Tidal Disruption Event Observations

TDE17 Cambridge – September 11, 2017
Tidal disruption of stars by black holes of $10^6$–$10^8$ solar masses in nearby galaxies

Martin J. Rees
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Stars in galactic nuclei can be captured or tidally disrupted by a central black hole. Some debris would be ejected at high speed; the remainder would be swallowed by the hole, causing a bright flare lasting at most a few years. Such phenomena are compatible with the presence of $10^6$–$10^8\ M_\odot$ holes in the nuclei of many nearby galaxies. Stellar disruption may have interesting consequences in our own Galactic Centre if a $\sim 10^6\ M_\odot$ hole lurks there.

What is the state of affairs since Dr. Rees’ seminal paper in 1988?
Theoretical Framework

Rees 1988
Call for Detailed Numerical Calculations

This paper has outlined several potentially observable effects that call for detailed stellar-dynamical and hydrodynamic calculations. Precise modelling should also allow for a realistic spread in the stellar population.
Call for Detailed Numerical Calculations

This paper has outlined several potentially observable effects that call for detailed stellar-dynamical and hydrodynamic calculations. Precise modelling should also allow for a realistic spread in the stellar population.

**Stellar Dynamics:**
- Magorrian & Tremaine (1999)
- Brockamp+ (2011)
- Stone & Metzger (2016)

**Hydrodynamics:**
- Evans & Kochanek (1989)
- Lodato+ (2009, 2011)
- Guillochon+ (2013)
- Macleod+ (2013)
- Law-Smith+ (2017)

Image Credit: J. Guillochon
Call for Detailed Numerical Calculations

This paper has outlined several potentially observable effects that call for detailed stellar-dynamical and hydrodynamic calculations. Precise modelling should also allow for a realistic spread in the stellar population.

**Stellar Dynamics:**
- Magorrian & Tremaine (1999)
- Brockamp+ (2011)
- Stone & Metzger (2016)

**Hydrodynamics:**
- Evans & Kochanek (1989)
- Lodato+ (2009, 2011)
- Guillochon+ (2013)
- Macleod+ (2013)
- Law-Smith+ (2017)

Image Credit: J. Guillochon
Worthwhile to Search for TDEs!

The stellar disruption phenomenon is relevant to high-resolution observations of nearby galaxies, and to the properties of AGNs in general. In the meantime, it would seem worthwhile to search for thermal flares lasting $\lesssim 1$ yr in the nuclei of ordinary quiescent galaxies.
Worthwhile to Search for TDEs!

The stellar disruption phenomenon is relevant to high-resolution observations of nearby galaxies, and to the properties of AGNs in general. In the meantime, it would seem worthwhile to search for thermal flares lasting \( \leq 1 \) yr in the nuclei of ordinary quiescent galaxies.

Future: thousands?

Now: 2 dozen

\( \sim 2 \) TDEs/yr
**Multi-λ Searches**

![Graph showing the log (Peak Luminosity) vs. Year of Discovery for different spectra (γ-ray, X-ray, UV, Optical) with data points for various telescopes and satellites: ROSAT, SDSS, GALEX, PTF, XMM, PS1, CXO, ASASSN, Swift. The graph includes a shaded area indicating \( L_{\text{Edd}} (M_{\text{BH}} = 10^6 \text{–} 10^7 \ M_\odot) \).]
Milestones

First UV and Optical Light Curves

$\gamma$-ray
X-ray
UV
Optical

$L_{\text{Edd}}(M_{\text{BH}} = 10^6 - 10^7 \, M_{\odot})$

Year of Discovery


GALEX

ROSAT  SDSS  GALEX  PTF  XMM  PS1  CXO  ASASSN  Swift

Milestones

First UV and Optical Light Curves

$\gamma$-ray
X-ray
UV
Optical

$L_{\text{Edd}}(M_{\text{BH}} = 10^6 - 10^7 \, M_{\odot})$

Year of Discovery


GALEX

ROSAT  SDSS  GALEX  PTF  XMM  PS1  CXO  ASASSN  Swift
Relativistic Events:
-- Highly super-Eddington luminosity implies geometric beaming
-- Rising radio flux from a newly-formed jet
-- QPOs and Fe Kα reverberation detected in X-rays

Milestones

Swift

Bloom+ 2011
Burrows+ 2011
Zauderer+2011
Levan+ 2011
Reis+ 2012
Cenko+ 2012
Milestones

