A New Channel for X-ray Flashes: Tidal Disruptions of White Dwarfs by Intermediate Mass Black Holes


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White Dwarfs

Facts about WDs
Mass: $0.2-1.4 M_{\text{sun}}$, radius: $(2-9) \cdot 10^{3}\text{km}$.
Supported by electron degeneracy pressure.

WD is a solar mass squeezed within the Earth’s radius
Black holes

Stellar mass BHs
Many established sources w/ masses 5-15$M_{\text{sun}}$

Supermassive BHs
Dozens of established sources w/ masses 10$^6$-10$^{10}$$M_{\text{sun}}$

Intermediate mass BHs
Candidates w/ masses 10$^3$-10$^4$$M_{\text{sun}}$
=> $R_g \sim$ Earth radius
found by stellar dynamics in globular clusters, nuclear broad lines in dwarf galaxies, soft luminous blackbody X-ray sources

Is there a definitive proof yet?

Qualitatively new ways to identify sources

Lutzgendorf et al. 2013
Dong et al. 2007
Davis et al. 2012
Tidal disruptions

(this is actually an “ultra-close” disruption with $R_T/R_p=6$)

Some debris fall onto the BH and form accretion disk

Haas, Shcherbakov et al. 2012
How to find IMBHs?

Greene & Ho 2007

White dwarfs have radius $\sim$ IMBH radius + disrupted close to the BH => violent event

IMBHs may be there in small galaxies, but be mostly inactive

How to illuminate IMBH population?

Tidal disruptions of stars

Normal stars are disrupted too far => slow and weak flare

Neutron stars => swallowed as whole

White dwarfs have radius $\sim$ IMBH radius + disrupted close to the BH => violent event

Intermediate mass BHs should be effectively illuminated by tidal disruptions of WDs

SDSS DR4 data

Greene & Ho 2007
General features of tidal disruptions

- A star approaches on a parabolic orbit
- Pericenter radius $R_p$ is less than tidal radius $R_T \Rightarrow$ tidal disruption
- 50% of debris fall back and form accretion disk
- Typical event duration is 1hr for IMBH-WD encounter (1mo for SMBH-star)
- Typical accretion rate is $10^3 M_{\odot}/yr$ for IMBH-WD (1$M_{\odot}/yr$ for SMBH-star)
- Accretion rate drops w/ time as $M \sim t^{-5/3}$

Rees 1988

Evans & Kochanek 1989
Electromagnetic signatures

Infall of material onto a BH releases a lot of energy

How is energy converted into photons, which we observe?

Photons are trapped in dense debris

Eddington limit \( L_{Edd} = 10^{41} \text{ erg/s} \) for \( 10^3 M_{\text{Sun}} \) BH

But gas infall generates heat at rate

\[
P \sim 0.1 \dot{M} c^2 \sim 10^{49} \text{ erg/s} \sim 10^8 L_{Edd}
\]

Outflow/jet allows to release trapped photons faster and achieve high luminosity

Photons are advected with the outflow and released in lower density region with optical depth \( \tau_\sigma = 1 \) (photosphere)
Nuclear ignition

Tidal pinching:
WD is squeezed to orbital plane
Carter & Luminet 1982; Rosswog et al. 2009

Thermonuclear ignition
Track of density/temperature
Haas, Shcherbakov et al. 2012

Similar to supernova Type Ia?
(when the WD burns after getting too heavy)
Different from Type Ia:
wide range in final composition,
energy release $E_{\text{kin}}$, and ejecta mass $M_{\text{ej}}$;
mostly underluminous explosions w/ small $M_{\text{ej}}$.  

Rosswog et al. 2009
General picture of WD disruption by IMBH

- Nuclear explosion leads to unbound debris fraction of >50%
- Photons thermalize before escaping from photosphere, and reach soft X-ray energies

Search for 1hr long X-ray (blackbody) transients accompanied by weak supernovae
Swift satellite

- Designed to search for gamma-ray bursts: short (0.1-1000s) powerful “bursts” of hard X-rays/gamma-rays
- Sees 10% of the sky simultaneously
- In orbit since 2004
- Can take simultaneous hard X-ray/soft X-ray/UV/optical spectra
- Discovered almost 1000 bursts with a wide range of properties

Credit: NASA
GRB060218: observational facts

• One of the longest ($t_{90}=2600s$) gamma-ray burst observed w/ Swift (out of 859) (another ultra-long GRB is an “established” tidal disruption Swift J1644+57)

• Soft spectrum: X-rays <5keV, typical GRB is dominated by >100keV photons

• Accompanied by a peculiar supernova SN2006aj
  with estimated low ejecta mass $M_{ej}=1-2M_{Sun}$

• Supernova position is consistent w/ the center of the host galaxy

• Was extensively observed in radio/optical/UV/X-rays by various instruments

Consistent with a WD disruption by an IMBH
Blackbody (BB) component from thermalized photons.
Compton upscattering by relativistic electrons in photosphere.
Soft spectrum is influenced by absorption in host galaxy.
Spectrum may change with time => divide into 11 time intervals and model them jointly.

