(Grand) Unification (Theory)
CV-BH-NS-ULX-AGN

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Why look for unification?

\[
\frac{\Delta E}{\Delta m} = \frac{GM}{R} = \text{constant}
\]
Scale-invariant jets

Heinz & Sunyaev 2003

radio emission is synchrotron from a continuous jet scaled to $R_g$

dimensional analysis yields

$$L_r \propto M^{17/12-\alpha/3} \dot{m}^{17/12+2\alpha/3} \propto \dot{M}^{1.4}$$

relate $\dot{M}$ to X-ray luminosity

$$l_x \propto \dot{m}^\xi$$

then

$$\log L_r = \frac{1.4}{\xi} \log L_X + \frac{1.4(\xi - 1)}{\xi} \log M$$
Fundamental plane of BH accretion

Merloni, Heinz, Di Matteo 2003
Falcke, Körding, Markoff 2004

( with $\xi \approx 2$ favouring radiatively-inefficient accretion )
Flickering in accreting objects

CV lightcurve (MV Lyr)

power spectrum

Scaringi 2012
Fundamental plane of black hole variability

McHardy+2006
break frequency $\nu_b$ scales as

$$\nu_b \sim \frac{\dot{M}}{M^2}$$

i.e. scale-free

$$\frac{\nu_b}{\nu_K} \sim \dot{m}$$
Fundamental plane of accretion variability

Scaringi+ 2015
break frequency actually scales as

$$\nu_b \sim \frac{\dot{M}}{R^2_x}$$

what sets the scaling ?!
Physics common to accreting objects

Disk magnetosphere interaction

Romanova+ 2004

Outflows: winds & jets

Tchekhovskoy 2016

Accretion flows

Flock+ 2011
Disk-magnetosphere interaction

1. magnetospheric radius
\[ \beta(R_m) = \frac{P}{P_{B*}} \approx 1 \]
2. stellar radius \( R_\star \)
3. corotation radius
\[ \Omega_k(R_{co}) = \Omega_\star \]
4. light cylinder radius
\[ R_{lc} = \frac{c}{\Omega_\star} \]

physics set by 4 characteristic radii

\[ R_m < R_\star \]
\[ R_\star < R_m < R_{co} \]
\[ R_{co} < R_m < R_{lc} \]
\[ R_m > R_{lc} \]
Disk-magnetosphere interaction

dwarf novae & neutron star XRBs in outburst, novae-like

intermediate polars, accreting X-ray pulsars, T Tauri, ULXs

AE Aqr, transitional ms pulsars?

black widows, $\gamma$-ray binaries, transitional ms pulsars

Romanova+2008
Simulations interface well with observations

boundary layer  funnel flow

- magnetospheric radius ?
- column accretion ?
- variability ?
- outflows ?
- torques ?

Parfrey Tchekhovskoy 2017
Understanding accretion flows

semi-analytical  ←  numerical

Petrucci, Ferreira

Zhu & Stone 2017
Shakura Sunyaev 1973

radiatively-efficient thin disks

angular momentum transport

\[
\frac{\partial R^2 \Omega \Sigma}{\partial t} = \frac{1}{2\pi R} \frac{\partial}{\partial R} \left[ R^2 \Omega \left( \dot{M} - 3\pi \nu \Sigma \right) \right]
\]

turbulent viscosity parametrised as

\[\nu \sim \alpha c_s H\quad \text{i.e. stress is} \quad W_{r\phi} = \alpha P\]

cooling balances heating

\[\sigma T_{\text{eff}}^4 = \frac{9}{8} \nu \Sigma \Omega^2\]
Evidence for thin disks in binaries

In steady state $T_{\text{eff}} \propto (\dot{m}/m)^{1/4} r^{-3/4}$

Eclipse mapping in CVs

Disk blackbody in XRBs with $L \propto T^4$

Baptista & Horne 1994

Done+ 2007
Evidence for thin disks in AGNs?

thin disk signature harder to find, if present at all

disk bb in quasar polarised light

UV continuum does not follow expectations

Kishimoto+ 2008

Davis+ 2007
Conditions in disks are NOT scale free

physical conditions in the disk depend on thermodynamics, opacities, etc.

radiation pressure very strong in AGNs

\[ \frac{r_{\text{rad}}}{r_S} \approx 1400 \alpha_{0.1}^{2/21} m_8^{2/21} \dot{m}^{16/21} \]  
(Shakura Sunyaev 1973)

self-gravity limits the disk size

\[ \frac{r_{\text{sg}}}{r_S} \approx 620 \alpha_{0.1}^{14/27} m_8^{-26/27} \dot{m}^{-8/27} \]  
(Kawaguchi+ 2014)
Disk Instability Model (DIM)

Thermal equilibrium of a thin ring shows hysteresis

Thermal equilibrium of a thin ring shows hysteresis

hot branch

$q^{-}\rightarrow q^{+}$

cold branch

$q^{+}\rightarrow q^{-}$

disk radius = $5\times 10^{9}$ cm
Stability of a thin accretion disk to the DIM

There is an S-curve for each radius and choice of $\alpha$

$T_c$

$R = 10^8$ cm

$\Sigma$ (g/cm$^2$)

$\Sigma$ (g/cm$^2$)

