Radiation-Hydrodynamic Simulations of Disk Winds in X-ray Binaries

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Knox Long, Daniel Proga, James, Matthews, Stuart Sim, Mandy Bailey, Sam Mangham
The Structure of X-ray Binaries

- Accretion disc
- Jet
- X-ray heating
- Hot spot
- Accretion stream
- Disc wind
- Companion star

RHD Simulations of Disk Winds in XRBs
Outbursts of X-ray Binaries
XRBs in outburst exhibit blue-shifted absorption in X-ray lines!
Evidence for Disk Winds

XRBs in outburst exhibit blue-shifted absorption in X-ray lines!

- always see H/He-like Iron lines
- \( v_{\text{wind}} \approx 300 - 3000 \text{ km s}^{-1} \)
Evidence for Disk Winds

XRBs in outburst exhibit blue-shifted absorption in X-ray lines!

Outflow!
Evidence for Disk Winds

Only observed...

...in the soft state

...in edge-on systems

Ponti+2012

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RHD Simulations of Disk Winds in XRBs
Interpretation

**SOFT STATE**
Geometrically thin disc (H/R<<1)

Low inclination LMXB
No wind

High inclination LMXB
Wind
Carries away angular momentum

Accretion disc

Ponti+2012
Motivation: Why Should You Care?

- XRB disk winds are **powerful**: \( \dot{M}_{\text{wind}} > \dot{M}_{\text{acc}} \)
  - Accretion
    - disk winds may remove significant amounts of angular momentum
  - Veiling
    - all of our observations are viewed *through* the outflow
  - State changes and radio jets
    - disk winds might be involved in triggering state transitions
Driving Mechanisms

• Magneto-centrifugal acceleration
  – “Bead-on-a-wire” (Blandford & Payne 1982)

• Radiation pressure
  – Continuum → but usually $L < L_{edd}$
  – Lines → too ionized

• Thermal driving
  – Disk atmosphere is irradiated by X-rays → $T_{top} \approx T_{Compton}$
  – Mass loss is inevitable at large radii → $v(T_{Compton}) > v_{esc}(R)$
  – Defines the “Compton Radius”

$$R_{IC} = \frac{GM_{BH} \mu m_H}{k_B T_{IC}}$$
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The Physics of Thermally-Driven Disk Winds

Thermal Instability

$T_{eq}$ (K)

$\log(\xi/T_{eq})$

Cooling > Heating

Heating > Cooling

Higginbottom+16
The Physics of Thermally-Driven Disk Winds

Hydrodynamics

ZEUS (Stone, Proga,...)

\[
\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0
\]

\[
\rho \frac{D\mathbf{v}}{Dt} = -\nabla P + \rho \mathbf{g}
\]

\[
\rho \frac{De}{Dt} \left( \frac{e}{\rho} \right) = -P \nabla \cdot \mathbf{v} + \rho \mathcal{L}(\xi, T)
\]

Source of ionizing radiation \(L_x\)

Fixed density boundary \(\rho(r) = \rho_0 \left( \frac{r}{R_{1C}} \right)^{-2}\)

For a given cell, we need the radiative heating/cooling rate

RHD Simulations of Disk Winds in XRBs
The Physics of Thermally-Driven Disk Winds

Previous Work

- Heating and cooling rates matter!

- But all work to date neglected radiation transport
  - Should at least account for attenuation of X-rays in the outflow itself!

- Need to couple hydrodynamics with radiative transfer: ZEUS + PYTHON
  e.g. Long & Knigge 2002; Higginbottom+13+14; Matthews+15+16; Mangham+17
RHD vs HD: 5x Lower Mass-Loss Rate

(but this is still 2x $\dot{M}_{\text{acc}}$)

Optically thin HD

RHD

Higginbottom+18

Nick Higginbottom

RHD Simulations of Disk Winds in XRBs
Comparison to Chandra Observations of J1655

![Graph showing flux (relative to continuum) vs. wavelength (Å) with peaks at Fe K edge, Fe XXVI Ly α, and Fe XXV Ly α. The graph includes a 70° ray trace in black, an 80° ray trace in red, and observed data in blue.]
Inclination Dependence

Higginbottom+2018

![Graph showing the dependence of EW (eV) on inclination angle for Fe XXV and Fe XXVI. The graph highlights the changes in EW with different inclination angles, with Fe XXVI showing a higher EW at lower inclination angles.]
"Efficiency": \( \frac{\dot{M}_{\text{wind}}}{\dot{M}_{\text{acc}}} \)

Data from
Ponti+2012

Higginbottom+18
Luminosity Dependence

Theoretical
Begelman+83

Empirical
Ponti+12

Region E: Isothermal atmosphere
Region A: Isothermal wind
Region B: Steadily heated wind
Region D: Weakly heated atmosphere
Region C: Gravity inhibited wind

\[ \frac{L}{L_{\text{crit}}} \]

\[ \frac{\dot{M}_{\text{wind}}}{\dot{M}_{\text{acc}}} \]

\[ \log \left( \frac{L_{\text{Tot}}}{L_{\text{Edd}}} \right) \]

\[ \dot{M}_{\text{wind}} = 2 \dot{M}_{\text{acc}} \]
**Luminosity Dependence**

**RHD Results**

Efficiency stays $\sim$constant

Consistent with Done+18
One (weird) system actually drives the entire "observed" luminosity dependence!
Luminosity Dependence

Wind Speed and Line Profiles

velocity (km s\(^{-1}\))

Flux (relative to continuum)

\(\lambda (\text{Å})\)

- 4% Ledd
- 10% Ledd
- 30% Ledd
- 60% Ledd