XMM-Newton Follow-up of Tidal Disruption Events from ZTF

Suvi Gezari

NASA/Goddard – October 21, 2019
ZTFbh: AGN and TDE SWG

Who are we?

Suvi Gezari, UMd (coordinator), Matthew Graham, Caltech (deputy coordinator)

Sara Frederick, UMd (current grad student)
Charlotte Ward, UMd (current grad student)
Erica Hammerstein, UMd (current grad student)
Sjoert van Velzen, UMd/NYU (postdoc)
Tiara Hung, UCSC (former grad student)

Brad Cenko, GSFC
Shri Kulkarni, Caltech
Peter Nugent, LBNL
Tom Barlow, Caltech
Lin Yan, Caltech
Po-Chieh Yu, NCU
Zeljko Ivezic, UW
Robert Stein, DESY
David Shupe, Caltech/IPAC
Nathaniel Roth, UMd and GSFC
Daniel Stern, Caltech/JPL
Scott Anderson UW
Nadia Blagorodnova, Radboud

ZTFbh SWG Dinner @ Daisy Mint
March 19, 2018
What are we doing?

We are conducting a systematic study of extragalactic nuclear transients.

What are we interested in?

Nuclear Transients (< 0.5 arcsec from host galaxy center):
- variable active galactic nuclei
- changing-look quasars (CLAGN)
- tidal disruption events (TDEs)
- supermassive black holes (binary, recoiling, intermediate-mass)

What tools do we use?

AMPEL
SEDM/P60
PI: Mansi Kasliwal
Tidal Disruption of a Star
What happens when a star ventures too close to a black hole?

It gets ripped apart!

Evans & Kochanek 1989
Tidal Disruption of a Star

The star is ripped apart when tidal forces overcome the self gravity of the star:

\[
\frac{G M R_\star}{r^3} = \frac{G m_\star}{R_\star^2}
\]

Tidal Force \hspace{1cm} Self-Gravity

\[
r_T \approx R_\star \left(\frac{M_{\text{BH}}}{m_\star}\right)^{1/3}
\]

Tidal Disruption Radius
How close do you have to get?

It depends on the type of star and the mass of the black hole!

\[ r_S = \frac{2GM_{BH}}{c^2} \]

Event Horizon
Probing Black Hole Mass

\[ t_{\text{peak}} \sim M_{\text{BH}}^{1/2} \]

\[ \sim t^{5/3} \]

Gezari 2014, Adapted from De Colle+ 2012
Probing SMBH Demographics

Probing BH mass range where even local scaling relations are poorly constrained.
Multi-\(\lambda\) Searches

\[
\log (\text{Peak Luminosity})
\]

\[
\gamma\text{-ray}
\]

\[
X\text{-ray}
\]

\[
\text{UV}
\]

\[
\text{Optical}
\]

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

Year of Discovery


ROSAT SDSS

GALEX PTF

XMM PS1

CXO ASASSN Swift
We’ve Come a Long Way...

**X-ray Searches...**

Esquej+ 2008

**Ultraviolet/Optical Searches...**

Gezari+ 2015
Some Basic Predictions Have Held True…

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 $L_E = 10^{44} \, M_\odot \, \text{erg s}^{-1}$.

Rees 1988
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Rees 1988

Observations

Wevers + 2017

Hung, Gezari+ 2017
Surprises Along the Way
We are finding common characteristics…

- \( t^{5/3} \) decline
- Large radii: 10-100 \( R_T \)
- Constant temperature

Hung, Gezari+ 2017
Lodato + 2011

that are in tension with theoretical predictions...

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

\[ T(R_T) \sim 10^5 \text{ K} \]

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

Lodato+ 2011
UV/Optical Light Curve Follows Fallback Rate

Models for $dM/dt$, scaled to light curve.

PS1-10jh: Gezari+ 2012, 2015
Why is this a Surprise?

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

Bonnerot+ 2016
Why is this a Surprise?

Shiokawa+ 2015

Gezari+ 2015
Helium-Only Spectra

Can put strong constraints on Hα.

CAUTION: Telluric line

He II/Hα > 5

T_{BB} = 30,000 K

BB + Sept. 2012 spectrum

Sept. 2012 spectrum

Day +707

Day -22

PS1−10jh

Difference

He II λ3203

He II λ4686

Rest Wavelength (Å)

Rest Wavelength (Å)

Gezari+ 2015
Enhanced He to Hα Ratios

Gezari+ 2012, Arcavi+ 2014

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)
New Insights from TDE ASASSN-15oi

Holoien+ 2016
New Clues from Delayed X-ray Emission in ASASSN-15oi

ASASSN-15oi

XMM and Swift measure x10 brightening of soft X-rays, with little change in spectral shape ($kT_{BB} \sim 45$ eV)

Viewing angle? X
Variable obscuration? X
Circularization delay? ✓

Gezari, Cenko & Arcavi (2017)
Spectral Evolution Probed by XMM

No evolution in soft blackbody temperature during factor of 10 increase in X-ray flux!