GD 2003

Dubus, Porquerolles 9/2017
Critical mass accretion rate for stability

e.g. disc with a size $> 10^{10}$ cm is unstable if mass transfer rate $< 10^{15}$ g s$^{-1}$

\[ \dot{M} = 10^{15} \text{ g s}^{-1} \]

\[ \Sigma \text{ (g/cm}^2\text{)} \]

GD 2003

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DIM drives changes in mass accretion rate

X-ray binaries (Done+ 2007)

[Graphs showing data for X-ray binaries]

Dwarf novae (Cannizzo+ 2012)

[daily variations in light curves]

[DIM likely irrelevant in AGNs: Hameury+ 2009]
DIM explains (in)stability of XRBs

stability depends on mass transfer rate & disk size (& irradiation), not $\alpha$

Coriat+ 2012
Is the dwarf nova SS Cyg stable? YES

Schreiber & Lasota 2007 (Smak 1982)

big step forward from GAIA distances + Kepler/LSST lightcurves

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Getting the right lightcurve

requires additional ingredients:

- change in $\alpha$ with temperature
- truncation due to magnetosphere
- switch from thin disk to hot accretion flow
- irradiation by central object or inner disk
- variable mass transfer from companion
- tidal torques
- stream impact heating
- outflows
- …
higher $\alpha$ with $T$ required in dwarf novae and transient LMXBs

$\alpha=0.04$

$\alpha_{\text{hot}}=0.2$, $\alpha_{\text{cold}}=0.04$
Enhanced transport on hot branch

Thermal equilibrium of a thin ring shows hysteresis

$$\alpha_{\text{cold}} = 0.04$$

$$\alpha_{\text{hot}} = 0.2$$

hot branch

cold branch

$q^- \rightarrow q^+$

$q^+ \rightarrow q^-$

disk radius = 5x10^9 cm
Basic unifying process: MRI-driven transport

Turbulence generated by Magneto-Rotational Instability in weakly magnetised sheared flows

\[ W_{r\phi} = \left\langle \rho (v_r v_\phi - v_{Ar} v_{A\phi}) \right\rangle \equiv \alpha \langle P \rangle \]

Measure \( \alpha \) from local (shearing box) simulations [unification!]

caveat emptor: numerical and physical convergence (e.g. Ryan+ 2017)
Evidence for $\alpha(T)$ in MRI simulations

Hirose+ 2014

- stratified shearing box
- no net magnetic flux
- radiative transfer
- ideal MHD
- opacities & thermodynamics appropriate to DN (& XRBs)

S-curve still present (Latter+ 2012)

Increased $\alpha$ due to convection
Further evidence & non-ideal MHD sims

Scepi Lesur GD, submitted

- \( \alpha \) is enhanced
- role of convection unclear
- resistivity (non-ideal MHD) quenches turbulence at low T (Gammie Menou 1998)

\[ T_{\text{mid}} (\text{K}) \]

\[ \alpha = 0.03, 0.04, 0.05, 0.06, 0.10 \]

\[ \Sigma (\text{g cm}^{-2}) \]

no turbulence

ideal MHD

resistivity turned on

\[ \alpha \]

Time
Enhanced $\alpha$ connected to properties of MRI-driven turbulence

Lightcurves with $\alpha$ from MRI simulations don’t work well

No MRI-driven transport in quiescence ?!

Coleman et al. 2015
Can a net vertical magnetic field help?

(1) \(<B_z>\neq 0\) strongly enhances transport

\[
\alpha \propto \left( \frac{P_0}{B_0^2} \right)^{-0.5}
\]

(Hawley+1995)

(2) may help sustain turbulence in quiescent branch (Fleming+ 2000)

(3) messy:

- origin & transport of \(<B_z>\)?
- link to state changes?
- large-scale outflows?

\[\overline{\alpha} = \langle \frac{T_{xy}}{V} \rangle / \langle \frac{p_{\text{gas}}}{V} \rangle\]

\[\overline{\alpha_{\text{mag}}} = \langle \frac{T_{xy}}{V} \rangle / \langle \frac{p_B}{V} \rangle\]

\[\overline{\alpha} = 1.1 \times 10^1 \left( \beta_{\text{mid}}^0 \right)^{-0.53}\]

\[\overline{\alpha_{\text{mag}}} = 0.30 \left( \beta_{\text{mid}}^0 \right)^{0.40}\]

zero net flux asymptote

Salvesen+ 2016
Flickering in accreting objects

CV lightcurve (MV Lyr)

Scaringi 2012

flux-rms (Uttley & McHardy 2001)
Accretion fluctuations propagate inward, modulated at faster timescales at smaller $R$.

MRI-driven fluctuations too fast? (Lyubarskii 1997)
MRI-driven variability?

Relevant timescale is MRI dynamo cycles (King+2004, Hogg & Reynolds 2016)

flux - rms from global MRI simulation

Toroidal Magnetic Field, $\langle B_y \rangle_{xy}$

Hogg & Reynolds 2016

Net flux, convection change dynamo timescale

$<B_z>=0$

Salvesen+2017

$<B_z>\neq 0$
Grand Unification Theory feelings

- **Scalings are puzzling**

- **Unification by analogy**: physical processes common to all objects
  - disk magnetosphere interaction
  - accretion flows
  - outflows & winds [?]

- **Many reasons for scalings to break**: radiation, microphysics, thermodynamics…
  - consequences can be key to interpret observations (e.g. disk instability model)

- **Progress** in connecting phenomenological models (& observations) with statistical properties of turbulence in disks from ab initio numerical simulations.