High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with the Chandra X-ray observatory

Diploma Thesis

Manfred Hanke
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Diploma Thesis

Manfred Hanke

- supervised by Jörn Wilms
- performed at Dr. Karl Remeis-observatory
- in collaboration with Mike Nowak (MIT), Katja Pottschmidt (UCSD) and others
After this talk, you will know more about

- general relativity
- astrophysics
- + a very interesting source

- our detectors

- my proper work

- Black Holes and X-ray Binaries
- Cygnus X-1

- X-ray Astronomy and the Chandra X-ray Observatory

- A Chandra observation of Cygnus X-1
- My high-resolution Spectroscopy

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The Sky

in optical light: mostly stars

(http://home.arcor-online.de/axel.mellinger/)

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The Sky

in X-rays: mostly black holes

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A star withstands gravity by its gas pressure.
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When the fuel for nuclear fusion is gone, the star has to shrink.

With a mass below Chandrasekhar’s limit of $1.4 \, M_\odot$, a white dwarf can form.

Gravity is balanced by the degenerate electrons’ Fermi pressure.
Stellar evolution and black holes

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A more massive collapsar can end as a neutron star, which is, after $e^- + p \rightarrow n + \nu_e$, nothing but a giant nucleus, held by the $n$-pressure.

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A more massive collapsar can end as a neutron star, which is, after $e^- + p \rightarrow n + \nu_\text{e}$, nothing but a giant nucleus, held by the $n$-pressure, or, if gravity is too strong for degenerate neutrons, as a black hole, which is an infinitely curved singularity in space-time – thus a never-ending collapse.

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Back holes: singularities in space-time

The singularity (where GRT breaks down) is luckily hidden by the event horizon:

**Matter or light** (thus any information) which is closer than $R_S \cdot \frac{1+\sqrt{1-a^2}}{2}$

(Schwarzschild radius $R_S = 2 \frac{GM}{c^2} \approx 3 \text{ km} \cdot \frac{M}{M_\odot}$) can never escape from the singularity!

[Below $R_S$, Newton’s escape velocity $v_{esc}(r) = \sqrt{\frac{2GM}{r}}$ exceeds the speed of light.]

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“No-hair-theorem”:

A black hole is fully characterized by its mass $M$, spin $a$ and electric charge $Q$.

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Can black holes be observed?

"How black are black holes in fact?"

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Nuclear fusion

\[ 4 \text{H} \rightarrow ^4\text{He} + 2e^+ + 2\nu_e \]

produces \(6 \times 10^{11} \text{ J/g}\) which is 0.007 of the rest-energy of the consumed hydrogen.

This is, of course, much more than chemical reactions deliver.
Accretion power in astrophysics

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This is, of course, much more than chemical reactions deliver.

Accretion of matter

in the gravitational potential of a compact object is, however, more efficient:

The potential energy of a mass \( m \) above one Schwarzschild radius is:

\[ E_{\text{pot}} = \frac{GmM}{R_S} \]

\[ = \frac{1}{2} mc^2 \]

A considerable fraction (0.1–0.42 \( mc^2 \)) of this energy can even be released.

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Thus: Isolated black holes are really black apart from Hawking radiation.

In a binary system, however, mass can easily be accreted from the companion star and much energy will be released – especially in form of X-rays.
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- **High-mass XRB:**

A young, massive (O-/B-) star’s strong stellar wind is focused onto the black hole.

- **Low-mass XRB:**

A evolved (late-type) star fills its Roche lobe (bound volume) and loses mass via $L_1$ overflow.

