Chandra-HETGS
Observations of LMC X-1

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- One of the few persistent BHC
- HMXB: Focused Wind-Fed
- Soft X-ray Dominated State
- Line of Sight will Often Intersect Secondary Wind
• 21 cm Map of LMC

• LMC X-1 Sits Near 30 Doradus Star Forming Region

Elmegreen, Kim, Staveley-Smith (2001)
• Mass: 10.9 +/- 1.6 Solar Masses, Inclination 36.°4 +/- 1.°9  (Orosz et al. 2009)

• Distance: 48.1 kpc

• Absorbed 0.5–8 keV Flux ≈ 10% L_{Edd}

• Orbital Period 3.909 Days, O7/8 Giant Companion

• Sits 0.5° from 30 Doradus Star Forming Region => Larger column than much of the rest of the LMC (e.g., > LMC X-3)
• Performed 10 Chandra-HETGS Observations over ~ 1 month: 150 ksec

• Study Accretion Flow Emission — Primarily the Accretion Disk

• Direct Measure of Absorption Edges

• Spectroscopic Signatures of Secondary

• Study Orbital Variations?
Fit: Absorbed, Comptonized Disks

Energy (keV)

$\nu F_\nu$ (ergs cm$^{-2}$ s$^{-1}$)

$\chi^2$

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Fit: Absorbed, Comptonized Disks

Energy (keV)

$\nu F_\nu$ (ergs cm$^{-2}$ s$^{-1}$)

$\chi^2$

Disk
Fit: Absorbed, Comptonized Disks

\[ F_\nu (\text{ergs cm}^{-2} \text{s}^{-1}) \]

\[ \chi^2 \]

Energy (keV)
Fit: Absorbed, Comptonized Disks

Energy (keV)

\[ N \times \left( \frac{\text{ergs cm}^{-2} \text{ s}^{-1}}{\text{ergs cm}^{-2} \text{ s}^{-1}} \right) \]

Corona

Disk

ISM & Local Absorption

\[\chi^2\]

\[ 0.5 \quad 1 \quad 2 \quad 2.5 \quad 5 \]

\[ 10^{-12} \quad 10^{-11} \quad 10^{-10} \quad 10^{-9} \quad 10^{-8} \]

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Fit: Absorbed, Comptonized Disks

Energy (keV)

\[ \nu F_\nu = \text{ergs cm}^{-2} \text{ s}^{-1} \]

No Idea
Disk
Corona
ISM & Local
Absorption
Secondary
Atmosphere

\[ \chi^2 \]

\(-200\) \(-100\) \(0\) \(100\) \(200\)
Emission from Secondary

\[ \lambda F_{\lambda} \text{ (ergs cm}^{-2} \text{s}^{-1}) \]

\[ \chi^2 \]

Wavelength (Å)
• Velocities are Inconclusive: \( \leq 500 \, \text{km s}^{-1} \)

• Widths: \( \approx 500 \, \text{km s}^{-1} \)

• No Evidence for Orbital Phase-Dependence

• This is in contrast to Cyg X-1
  • Hard State: Orbital Phase-Dependence
  • Soft State: No Lines (Totally Ionized Wind)

• See Poster # 18 by Ivica Miškovičová
Absorption Edge Structure

Hanke et al. (2009) - RGS, Epic, Swift, Chandra
Absorption Edge Structure

Chandra-HETGS

Wavelength (Å)

χ²

Ne IX

Ne III

Ne II

λF₇ (ergs cm⁻² s⁻¹)

2×10⁻¹¹

5×10⁻¹¹

5 0 5

-5
Absorption vs. Orbital Phase

N_{Ne} (10^{18} \text{ cm}^{-2})

Orbital Phase

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Absorption vs. Orbital Phase

![Graph showing correlation of column density vs. orbital phase]

- The graph depicts the correlation between column density ($N_H$) and orbital phase.
- The data points are represented by blue dots with error bars.
- Multiple models are fitted to the data, including 'diskbb + powerlaw', 'eqpair', 'simpl(kerrbb)', and 'simpl(diskbb)'.
- The models are compared to observed data points, showing the agreement between the models and the observed data.

Table 3 provides values for various parameters, including photon index ($\Gamma$) and column density ($N_H$), across different orbital phases. The table includes columns for each model and phases, showing the consistency of the models across different observations.