Blackbody radii consistent with inner radii of accretion disk around $10^6 M_{\odot}$ black hole.  

Gezari, Cenko & Arcavi 2017

$L_{BB} = 9 \times 10^{41} \text{ erg/s} 
\rightarrow 
L_{BB} = 1 \times 10^{43} \text{ erg/s}$

$R_{BB} = 3 M_6^{-1} r_g 
\rightarrow 
R_{BB} = 15 M_6^{-1} r_g$

Soft blackbody ($kT = 45 \text{ eV}$) component increases by a factor of 12.

Power-law (Gamma=2.5) component remains constant.
Delayed X-ray Emission due to Circularization Delay?

Prompt UV/Optical Emission from Stream-Stream Collisions?

Observations consistent with Piran+ 2015 Model:
- Prompt UV/Optical component from circularization process!
- Delayed soft X-ray emission from accretion in nascent disk!
Strong Evolution in $L_{\text{Opt}}/L_X$

$L_{\text{Opt}}/L_X \sim 1$ characteristic of most optical+X-ray TDEs?
Accretion Timescales

The characteristic timescale for a TDE is set by the orbital period of the most tightly bound debris, known as the fallback time ($t_{fb}$), which for a solar-type star is:

$$t_{fb} = 41 \text{ d } M_6^{1/2}.$$ 

The circularization timescale ($t_{circ}$) driven by relativistic apsidal precession of the debris streams depends on the black hole mass as

$$t_{circ} = 8.3t_{fb} M_6^{-5/3} \beta^{-3}$$

where $\beta = R_T/R_p$, Bonnerot et al. (2016). Meanwhile, the viscous inflow time scale for a standard $\alpha$-disk model (Shakura & Sunyaev 1973) is

$$t_{visc} = \alpha^{-1}(h/r)^{-2} P_{out} \sim 0.1t_{fb}(\alpha/0.1)^{-1}(h/r)^{-2}$$

where $\alpha$ is the standard viscous parameter, $h$ is the scale-height of the disk, and $P_{out}$ is the orbital period of the outer edge of the disk.

1 yr rise time of X-ray to peak is tantalizingly close to the circularization timescale of a $10^6 M_{\text{sun}}$ TDE!
Where do we go from here...
Where do we go from here...

**More** events...
The Golden Age of Wide-Field Optical Surveys
The Zwicky Transient Facility (ZTF)

Started in March 2018

UMd is a member of the ZTF collaboration, along with:

- ipac
- Caltech
- DESY
- Los Alamos
- Oskar Klein Centre
- W
- WISS
- WHIZMANN INSTITUTE OF SCIENCE
ZTF will survey an order of magnitude faster than PTF.

<table>
<thead>
<tr>
<th></th>
<th>PTF</th>
<th>ZTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Area</td>
<td>7.26 deg²</td>
<td>47 deg²</td>
</tr>
<tr>
<td>Readout Time</td>
<td>36 sec</td>
<td>10 sec</td>
</tr>
<tr>
<td>Exposure Time</td>
<td>60 sec</td>
<td>30 sec</td>
</tr>
<tr>
<td>Relative Areal Survey Rate</td>
<td>1x</td>
<td>14.7x</td>
</tr>
<tr>
<td>Relative Volumetric Survey Rate</td>
<td>1x</td>
<td>12.3x</td>
</tr>
</tbody>
</table>

3800 deg²/hour  
⇒ 3π survey in 8 hours,  
⇒ > 250 observations/field/year

New ZTF camera:  
16 6k x 6k e2v CCDs

Existing PTF camera  
MOSAIC 12k

We discovered two TDEs in 4 months with iPTF...expect 1-2 TDEs per month with ZTF!
ZTF@UMd

ASTR 498S: Research Course in "Big Data" Astronomy

Discovery Channel Telescope (4.3m)
Offset Distribution

![Histogram of Offset Distribution](image)

- **Known SNe**
- **Known AGN**
- **Unknown**

- **X-axis:** Mean Offset (arcsec)
- **Y-axis:** #

The histogram shows the distribution of offsets for different categories: known SNe, known AGN, and unknown. The bars indicate the frequency of offsets within each bin.
Filtering Out Pesky SNe
Filtering Out Pesky SNe

![Graph showing rate of color change vs mean pre-peak g-r color for different types of explosions. Legend includes TDE, AGN, SN Ia, and SN other.]
WINTER IS COMING
GOT Nicknames

**ZTF18abxftqm** TDE 01:07:33.61 +23:28:34.4

**OverView** Photometry Spectroscopy Observability ExamIne Finding chart

**New** Ref Sub SDSS PS1

First saved in public data.

