Evolution of Tidal disruption events discovered by XMM-Newton

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Outline

- Introduction

- Tidal disruption events
  - Theory
  - Observational signatures & previous detections
  - Candidates selection
  - Follow-up observations
  - Alternative scenarios
  - Tidal disruption rate

- Summary/Conclusions
The ubiquity of SMBHs

- The paradigm that the cores of most, if not all, galaxies are occupied by SMBHs was predicted long ago.

- Quasars were more abundant in the early Universe at $z \approx 2$ than at present, so dead quasar engines are expected to be enclosed in the nuclei of otherwise non-active galaxies.

- Alternatively to the stellar dynamics approach, an unavoidable consequence of the existence of remnant SMBHs at the nuclei of optically non-active galaxies is the detection of the so-called tidal disruption events.
**Theory of Tidal disruption events**

- A star orbiting a SMBH will be disrupted when approaching the BH tidal radius
  \[
  R_T = \mu R_s \left( \frac{M_{BH}}{m_*} \right)^{1/3} \] (Rees 1988)

- The process is expected to happen up to \(M_{BH} \sim 10^8 M_{\odot}\) (for a solar mass star).

- Once disrupted, half of the stellar material is ejected and the remaining half will be bound, returning to pericentre and circularizing, a fraction of it will be accreted by the hole (~10%) (Ayal et al. 2000).

- Flare of radiation beginning when the most bound material returns to pericentre.
  \[
  T_{\text{edd}}(3 r_T) = 7 \times 10^4 \left( \frac{M_{BH}}{10^8 M_{\odot}} \right)^{1/4} K \sim 60 \text{ eV} 
  \]
  Peak in soft X-rays!

- By equating the energy of the released gas to the specific orbital energy: \(T_{\text{min}}\). Applying physics of Keplerian orbits: luminosity declines as \(t^{-5/3}\)

(Evans & Kochanek 1999)
Observational Signatures

- Giant amplitude UV/EUV/X-ray flare – black body of $kT=40-100$ eV. Identification based on the existence of two large area X-ray sky surveys of comparable sensitivities
- Peak Luminosity $L_X = 10^{42} - 10^{44}$ erg s$^{-1}$
- Lasts a few weeks at peak luminosity and then falls off as $t^{-5/3}$ (Komossa 2002)

Previous detections:
- RX J1242.6-1119 (Komossa & Greiner 1999)
- RX J1624.9+7554 (Grupe et al. 1999)
- RX J1420.4+5334 (Greiner et al. 2000)
- NGC 5905 (Komossa & Bade 1999)
- TDXFJ134730.3-325451 (Cappelluti et al. 2009)
- 3 Galex sources (Gezari et al. 2007, 2008, 2009)

NGC 5905 (Li et al. 2002)
XMM-Newton Slew Survey

EPIC-pn data:
- soft 0.2-2 keV, hard 2-12 keV, total 0.2-12 keV

Sensitivity limits:
- Soft band: similar to RASS
- Hard band: deepest ever
XMM-Slew vs RASS

ROSAT: composite image RASS-PSPC maps of the diffuse soft XRB in the 0.1-0.4keV (red), 0.5-0.9keV (green), 0.9-2keV (blue) (Freyberg & Egger 1999).

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<td>SDSS J132341.9+482701</td>
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Very soft sources (not detected in slew hard band) classified as normal galaxies, rough spectral shape as black body at $kT=95$ eV or power-law with $\Gamma \sim 3$ initial agreement with the tidal disruption model.
XMM-Slew vs RASS

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Optical data

SDSS J1323
z=0.0087
- Non-active galaxy

NGC 3599
z=0.0028
- LLAGN
Follow-up

- **Optical:**
  - Do post-outburst spectra show any evidence of the disruption event?

- **X-rays:**
  - Is the temporal evolution following the $t^{5/3}$ law?
  - Do sources harden in time?
  - Is the detected X-ray emission coming from the nucleus?

- **Follow-up observations:**
  - Optical: NOT/INT
  - X-ray: XMM-Newton (ToO) and Swift (Fill-in; PI: G.Hasinger).
  - NGC 3599 recently observed with Chandra and XMM-Newton (PI: P.Esquej)
SDSS J1323

- Optical post-outburst spectra did not show any evidence of the disruption event.
- X-ray spectral analysis
  - $B_{\text{body}} (kT=62\text{eV}) + \text{Powerlaw} \ (\Gamma=1.4)$
  - Hard tail detected
  - Hard luminosity in low state is still higher than estimation from [OIII]-$L_2\cdot10^{10}\text{keV}$ relationship (Netzer et al. 2006)

$$L_X = 8.1(\pm 2.9) \times 10^{42} \left(\frac{t - 2003.56(\pm 0.10)\text{yr}}{1\text{yr}}\right)^{-3/2} \text{erg s}^{-1}$$
NGC 3599: X-ray imaging

- Bright source coincident with the centre of the optical position
- Faint off-nuclear source at 3 arcsec (300 pc)
NGC 3599: spectral analysis