The results indicate that the models are consistent with the observed data, with the 'diskbb + powerlaw' model showing the best fit in most cases. The photon index and column density values are similar, suggesting a systematic agreement between models.

Figures 1 and 2 illustrate the absorption vs. orbital phase, with error bars representing the systematic error due to the choice of the continuum model. The upper limit of the systematic error is also shown.

The paper discusses the correlation between the donor star and the absorption, requiring a systematically higher power law for X1. The derived absorption might depend on the shape of the source, and the empirical models typically describe the data equally well.

In all fits, the model parameters, including absorption, are similar to previously obtained values. The power law index for X1 is steep, indicating a high photon index. The authors note that the derived absorption is consistent with previous tables, with absorption values ranging from $N_H = 10^{20}$ to $10^{22}$ cm$^{-2}$, depending on the data above 2 keV.

Diskbb models are used to constrain the correlation, allowing for better data fitting. For X1, the data above 2 keV allowed for a better fit of the power law, leading to a systematically higher photon index.
Shakura-Sunyaev Disk

\[ F = \frac{3 \dot{M}}{8\pi} \Omega^2 \left[ 1 - \beta \left( \frac{R_i}{R} \right)^{1/2} \right] \]

\( R_{\text{IN}} = 6 \, \text{GM}/c^2 \)

\( R_{\text{OUT}} \)
Shakura-Sunyaev Disk

\[ F = \frac{3 \dot{M}}{8 \pi \Omega^2} \left[ 1 - \beta \left( \frac{R_i}{R} \right)^{1/2} \right] \]
An Aside on Thermodynamic Efficiency of Radiative Processes

• Blackbody radiation is the “most thermodynamically efficient”

\[
N_{BB} \propto T_{BB}^3, \quad y \equiv \frac{4kT_c}{m_e c^2} \max(\tau_{es}, \tau_{es}^2)
\]

• For the same average photon energy, and same total luminosity, non-thermal requires greater area
An Aside on Thermodynamic Efficiency of Radiative Processes

- Also true for atmospheric electron scattering: “Modified Blackbody”

\[ F \sim \sigma T^4 \left( \frac{\kappa_R}{\kappa_{es}} \right)^{1/2} , \quad \kappa_R \ll \kappa_{es} \]

- “Color Correction”: \( T_C = f_C T_{Eff} \), \( f_C > 1 \),
Area scales as \( f_C^4 \)

- Essentially any “correction” means the area is bigger than required for just blackbody
LMC X-1 HETGS Spectra

Energy (keV)

$vF_v$ (ergs cm$^{-2}$ s$^{-1}$)

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LMC X-1 HETGS Spectra

Note Lack of Differences
Contrast to 4U 1957+11

Suzaku Observations
(Nowak et al. 2011)
Soft State = Constant Radius

RXTE Observations (Wilms et al. 2001, Nowak et al. 2008)
Soft State = Constant Radius

RXTE Observations (Wilms et al. 2001, Nowak et al. 2008)
Disk Normalization

Chandra: LMC X-1
(RXTE the same)

Gou et al. (2009) - Spin fits really are a comment on emitting area – for a given fitted temperature, small emitting area
Chandra: LMC X-1
(RXTE the same)

Disk Normalization

Chandra: LMC X-1
(RXTE the same)

Is This Because it's Wind-Fed?

Beloborodov & Illiaronov (2001)
Summary

• See Emission Lines at All Orbital Phases, Despite High, Soft Flux => Strong Wind

• See Absorption Stronger than ISM, with Large Variability => Strong Wind

• “Disk” Has a Small, and Highly Variable, Emitting Area => Strong Wind?
Disk-Absorption Correlations

$N_H (10^{22} \text{ cm}^{-2})$

$kT_{\text{disk}} \text{(eV)}$

$10^{-3}$ $1.5 \times 10^{-3}$ $2 \times 10^{-3}$

Disk Normalization
Disk-Corona Correlations

Compactness, $l_h/l_s$

Disk Normalization

$2\times10^{-3}$

$1.5\times10^{-3}$

$10^{-3}$

Compactness, $l_h/l_s$

$kT_{\text{disk}}$ (eV)

750

800

850

900

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