**ADDITIONAL INFO**

NEO TESS SNEX SIMBAD Vizier HEASARC SkyView MPChecker Extinction

J FIT PACT DIS WISE Subaru VLT FIRST CRTS - ANS

IPTF Marshall Legacy/Survey Avro Packets

**Auto Annotations**

2019 Aug 05 AMPELBOT [saved_by_id]: AMPELBOT
2018 Oct 15 spjort [saved_by_id]: ZTFBH Nuclear
2018 Nov 06 jnordin [saved_by_id]: AMPFEL Test
2018 Nov 04 ysharma [Saved_date]: 2018-11-03 RCF
2018 Nov 03 fremling [passed_filter]: Redshift

Completeness Factor
2018 Oct 22 fremling [IAU name]: AT2018hco
2018 Sep 28 suvi [passed_filter]: Nuclear Transients
2018 Sep 27 jesper [SDSS, photon auto]: 0.109 ± 0.0076 (0.276°, reference)
2018 Sep 27 jesper [passed_filter]: ZTF Science Validation

Auto Annotation Submission Form

**Comments**

2019 Sep 11 eklhammer [comment]: telluric corrections applied
2019 Sep 11 eklhammer [comment]: issues with blue end flux calibration
2019 Jan 09 suivi [info]: host galaxy not detected in GALEX AIS in NUV
2019 Jan 03 raw [comment]: pysedm_report [view attachment]
2018 Dec 06 jesper [info]: ATEL #12283 Title: Classification of AT2018hco/ZTF18abxftqm as a tidal disruption flare
2018 Dec 03 suivi [redshift]: 0.088
2018 Dec 01 suivi [classification]: TDE
2018 Nov 27 suivi [info]: Sansa Stark (ZTF18h SWG Name)
2018 Nov 27 raw [comment]: pysedm_report [view attachment]
2018 Nov 15 suivi [info]: triggered Swift
2018 Nov 15 suivi [info]: revised redshift based on Ca H,K in APO spectrum
2018 Nov 10 kds [classification]: TDE?
2018 Nov 10 kds [redshift]: 0.09
2018 Nov 04 migraham [comment]: APO-DIS spectrum 16:11-0:00; dewar contamination lead to poor quality spectra, flux calibration not trustworthy
ZTF+Swift Light Curves

Cersei

AT2018lna / Cersei

Rest-frame days since peak

AB mag

Jaime

AT2019azh / ASASSN-19dj / Jaime

Rest-frame days since peak

AB mag

Bran

AT2019dsg / Bran

Rest-frame days since peak

AB mag

Brienne

AT2019ehz / Gaia19bpt / Brienne

Rest-frame days since peak

AB mag
Slow Rise and Fade Times

late-time (post-peak) and color-independent selection

rise e-folding time (log_{10} day) vs. fade e-folding time (log_{10} day)

- AGN
- SN Ia
- SN other
- TDE
Blue with No Color Evolution

late-time (post-peak) selection

rate of color change (1/day)

mean g-r color

AGN
SN Ia
SN other
TDE
Spectral Types

H-only

H+He+NIII/OIII

He-only
van Velzen, Gezari, et al. 2018

AT2018zr was one of only 5 TDEs discovered before peak!

van Velzen, Gezari, et al. in prep.

In the first 1.5yr of ZTF survey operations, we have detected 14 more!
UV-Bright BB Temperature

van Velzen, Gezari+ in prep.
Red Galaxy Hosts

van Velzen, Gezari+ in prep.
New Landscape of Optical+X-ray TDEs

Before ZTF

van Velzen, Gezari, et al. 2018

*AT2018zr was one of only 5 TDEs with an optical and X-ray detection!*

After ZTF

van Velzen, Gezari, et al. in prep.

*In the first 1.5yr of ZTF survey operations, we now have detected 3 more TDEs in the soft X-rays, and with dramatic variability!*
What is driving changes in $L_{\text{opt}}/L_x$?

- Viewing Angle?
- Reprocessing?
- Circularization?

Dai et al. 2018

Bonnerot+ 2016
Conclusions

• ZTF is on track to be the first survey to produce a **statistically significant, systematically selected** TDE sample
• Will enable **population studies** of TDEs and their host galaxies and central black holes
• **Swift and XMM-Newton** follow-up have been critical for probing the UV and X-ray components
• **Soft X-ray evolution** may hold the key for unlocking the nature of the UV/optical component, and for probing the real-time formation of the accretion disk
In Principle, Soon We Will Have

Surveys with time domain component.
LSST’s Bread & Butter
Transients & Variables
(known knowns)

- **2 million** variable quasars
  (Sesar+ 2007)

- **10 million** supernovae
  (LSST Science Book)

- **50 million** variable stars
  (Sesar+ 2007)
A Smart & Colorful Rolling Cadence Proposal for LSST Wide-Fast Deep Survey

LSST has the capability to discover 200 TDEs yr\(^{-1}\) per 1000 deg\(^2\)...but changes to the baseline LSST Wide-Fast Deep Survey cadence are required for early detection, photometric classification, and light-curve characterization.

Gezari+ 2018, LSST Cadence White Paper