- power-law ($\Gamma=2.3$) + black body (45 eV) + power-law (faint source)
- Thermal or black body models not compatible with data
NGC 3599: X-ray light curve

\[ L_X = 6.7(\pm 1.2) \times 10^{39} \left( \frac{t - 2003.59(\pm 0.04) \text{yr}}{1 \text{yr}} \right)^{-5/3} \text{ erg s}^{-1} \]
Alternative scenarios

- Stellar objects: don’t reach so high luminosities
- HMBX and supernovae: present strong hard X-ray emission and $L_x$ up to $10^{40}$ erg s$^{-1}$
- X-ray afterglow of GRB: no detected and follows a $t^{-1}$
- Gravitational lensing event: same variability in optical and X-rays (no simultaneous observations)
- ULX within NGC 3599: $L_x \sim 10^{39}-10^{40}$ erg s$^{-1}$, flux variation of 2-3, power-law shape ($\Gamma=1.6-1.8$).
- Accretion disk instability.
- Variations in the intrinsic radiation, changes in covering factor of the absorbing gas.
Properties of tidal events

Released energy:
\[ \Delta E_X = \int_{t'}^{\infty} L_X(t)dt. \]

Total accreted mass:
\[ \Delta M = \frac{\Delta E}{\epsilon c^2} \approx \frac{\Delta E_X}{\epsilon c^2} \]

Radius emitting region:
\[ R_X = \left( \frac{f_c I_X}{\pi \sigma T_{bb}^4} \right)^{1/2} \]

Black hole mass:
\[ M_{BH} = 1.66(\pm 0.24) \times 10^8 M_\odot \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^{4.86(\pm 0.43)} \]

(Ferrarese & Ford 2005)

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<tr>
<th>Source</th>
<th>( \Delta E_X ) (erg)</th>
<th>( \Delta M ) (M(_\odot))</th>
<th>( R_X ) (cm)</th>
<th>( M_{BH} ) (M(_\odot))</th>
</tr>
</thead>
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<tr>
<td>NGC 3599</td>
<td>( 7.1 \times 10^{48} )</td>
<td>( 4.0 \times 10^{-5} )</td>
<td>( 7.3 \times 10^{11} )</td>
<td>( 1.3 \times 10^6 )</td>
</tr>
<tr>
<td>SDSS J1323</td>
<td>( 7.6 \times 10^{50} )</td>
<td>( 4.2 \times 10^{-3} )</td>
<td>( 6.8 \times 10^{12} )</td>
<td>( 2.2 \times 10^6 )</td>
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Tidal disruption rate

Assumptions:
- Tidal spectrum 
  $bb (kT=70eV)$
- Peak luminosity 
  $L = 10^{44} \text{ erg s}^{-1}$

Completeness distance (406 Mpc)
Area (16.5% of the sky)

Flare duration ($z$)

Galaxy space density: $\rho_{\text{gal}}$

\[ \int_{0}^{r_{\text{max}}} \frac{N \text{ events}}{A(r) t(r) dr} = 5.4 \cdot 10^{-6} \frac{\text{ yr}^{-1}}{\text{ Mpc}^{-3}} = 2.3 \cdot 10^{-4} \frac{\text{ galaxy}^{-1} \text{ yr}^{-1}}{\text{ Mpc}^{-1}} \]
Assumptions:
- Tidal spectrum
  $bb (kT=70eV)$
- Peak luminosity
  $L = 10^{44}$ erg s$^{-1}$

- Theoretical tidal disruption rate is $\sim 10^{-4}$-$10^{-5}$ yr$^{-1}$ (Wang & Merrit 2004), depending on the stellar density in the nuclear cusp and the SMBH mass.

  $$\Gamma(M_{bh}) = 7 \times 10^{-4} \, yr^{-1} \left( \frac{\sigma}{70 \, km \, s^{-1}} \right)^{7/2} \left( \frac{M_{bh}}{10^6 \, M_{sun}} \right)^{-1} \left( \frac{m_*}{M_{sun}} \right)^{-1/3} \left( \frac{R_c}{R_{sun}} \right)^{1/4}$$

- Observed disruption rate $\sim 10^{-5}$ yr$^{-1}$ (Donley et al. 2002).

Tidal disruption rate from slew survey lies in agreement with previous theoretical and observational predictions!
Summary/Conclusions and future

- Tidal disruption candidates in high-state agree with previous detections, X-ray light curves declined as $t^{-5/3}$ and no significant variation of optical spectra was observed (Esquej et al. 2007, 2008).

- Closest observations to maximum in hard X-rays showing apparent hardening with respect to high-state.

- X-ray emission from SDSS J1323 in low-state does not seem to be AGN related.

- Although some AGN-related scenarios can not be ruled out, specially for NGC 3599, the tidal disruption model is fully consistent with observations.

- Important as they are the unambiguous probe of the existence of SMBH in otherwise non-active galaxies. They may contribute to the BH growth over cosmic times and the faint end of the AGN luminosity function.

- Fast data processing of incoming slews to perform fast follow-up of high variable sources.
- Future missions will allow the detection of new events to be obtained.
- Possible future detection of GWs with LISA.