First Clear Detection of Rise of Light Curve & Transient Broad Lines

Pan-STARRS1

Gezari+ 2012
Milestones

Nearby Events & First Strong Detections of X-ray & Radio Component & Non-relativistic Outflows

ASAS-SN

$\gamma$-ray
X-ray
UV
Optical

$L_{\text{Edd}}(M_{\text{BH}} = 10^6 - 10^7 M_\odot)$


Year of Discovery

Holoien+ 2014, 2016ab
van Velzen+ 2015, 2016
Alexander+ 2015
Miller+2015
Jiang+ 2016

Van Velzen, Alexander, Miller, Jiang, Holoinen, ASAS-SN
Milestones

Closest, Fastest, Least-Luminous

\( L_{\text{Edd}}(M_{\text{BH}} = 10^6 - 10^7 \, M_\odot) \)

\( \gamma\text{-ray} \)
\( X\text{-ray} \)
\( UV \)
\( \text{Optical} \)

Year of Discovery


Blagorodnova, Gezari+ 2017
Many Questions Still Remain

(1) What fraction of the debris goes down the hole, rather than being expelled? (2) What is the radiative efficiency for the accretion process? In other words, how many ergs are radiated for each gram that is swallowed? (3) How long does it take to ‘digest’ or expel the debris from one star? In particular,
Many Questions Still Remain

But New Questions Have Emerged:
Origin of optically bright emission
Enhanced He to Hα broad-line ratios
Launching of relativistic jets
Relation to host galaxy merger or SF history
Possible consequences of a binary SMBH
Timescale for Accretion

There would therefore be no conspicuous flare until, as discussed above, the bound debris fell back onto the hole after a time delay $t$. 
Timescale for Accretion

There would therefore be no conspicuous flare until, as discussed above, the bound debris fell back onto the hole after a time delay $t_f$.

**The Great Circularization Debate of 2015:**
- Hayasaki, Stone & Loeb 2015
- Guillochon & Ramirez-Ruiz 2015
- Shiokawa+ 2015
- Piran+ 2015
- Bonnerot+ 2016

Bonnerot+ 2016
Light Curve Follows Fallback Rate

There would therefore be no conspicuous flare until, as discussed above, the bound debris fell back onto the hole after a time delay $t_f$.

Theory vs. Observations

Shiokawa+ 2015  
Gezari+ 2015
Why Is This a Surprise?

$L \sim t^{-5/3}$
$L \sim T^4 R^2$
$L_{RJ} \sim T \sim t^{-5/12}$

Disk Model: $t^{-5/12}$ decline expected in UV and optical

$T(R_T) \sim 10^5$ K

Lodato+ 2011
Eddington-Limited Flares from Fallback of Debris

The most obvious consequence of a $10^6-10^8 \, M_\odot$ black hole would be transient flares whenever bound debris from a star was swallowed. The rate is given by equation (2) with $r_{\text{min}} = r_T$, the luminosities being as high as $L_E = 10^{44} \, M_6 \, \text{erg s}^{-1}$. 
Eddington-Limited Flares from Fallback of Debris

The most obvious consequence of a $10^6-10^8 M_\odot$ black hole would be transient flares whenever bound debris from a star was swallowed. The rate is given by equation (2) with $r_{\text{min}} = r_T$, the luminosities being as high as $L_E = 10^{44} M_\odot$ erg s$^{-1}$.

Observations

Hung, Gezari+ 2017

Wevers+ 2017
Observational Signatures

On the other hand, a sufficiently large sample of such galaxies should reveal some members of the ensemble in a flaring state. Such objects could be searched for out to large distances: they would differ from typical AGNs through the lack of any extended structure (emission line or radio components).
Observational Signatures

On the other hand, a sufficiently large sample of such galaxies should reveal some members of the ensemble in a flaring state. Such objects could be searched for out to large distances: they would differ from typical AGNs through the lack of any extended structure (emission line or radio components).

Expected: No NLR

Arcavi+ 2014

Holoien+ 2016
Observational Signatures

On the other hand, a sufficiently large sample of such galaxies should reveal some members of the ensemble in a flaring state. Such objects could be searched for out to large distances: they would differ from typical AGNs through the lack of any extended structure (emission line or radio components).

