SUPER-EDDINGTON ACCRETION

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HYPERACCRETION:

- Mass supply rate large enough to produce $L >> L_E$:
  \[ \dot{M}_{in} >> \dot{M}_E = \frac{L_E}{\varepsilon c^2} \]
- Optical depth $\tau$ large: Radiation diffuses \textit{relative to gas} at speed $v_{\text{diff}} \sim c/\tau$
- Radiation can be “trapped” where $v_{\text{diff}} = v_{\text{in}}$
  \[ \tau = \frac{c}{v} \quad R_{\text{trap}} = \frac{\dot{M}_{in} \kappa}{4\pi c} \]
- Energy liberated at $R < R_{\text{trap}}$ might not escape
ENERGETICS OF HYPERACCRETION: 

\[
\frac{G M \dot{M}_{in}}{R_{\text{trap}}} \sim L_E
\]

- Liberated energy > \( L_E \) subject to trapping effects
- Spherical accretion (\( \mathcal{L} < GM/c \)) into BH can drag radiation in
  - BH inner boundary crucial
  - Max escaping energy can depress but not shut off Bondi-like accretion at arbitrary \( \dot{M} \)
- Rotating accretion (\( \mathcal{L} > GM/c \)): torques transport energy outward
  - Outward “viscous” transport + diffusion > inward advection can lead to mass loss/suppression of \( \dot{M} \)
HYPERACCRETION: 
THE “SLIM DISK” APPROACH

$R > R_{trap}: \dot{M} = \text{const.}$

thin Keplerian disk

$R < R_{trap}: \dot{M} \propto R$

regulates $L \sim L_E \times \text{log factor}$

Fig. 8. Lines of matter flow at supercritical accretion (the disk section along the $Z$-coordinate). When $R < R_{sp}$ spherization of accretion takes place and the outflow of matter from the collapsar begins.
SS433: A CLASSIC CASE OF HYPERACCRETION?

\[ \dot{M}_{in} \sim 10^3 \dot{M}_E \]

\[ R_{trap} \sim 10^3 R_g \]

Strong wind from large \( R \)
“Slim disk” hyperaccretion models: power output exceeds $L_E$ by only a logarithmic factor

... beaming does the rest
A second mode of hyperaccretion?

- Rotational/internal energy ratio drops below threshold
- Flow becomes very weakly bound (Bernoulli → 0)
- “Closes up” to axis

\[ \Rightarrow \]

- Loses ability to regulate energetics via wind
- Flow becomes “star-like” (with a rotational funnel)
- Tries to remain bound by steepening density/pressure profiles
Disk Closes Up When $\mathcal{L} \sim 80-90\% L_K$

- Gyrentropes: $\alpha(\ell)$
- Quasi-Keplerian

\[ \gamma = 4/3 \]

\[ \dot{M} = \text{const.} \]

\[ \dot{M} \propto r \]

\[ \ell / \ell_{\text{Kep}} \]

\[ 0.74, 0.88 \]
Smaller $\mathcal{L} \implies$ steeper $\rho$
This could be the situation in super-Eddington TDEs

\[ \sim 100L_{\text{Edd}} \]

\[ \sim L_{\text{Edd}} \]

After beaming correction \( \sim 10-100 \)

\[ F_X(0.3-10 \text{ keV}) \text{ in erg cm}^{-2} \text{s}^{-1} \]

\[ \text{Days since trigger, } t - t_{\text{trig}} \]

Tchekhovskoy et al. 2014

Sw J1644+57
Ultraluminous X-ray Pulsars

- 3 known (pulsations discovered by nuSTAR)
- $L_x \rightarrow 10^{40-41}$ erg/s
  $\sim 100-1000$ $L_E$
- Sinusoidal pulses $\rightarrow$ not beamed!
- Spin periods $\sim$ 1s
- All spinning up rapidly, $P/\dot{P} <$ few 100 yr
- Broadband, flattish spectrum

Luangtip et al., 2016

Israel et al., Sci, 2017
How can the radiation escape?
How can the matter accrete?
ULP (PULX? Pulxar?) Paradoxes

- **Pulses** — magnetized accretion column
  - Need field $> 10^{14}$ G for radiation to escape sideways
    - Large magnetosphere if dipole (multipole a way out)
      - Large moment arm, NS spins up too **fast**
  - or

- **Rapid spin-up** — NS close to spin equilibrium
  - Need magnetosphere radius to spin at Kepler rate
    - $r_M$ large, large moment arm, NS spins up too **fast**

Standard Models Severely Strained
Getting radiation out of the polar cap: PHOTON BUBBLES

• Destabilized waves in atmosphere
• Require strong (\(~\)rigid) B-field \(\rightarrow\) 1D motion
• Two kinds:
  – Gas-pressure driven (Gammie 98, MCB 01, 06a)
  – Buoyancy driven (Arons 92, MCB 06b)
• Radiation advected *along* funnel, not across!
• Does not require superstrong fields
Buoyant Photon Bubbles

Hsu, Arons & Klein 1997 simulations

DENSITY

VELOCITY

Dense bubble wall

Low density occupies most volume

Lower-speed downward-moving gas dominates mass flux

High-speed upward-moving gas advects radiation
Outside the accretion column: CONVECTIVE ENVELOPE

- Trapping radius $\gg$ magnetosphere radius
  - $\tau$ must be huge to carry radiation convectively
- Convection efficient near $r_M$, saturated further out
- Convective flux converted $\rightarrow$ KE + diffusive flux just below $r_{\text{trap}}$
- Wind, escaping radiation comparable, $\sim$ hundreds $L_E$
Mushtukov et al. 2016

Accretion column

Accreting convective envelope

Trapping radius
**Pulses**

- \( R_{\text{trap}} < R_{\text{corot}} \rightarrow \) envelope heals between pulses → strong pulses
- \( R_{\text{trap}} > R_{\text{corot}} \rightarrow \) no time to heal between pulses → pulses washed out

\[
\ell < \left( \frac{GM}{r_*^3} \right)^{1/3} \left( \frac{P}{2\pi} \right)^{2/3} \sim 200 P_{\text{sec}}^{2/3}
\]
Convection transports angular momentum through envelope.

Solid body rotation?

\[ \Omega_{\text{env}} \sim \left( \frac{GM}{r_{\text{trap}}^3} \right)^{1/3} \]

...coupling to NS spin just outside \( r_M \)

\[ \implies \text{much slower spinup} \]
Wind

\[
v_w \sim \left( \ell \frac{GM}{r_{\text{trap}}} \right)^{1/3} \sim 0.2c \quad \text{independent of } \ell
\]

\[\Rightarrow\text{consistent with observed winds}\]
ULPs vs. TDEs

• Low ang. mom. hyperaccretion mode
  – Starlike instead of disklike
  – Actual energy release $>> L_E$ (at least for jetted TDEs)

• But important differences:
  – BH vs. NS (hard surface) inner b.c.
  – Magnetic funneling
  – Rotation smears energy flux through envelope $\Rightarrow$
    forces strong convection coincident with accretion
  – No strong beaming for ULPs (but some evidence of
    jetlike nebulae for some ULXs)
The Moral:

- ULPs force us into new territory, very different from received wisdom about hyperaccretion
- Requirements to explain ULPs seem implausible...but we’ve been surprised before!
- Efficient radiative convective transport the key? ... ignored in the past

MAYBE SOME FUNDAMENTAL THINGS ABOUT HYPERACCRETION WE STILL DON’T UNDERSTAND