Model in X-ray data analysis package XSPEC

**compPS** model – blackbody Compton scattered by hot thermal electrons => joint $\chi^2$/dof = 1.10.
BB temperature $T=0.11 \text{keV}$, flux $F \sim 5 \cdot 10^{-9} \text{erg/s/cm}^2$.
Low-Z constant absorption $NH \sim 10^{22} \text{cm}^{-2}$.
Spectrum is heavily absorbed at late times as it becomes softer and softer.
System properties from X-ray spectrum

Model BB temperature $T$ and BB flux $F$, know the distance $d$

Source isotropic luminosity $L$

Standard jet acceleration model

Jet Lorenz factor $\Gamma$ and base radius $R_{\text{base}}$

$\Gamma \sim 2.7$, $R_{\text{base}} \sim 1.3 \cdot 10^{10} \text{cm}$

Assume jet base at several $R_g$

BH gravitational radius $R_g \sim 2 \cdot 10^9 \text{cm}$

BH mass $M_{BH} \sim 10^4 M_{\text{Sun}}$
GRB060218: lightcurve

Constant NH, spectrum softer w/ time => larger absorbed fraction

Disruption happened $\Delta t = 1900$ s before Swift trigger

Accretion rate $\dot{M}$ vs time (rescaled) from numerical simulations by Laguna et al. 1993

$M_{BH} \sim 10^4 M_{\odot}$, heavy WD, absorption is the key

Source flux perfectly matches $\dot{M}$ vs $t$ for tidal disruption!

Unabsorbed source flux $\sim (t + \Delta t)^{-5/3}$

Observed flux

Model flux corrected for absorption

0.3-10keV flux $10^{-9}$ erg/s/cm$^2$
Smoothness of lightcurve

Large BHs have large variability timescales

GRBs are associated with $\sim 10M_\text{Sun}$ BHs
Our tidal disruption has $\sim 10^4M_\text{Sun}$ BH

GRB060218 is expected to be not only longer, but also smoother

Characteristic timescale $\sim 500$s – clearly different from GRB population

Other GRBs selected to have same peak count rate
Late lightcurve – afterglow

Early times
Material falls back as $\dot{M} \sim t^{-5/3}$, spends little time in disk, quickly spirals onto the BH

Late times
Disk grows in size and mass, less and less debris fall back onto disk
Disk slowly drains into the BH

Accretion rate $\dot{M} \sim t^{-5/3}$
Accretion rate $\dot{M} \sim t^{-4/3}$

Figure: Ghisellini et al. 2007

Kumar et al. 2008

Shallow $\sim t^{1.3}$ decay is consistent w/ accretion rate behavior at late times

Time [s]
Supernova & host galaxy

Host dwarf galaxy with a supernova

Supernova SN2006aj

Hubble ACS (814W band)

Supernova – subtraction (early-late) image
Host galaxy – late image
Early=5mo, late = 8mo after supernova

Position of a supernova is consistent with the center of the dwarf host galaxy

Host galaxy stellar mass $M_{st} \sim 10^{7.2}M_{\odot}$

consistent w/ central BH mass $M_{BH} \sim 10^4M_{\odot}$

Ferrero et al. 2007
Marconi & Hunt 2003
Schramm & Silverman 2012
Jet launching & jet power

Ordered magnetic field of equipartition strength \( (B \sim 10^{11} \text{G}) \) is needed to launch a strong jet \( P_{\text{jet}} \sim 0.1 \dot{M}c^2 \)

Energy extraction by spinning black hole or rotating disk: slingshot acceleration by magnetic field lines

Blandford & Znajek 1977  
Blandford & Payne 1982

Weak Initial B-field in a WD \( (B \sim 10^4 \text{G}) \), very low jet power for that field

\[ P_{\text{jet}} \sim B^2 \]

B-field is amplified in accretion flow via MHD instabilities and dynamo, but typically to sub-equipartition values

Consistent with low GRB060218 jet power

\[ P_{\text{jet}} \sim 10^{-4} \dot{M}c^2 \]
Alternative theories for GRB060218

**Supernova shock breakout**
(launched by collapse of a star
shock heats outer stellar envelope)
- Shock cannot carry $10^{49}$-$10^{52}$ erg of energy;
- Progenitor star would be too big
  - Soderberg et al. 2006, Waxman et al. 2007

**Jet launched by a magnetar**
(neutron star with very large B-field)
- Toma et al. 2007; Fan et al. 2011

**Standard gamma-ray burst**
(accretion onto small BH
following collapse of a star => jet)
- Should have same duration,
  + be from same population
  - Bromberg et al. 2011
- Standard GRB population
  does not smoothly extend
to long/soft/weak sources

Event would be shorter
- Bufano et al. 2012

While other models cannot be reliably excluded
Our tidal disruption hypothesis is probably the most natural
Event rate

Knowing GRB060218 is observed:
- 1 event per 7 yrs of *Swift*
- *Swift* sees 10% of all GRBs
- Distance to source 140 Mpc

Theoretical rate in nuclei of dwarf galaxies (DG):
DGs have very tight nuclear star clusters
=> high tidal disruption rate
\(~10^{-3}/\text{yr/gal}\)

Mass segregation =>
WDs move towards the center,
15% of disrupted stars are WDs

Assume every dwarf galaxy hosts an IMBH
\(n_{DG} = 0.01/\text{Mpc}^3\)

Supernova rate \(~6 \cdot 10^4\ \text{evt/yr/Gpc}^3\):
1-3% of supernovae may be of tidal disruption origin!

Search among underluminous supernovae
with low ejecta mass in DG centers (to be performed)
Potential for optical searches

GRB060218 – double-hump optical transient coincident w/ galactic nucleus

Emission from slowly expanding jet fireball (different from GRB afterglow)

Search PanSTARRs & Palomar Transient Factory data for double-hump supernovae
Conclusions

- Tidal disruptions of WDs illuminate IMBH population
- Produce a jet with correspondent prompt jet emission
- Manifests as long soft weak X-ray transient 1hr in duration
- Associated supernova should be fast/have low ejecta mass + be located near the center of host galaxy
- GRB060218/SN2006aj is a good candidate from multiple prospectives: spectrum + lightcurve + timing + afterglow + supernova + host galaxy

Three independent estimates of BH mass $\sim 10^4 M_{\text{Sun}}$

Searching for more sources