TIDAL DISRUPTION EVENTS AS SITE OF EVOLVING RELATIVISTIC SPECTRAL LINE

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Possible power source of Seyfert galaxies and QSOs
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The possible presence of massive black holes in the nuclei of galaxies has been suggested many times. In addition, there is considerable observational evidence for high stellar densities in these nuclei. I show that the tidal breakup of stars passing within the Roche limit of a black hole initiates a chain of events that may explain many of the observed principal characteristics of QSOs and the nuclei of Seyfert galaxies.
About half of the gaseous stellar debris remain gravitationally bound in highly eccentric elliptical orbits that bring it back over a course of months to years.
passing object (mass $M_*$, radius $R_*$) around a central body, e.g. neutron star or black hole (mass $M_{BH}$) gets ripped apart by the tidal forces due to central object's strong gravity after reaching tidal radius [Hills, 1975; Rees, 1985] defined as

$$R_{\text{tidal}} = \left( \frac{M_{BH}}{M_*} \right)^{\frac{1}{3}} R_*$$

TDE signposts:
- bolometric luminosity decline $t^{-\frac{5}{3}}$
- no activity (of the galactic nucleus) observed prior to the tidal disruption
- soft X-ray spectra hardening with passing time
- high intensity $10^{45} - 10^{46}$ erg.s$^{-1}$
For the Sun-like star of this illustration, $R_S$ and $R_T$ become equal at $M_{BH} \approx 10^8 \, M_\odot$.

TDE of a Sun-like star by a (non-spinning) black hole heavier than $10^8 \, M_\odot$ couldn’t be seen.

(Gezari 2014)
1. $Q \ll 1 \ (r_g \ll r_t \ll R_*)$: A weak Newtonian tidal interaction, where the star's self-gravity and pressure dominate. Relevant when a stellar BH is swallowed by a star, and can result in an exotic star powered by accretion (e.g. Thorne & Zytkow 1975).

2. $Q \sim 1 \ (r_g \ll r_t \sim R_*)$: A strong Newtonian tidal interaction with significant mass loss and possible disruption, such as occurs in a close interaction between a stellar BH and a massive star (Sec. 4.3.2).

3. $Q \sim (c/v_*)^2 \ (R_* \sim r_g < r_t)$: A complete disruption in the Newtonian regime, as would be the case for disruption by an IMBH.

4. $(c/v_*)^2 < Q < (c/v_*)^3 \ (R_* \ll r_g < r_t)$: A complete tidal disruption by a lower-mass MBH of the type considered here (e.g. Sgr A*), which can be treated as Newtonian to a good approximation.

5. $Q > (c/v_*)^3 \ (R_* \ll r_t \ll r_g)$: Tidal disruption inside the event horizon. The star plunges into the MBH as a point particle on a GR trajectory.

**TDE classification by** $Q = (R_T/R_*)^{1/3}$ (Alexander 2017)
With increasing $M_{\text{BH}}$, rise time to peak accretion increases, the peak accretion rate decreases.

For the lighter black holes, the peak accretion rate surpasses the Eddington limit

At late times, the accretion rates exhibit the $t^{-5/3}$ decay of the gravitationally bound debris.

(De Colle et al. 2012)
$t_{\text{dyn}} \simeq 14 \text{ hours } \left( \frac{M_{\text{BH}}}{10^7 M_\odot} \right) \left( \frac{r}{100 r_g} \right)^{3/2}$

(2)

The thermal timescale is the typical timescale for the disk cooling or heating, and thus further depends on the viscosity parameter:

$t_{\text{th}} = t_{\text{dyn}}/\alpha \simeq 19 \text{ days } \left( \frac{M_{\text{BH}}}{10^7 M_\odot} \right) \left( \frac{r}{100 r_g} \right)^{3/2} \left( \frac{\alpha}{0.03} \right)^{-1}$.  

(3)

Cooling or heating fronts may travel throughout the disk on longer timescales, accounting for the disk geometry:

$t_{\text{front}} = t_{\text{th}}/(h/r) \simeq 380 \text{ days } \left( \frac{M_{\text{BH}}}{10^7 M_\odot} \right) \left( \frac{r}{100 r_g} \right)^{3/2} \left( \frac{\alpha}{0.03} \right)^{-1} \left( \frac{h/r}{0.05} \right)^{-1}$.  

(4)

Finally, the viscous timescale, over which material travels radially from a radius $r$ to the BH, is yet longer:

$t_{\nu} = t_{\text{front}}/(h/r) \simeq 21 \text{ years } \left( \frac{M_{\text{BH}}}{10^7 M_\odot} \right) \left( \frac{r}{100 r_g} \right)^{3/2} \left( \frac{\alpha}{0.03} \right)^{-1} \left( \frac{h/r}{0.05} \right)^{-2}$.  

(5)

(Trakhtenbrot et al. 2019)
Figure 1. Top panel: the evolution of the fluorescent iron line emission originated from a BP disc. Parameters: black hole spin $a = 0.9987$, inner disc inclination: $i_{in} = 85^\circ$, outer disc inclination: $5^\circ$, and truncation radius $r_{tr} = 20 \text{ GM/c}^2$. Middle panel: lightcurve of the iron line emission. The contribution from inner and outer discs are plotted in red and blue solid lines, respectively; while the black solid line represents the sum of the two. Bottom panel: time evolution of centroid iron line energy.

Figure 8. The residuals of the simulated eXTP/LAD spectra with respect to a power-law continuum, for Swift J1656+57 ($z=0.354$). The parameters are: $a = 0.9987$, $i_{in} = 85^\circ$, $i_{out} = 5^\circ$, and $r_{tr} = 20 \text{ GM/c}^2$. Here we take the black hole mass to be $10^8 \text{ M}_\odot$, and the time resolution to be $1 \text{ GM/c}^3$. In the spectrum both the “loop” contributed by the inner disc and the “tail” by the outer disc are seen.

Figure 9. The background-subtracted, time-averaged spectrum (the upper panel) and the data-to-continuum ratio (the lower panel) corresponding to Fig. 8. The background level is plotted in green colour. In the bottom panel the observer frame line energy is indicated by a vertical line. We also plot the data-to-continuum ratio for aligned discs that extend down to ISCO, with inclinations of $5^\circ$ (red) and $85^\circ$ (blue), respectively in the lower panel.
Figure 2.7: Numerical solution to the diffusion equation (1.40) describing the evolution of the surface density profile of the initial mass ring located at $R_0 = 23.6R_g$ with boundary conditions $\Sigma(R_{inner} = 6R_g, t) = \Sigma(R_{outer}, t) = 0$. Black crosses mark the margin for the half of mass of the accretion disc at a given time.
Figure 2.14: Spectral line profile evolution for the system set-up D with the inclination $I = 35$ deg, with the initial radiation intensity $I_\nu \approx \frac{1}{\bar{K}}$ (left panel) and $I_\nu \approx \frac{1}{\bar{K}}$ (right panel). Black dotted line marks the intrinsic frequency, red line marks the centroid energy of a given spectral line.
THANK YOU!