diffuse out.

Radiation pressure drives gas back outward.
The Bound Material: Super-Eddington Fallback Phase

- High fallback rate →
  High density at pericenter

- Electron scattering traps photons.
  Matter is so dense that most photons cannot diffuse out.

Trapped heat should...

1. unbind gas and drive
   **outflow**

2. be dragged along with gas
   **accretion disk** into the BH

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(Ohsuga & Mineshige 2007)
Maybe also (separate) magnetically-driven relativistic jet

(e.g., Bloom et al. 2011, Metzger & Giannios 2011)
Deep inside:
- photons are trapped by electron scattering → adiabatic so $T \propto \rho^{1/3}$

At photosphere:
- lower density, so photons can escape
- photons likely have blackbody spectrum
- if blackbody: large radius, cool temperature → large optical luminosity

As $\dot{M}_{\text{fallback}}$ and density drop, photosphere moves deeper in → $T_{\text{phot}}$ rises while $L_{\text{bol}}$ drops

see also Rossi & Begelman (2009)

\[\rho(r) \sim f_{\text{out}} \frac{\dot{M}_{\text{fallback}}}{4\pi r^2 v_{\text{wind}}}\]
The Bound Material: Super-Eddington Outflows

Photometric Signature: Blackbody Continuum

e.g.,

\[ M_{\text{BH}} = 10^6 M_\odot \]
\[ R_p = R_T \]

\begin{align*}
\text{at 10 days:} & \\
R_{\text{phot}} & \sim 1000 \ R_S \sim 20 \text{ AU} \\
T_{\text{phot}} & \sim 3 \times 10^4 \text{ K} \\
L_{\text{optical}} & \sim 10^{43} \text{ erg/s}! \\
M_{\text{AB}} & \sim -19
\end{align*}

\[ \nu L_\nu \text{ (erg/s)} \]

\[ \lambda \text{ (Angstroms)} \]

Strubbe & Quataert (2009)
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\[ M_{AB} \sim -19 \]

First optical discoveries!

SDSS: van Velzen et al. (2011)
PTF: Cenko et al. (2012)
Pan-STARRS: Gezari et al. (2012)

Strubbe & Quataert (2009)
The Bound Material: Super-Eddington Outflows

Outer gas imprints spectrum on blackbody continuum

\[
\tau_{es} \ll 1
\]
photosphere for electron scattering

\[
\tau_{es} \sim 1
\]

\[
\tau_{es} \gg 1
\]
outflow edge

\[ R \sim v_{\text{wind}} t \]

MOST PHOTONS

Blackbody continuum

\[
h_v (eV)
\]

\[
\nu \nu' (\text{erg/s})
\]

\[
\lambda (\text{Angstroms})
\]

\[
t = 10 \text{ days}
\]

\[
t = 30 \text{ days}
\]

\[
t = 100 \text{ days}
\]
The Bound Material: Super-Eddington Outflows

Outer gas imprints spectrum on blackbody continuum

- Outflow edge: $R \sim v_{\text{wind}}$
- Photosphere for electron scattering: $\tau_{\text{es}} \sim 1$
- Bound material: Super-Eddington outflows

Blackbody continuum

- Photoionization (bound→free): $\tau_{\text{es}} \ll 1$
- Absorption (bound→bound): $\tau_{\text{es}} \gg 1$

Most photons

$\nu L_{\nu}$ (erg/s)

$\lambda$ (Angstroms)

$1000$ $10000$

$10 \nu$ (eV)

$100$ $10^4$

$t = 10$ days

$30$ days

$100$ days

$10^4$

$10^5$

$10^6$

$10^7$

$10^8$
The Bound Material: Super-Eddington Outflows

Outer gas imprints spectrum on blackbody continuum

outflow edge
\[ R \sim v_{\text{wind}} \]

\[ \tau_{es} \ll 1 \]

\[ \tau_{es} \sim 1 \]

\[ \tau_{es} \gg 1 \]

\[ t = 10 \text{ days} \]

\[ 30 \text{ days} \]

\[ 100 \text{ days} \]

\[ \text{photosphere for electron scattering} \]

\[ \text{absorption} \quad \text{(bound} \rightarrow \text{free)} \]

\[ \text{bound} \rightarrow \text{bound} \]

\[ \text{emission} \quad \text{(free} \rightarrow \text{bound)} \]

\[ \text{bound} \rightarrow \text{bound} \]

\[ \nu L_{\nu} \] (erg/s)

\[ h\nu \] (eV)

\[ \lambda \] (Angstroms)

\[ 100 \]

\[ 10^4 \]

\[ 10^5 \]

\[ 10^6 \]

\[ 10^7 \]

\[ 10^8 \]

\[ 10^9 \]

\[ 10^{10} \]

\[ \text{most photons} \]
Spectroscopic signature to help identification of event

- outer gas is highly ionized:
  - few/no optical lines
  - most lines in FUV - EUV ($\lambda \lesssim 2000$ Å)

- absorption lines:
  - broad, strong blueshift ($v_{\text{wind}}/c \sim 0.1$)

Strubbe & Quataert (2011)

$M_{\text{BH}} = 10^6 M_\odot$
$R_p = R_T$
$t = 10$ days

similar to BAL QSO spectrum
Summary of Predicted Observable Properties

**luminous outflows**
(optical/UV emission, blueshifted absorption lines)

Strubbe & Quataert (2009, 2011)

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**super-Eddington fallback rate**

**sub-Eddington fallback rate**

\[ \dot{M}_{\text{fallback}} / \dot{M}_{\text{Edd}} \]

---

\[ \nu L_\nu \text{ (erg/s)} \]

---

\[ M_\text{fallback}/M_\text{Edd} \]

---

**accretion disk** (optical -- X-ray emission)
+ unbound material (faint offset emission lines)
Summary of Predicted Observable Properties

luminous outflows
(optical/UV emission, blueshifted absorption lines)

Strubbe & Quataert (2009, 2011)

Results:
Optical flares at $10^{43} - 10^{44}$ erg/s are starting to be found!
Will teach us about super-Eddington flows in other contexts as well.

accretion disk (optical -- X-ray emission)
+ unbound material (faint offset emission lines)