An Ionised Accretion Disc Wind in Hercules X-1

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Accretion disc winds

• Winds discovered in many different types of accreting systems
  • X-ray binaries, AGNs, ULXs
• The fastest outflows have potential to affect their surroundings greatly – AGN feedback + ULX bubbles
• Plethora of possible launching mechanisms
  • Radiation pressure, line driving, magnetic forces, thermal driving
Accretion disc winds in X-ray binaries

- Blueshifted ionised absorption features ubiquitous in high inclination soft state black hole XRBs, also seen in multiple neutron star systems

- Launching mechanism
  - Radiation pressure on electrons insufficient, wind too ionised for line-driving
  - Compton heating and magnetic fields strong candidates for wind driving

- Solid angle
  - Could be as small as 5-10° from the disc
  - Governs the mass outflow rate

Miller et al. (2008), Ponti et al. (2012), Diaz Trigo et al. (2012)
Hercules X-1

- Famous high inclination neutron star X-ray binary
- Cyclotron resonance feature at 37 keV
  - magnetic field of $10^{12}$ G truncating the accretion disc at $\approx 1000$ Rg
- Characteristic 35 day period of flux variations – almost edge-on precessing warped disc
- Importantly: large archive of XMM-Newton observations

Giacconi et al. (1971), Trümper et al. (1978), Hickox et al. (2005), Leahy & Igna 2010
Absorption lines in XMM spectra
Absorption lines in XMM spectra

Observation 0783770601

N VII  O VIII  Ne X  Fe K

Wavelength / Angstrom  Energy / keV

Flux / Counts/m²/s/Å

Continuum  Continuum + Wind
Ionised wind in the high state

- Blueshifted absorption detected in 9 out of 10 high state XMM observations
- Low state/short high observations: no significant detection in individual exposures or in stacked data
- Wind velocity between 200 and 1000 km/s
- Material highly ionised; ionisation varies between $\log \xi = 3 - 5$
- Correlations of wind properties with ionising luminosity, orbital and super-orbital phase
Ionisation parameter variation
Distance and wind mass outflow rate

• Use the ionisation parameter and column density:
  • $\xi = \frac{L_{\text{ion}}}{nr^2}$  \hspace{1cm} $L_{\text{ion}}$ – 1-1000 Ryd luminosity
  • $n_H = n\Delta R = nR\delta R$  \hspace{1cm} $\delta R$ – relative thickness of absorber

• Estimate the distance from the ionising source:
  • $R = \frac{L_{\text{ion}}}{n_H\xi} \delta R$

• The mass outflow rate:
  • $\dot{M} = \rho A v = C_V \mu m_p n \frac{\Omega}{4\pi} 4\pi R^2 v$
  • $\dot{M} = 4\pi \mu m_p \frac{L_{\text{ion}}}{\xi} v C_V \frac{\Omega}{4\pi}$
  \hspace{1cm} $\frac{\Omega}{4\pi}$ – wind launch solid angle
  \hspace{1cm} $C_V$ – clumping factor
  \hspace{1cm} $\mu$ – mean particle weight
Distance
Mass outflow rate

![Graph showing mass outflow rate vs. L_{ion} / erg s^{-1} and super-orbital phase.](imageURL)
Is the super-orbital period driving the correlations?

- If super-orbital variation drives the correlations, we are measuring the variation of vertical wind structure.
- Can estimate the solid angle corrected mass outflow rate.

Hickox et al. (2005)
Is the super-orbital period driving the correlations?

- If super-orbital variation drives the correlations, we are measuring the variation of vertical wind structure
- Can estimate the solid angle corrected mass outflow rate
- Assume a simple dependence between phase and inclination, and maximum inclination $\approx 5^\circ$
- Mass outflow rate $\approx 60\text{-}70\%$ of mass accretion rate through the disc

Leahy et al. (2002)
Conclusions

• We significantly detect ionised wind in the spectrum of Hercules X-1 during most XMM-Newton observations of its high state
• The wind originates in the accretion disc and is launched by Compton heating of the outer disc or by magnetic fields
• The wind ionisation varies significantly with both the luminosity and super-orbital phase of Her X-1
• If the wind variability is driven by the super-orbital phase, we are scanning variations in the wind vertical structure and can infer the solid-angle corrected mass outflow rate to be 60-70% of mass accretion rate
Extra Slides
Hercules X-1

Tananbaum et al. (1972)
A circumbinary wind in Her X-1?

- Blueshifted absorption lines found in UV
- Origin: a circumbinary wind launched from the irradiated side of secondary?

Boroson et al. (2001)
High state X-ray spectrum of Her X-1
Methods and detection significance

- Fit pn and RGS data with the final continuum model:
  - $hot \times (comptt + hh + 2\, gauss + 3\, gauss + cie)$
- Fit the continuum model, recover C-stat
- Then add the photo-ionised wind component $pion$, fit and recover fit improvement $\Delta C$-stat
- $\Delta C$-stat determines the detection significance, $\Delta C$-stat>25 usually considered a significant detection

- Low state observations: no significant detection in individual exposures or in stacked data

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<th>Observation ID</th>
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Wind launching mechanism

• Compton heating of the outer accretion disc
  • A wind is launched above a critical luminosity: \( L_{cr} = 0.03 \left( \frac{T_{IC}}{10^8 K} \right)^{\frac{1}{2}} L_E \)
  
  where \( T_{IC} = \frac{<\varepsilon>}{4k} \approx 3 \text{ keV} \approx 3.5 \times 10^7 K \)
  • For Her X-1 in high state, \( L_{cr} \gtrsim 1.1 \times 10^{37} \text{ erg/s is satisfied} \)

• The wind should be launched at radii larger than:
  • \( R > 0.1 \frac{GM\mu m_p}{kT_{IC}} \approx 8 \times 10^9 \text{ cm} \)

• Alternatively, wind could be launched magnetically
Photon pile-up

- Brightest observations could be affected by piled-up (but unlikely to introduce absorption lines)
- Average count rates up to 800 cts/s in pn (timing mode), up to 20 cts/s in RGS
- Least affected is RGS1
- Using just RGS1, at least one observation still shows significant detection of wind (ΔC-stat = 33.12)
Wind parameters vs ionising luminosity
Wind parameters vs orbital phase

- Systematic velocity / km s\(^{-1}\)
- \(\log(\xi / \text{erg cm} \ s^{-1})\)
- \(n_\text{H} / 10^{24} \text{ cm}^{-2}\)
Wind parameters vs super-orbital phase
Abundance ratios in the wind

- Use the wind absorption lines to constrain the abundances in the system

- Simultaneously fit 5 observations, fit N, O, Ne, Fe (fix either N or Fe to 1), other elements fix to 1 or 0
Abundance ratios in the wind

- Use the wind absorption lines to constrain the abundances in the system
- Simultaneously fit 5 observations, fit N, O, Ne, Fe (fix either N or Fe to 1), other elements fix to 1 or 0
- Confirm the previous results of $N/O \approx Ne/O \approx 4$
- Surprisingly also find very high $Fe/O \approx 10$

Fit improvement upon freeing abundances:

Jimenez-Garate+05