**Surprise: Enhanced He to Hα ratios**

- Gezari+ 2012, Arcavi+ 2014
- Hung, Gezari+ 2017
Observational Signatures

On the other hand, a sufficiently large sample of such galaxies should reveal some members of the ensemble in a flaring state. Such objects could be searched for out to large distances: they would differ from typical AGNs through the lack of any extended structure (emission line or radio components).
Observational Signatures

On the other hand, a sufficiently large sample of such galaxies should reveal some members of the ensemble in a flaring state. Such objects could be searched for out to large distances: they would differ from typical AGNs through the lack of any extended structure (emission line or radio components). If $\sim 10^6 M_\odot$

$T_{BB} \sim a \text{ few } 10^4 \text{ K (not } 10^5 \text{ K)}$

$R >> r_T$

Hung, Gezari+ 2017
How to Get Large Radii

Reprocessing Envelope
Loeb & Ulmer (1997)
Guillochon+ (2014)
Roth+ (2016)

Circularization of Debris
Piran+ (2015)
Jiang, Guillochon, & Loeb (2016)
Svirski, Piran, & Krolik (2017)
Bonnerot, Rossi, & Lodato (2017)

Radiatively Driven Wind
Miller (2015)
Metzger & Stone (2016)
How To Get High He-to-Hα Ratios

Reprocessing Envelope

Chemical Composition of the Star
Gezari+ (2012)
Strubbe & Murray (2015)
Kochanek (2016)
Law-Smith+ (2017)
Maximum $M_{BH}$ for Disruption

For hole masses $M_h > 10^8 M_\odot$, solar-type stars cannot be disrupted without entering the strongly relativistic domain. The form of the black hole (Schwarzschild or Kerr?) then has an important quantitative effect, as does (for a rotating Kerr hole) the orientation of the stellar orbit relative to the hole spin axis.

When the hole mass is $> 10^8 M_\odot$, most main sequence stars would be swallowed whole ($r_T < r_g$), and only giants would generate debris outside the hole\(^{1,2}\).

\[ M_{BH}/M_{crit} \]

I: captures suppressed  \hspace{1cm} III: no disruptions

Beloborodov+ (1992)

Kesden 2012

Newtonian

\[ a = 0 \quad a = 0.999 \]
Maximum $M_{\text{BH}}$ for Disruption

For hole masses $M_h > 10^8 M_\odot$, solar-type stars cannot be disrupted without entering the strongly relativistic domain. The form of the black hole (Schwarzschild or Kerr?) then has an important quantitative effect, as does (for a rotating Kerr hole) the orientation of the stellar orbit relative to the hole spin axis. When the hole mass is $>10^8 M_\odot$, most main sequence stars would be swallowed whole ($r_T < r_g$), and only giants would generate debris outside the hole\cite{1,2}.

van Velzen 2017

Observations

ASASSN-15lh: $M_{\text{BH}} > 10^8 \text{ Msun, Kerr black hole?}$

Leloudas+ 2016
30 years later...
How do we advance further from here?
30 years later...
How do we advance further from here?

More events...
Zwicky Transient Facility

Collaborators: Tiara Hung (graduate student at UMd), Brad Cenko (Goddard/JSI), Nadia Blagorodnova, Lin Yan, Shri Kulkarni (Caltech)
The PTF survey family has three phases.

**PTF yesterday**
The Palomar Transient Factory
(2009-2012) ~60 papers, 1850 citations
*General synoptic transient survey*

**iPTF today**
Intermediate Palomar Transient Factory
(2013-2016)
*Focused mini-surveys*

**ZTF tomorrow**
The Zwicky Transient Facility
(2018-2020+)
*High-cadence search for fast transients*
We discovered two TDEs in 4 months with iPTF...expect 1-2 TDEs per month with ZTF!
TDEs in Our Local Universe!

holes were prevalent in small or even dwarf galaxies, the nearest such flares, in any given year, may be no further away than the Virgo Cluster.
TDEs in Our Local Universe!

holes were prevalent in small or even dwarf galaxies, the nearest such flares, in any given year, may be no further away than the Virgo Cluster.

If ~$10^6 M_\odot$.

**Faint and fast**

**Well-studied across the EM spectrum**
In Principle, Soon We Will Have

Surveys with time domain component.
Aspen Winter Conference

Application Deadline: October 31, 2017

Using Tidal Disruption Events to Study Super-Massive Black Holes

Organizers:
Suvi Gezari, University of Maryland
Enrico Ramirez-Ruiz, UC Santa Cruz
Stefanie Komossa, MPIR
Peter Jonker, NISR and Radboud University

Let’s continue the conversation in Aspen...

Thank You!