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Cygnus X-1

Bright source of X-rays: $L \approx 10^4 L_\odot$, discovered in 1964 (Bowyer et al., 1965)
Companion star
HDE 226868:

$m_V = 8.84 \text{ mag}$

O9.7 Iab supergiant

$T_{\text{eff}} = 32000 \text{ K}$,

$R = 17 \, R_\odot$, $M = 17.8 \, M_\odot$

stellar wind:

$v(r) = 2100 \text{ km/s} \cdot (1 - R/r)^{1/2}$

(Herrero et al., 1995)
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is a high-mass X-ray binary,
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stellar wind:

$v(r) = 2 \times 100 \text{km/s} \cdot (1 - R/r)^{1/2}$

(Herrero et al., 1995)

The radial-velocity varies in 5.6 days with a semi-amplitude of 75.7 km/s.

→ mass of invisible secondary

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**Cygnus X-1**

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→ mass of invisible secondary

As HDE 226868 is close to filling its Roche lobe, the wind is strongly enhanced in direction towards the black hole (‘focused wind’; Friend & Castor, 1982).

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X-rays are absorbed by the Earth’s atmosphere.

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⇒ X-ray satellites observe from space.

‘Rossi’ X-ray Timing Explorer (since 12/1995; NASA)

‘Chandra’ X-ray observatory (since 7/1999; NASA) ← this work

X-ray Multi Mirror ‘Newton’ (since 12/1999; ESA)

INTErn. γ-Ray Astroph. Lab. (since 10/2002; ESA)

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Detection of X-rays

CCD-detectors:

- radiation hits (ideally) one pixel
- absorption → electron-hole-pairs, one for each 3.7 eV = $E_{\text{gap}}(\text{Si})$
- electrons are stored in a potential-well and read out after some exposure
- ⇒ charge pulse proportional to $h\nu$ provided that only one photon detected (→ problem of pile-up)
- energy-resolution limited by Poisson-statistics: $\Delta E \sim \sqrt{N_e} \sim \sqrt{E}$
Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with Chandra
1. High spatial resolution with *Chandra*

– the best X-ray mirror ever (resolution < 1′′) –

(“order-of-magnitude advances over previous X-ray astronomy missions”)

X-rays can be deflected via total reflection under grazing incidence. 

Paraboloids + hyperboloids ⇒ **Wolter (type I) telescope**

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with *Chandra*
Comparison with XMM-Newton

58 such mirrors $\Rightarrow$ larger collecting area, but not so good resolution

(http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31318)

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with Chandra
2. High spectral resolution with *Chandra*

*transmission gratings*

(https://chandra.harvard.edu/about/science_instruments3.html)

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with *Chandra*
**Chandra’s High Energy Transmission Grating Spectrometer**

**Medium + High Energy Gratings**

**two gratings at once:**
- grating-periods: 200 nm / 400 nm,
- resolution: 23 mÅ / 11 mÅ,
- range: 1 Å . . . 42 Å / 21.5 Å

[http://space.mit.edu/HETG/hetg_info.html](http://space.mit.edu/HETG/hetg_info.html)

**MEG and HEG produce two dispersed images (relatively tilted):**

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Chandra observation # 3814 of Cygnus X-1

(Principal Investigator: Katja Pottschmidt)

Observation during **superior conjunction of the black hole**
⇒ Investigation of the photo-ionized focused stellar wind

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with *Chandra*
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Observation during superior conjunction of the black hole
⇒ Investigation of the photo-ionized focused stellar wind

There are pronounced dips on time scales of hours and less, in which the count rate is reduced and the spectrum is harder.
⇒ Enhanced absorption from dense clumps in the accretion flow!

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with Chandra
Spectral shape: hard power law, photoabsorbed at low energies ($\sigma_{\text{phabs}} \sim E^{-3}$) by ISM + wind material (at least in the ‘non-dip’ case)

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with Chandra
The MEG spectra show a lower photon flux than the HEG spectra.
The CCD pixels are read out after an exposure of 1.7 s. But how many photons have caused the charge cloud?
Pile-up of photons in the CCD detector

The CCD pixels are read out after an exposure of 1.7 s. But how many photons have caused the charge cloud?

For a bright source like Cygnus X-1, photons may even pile up in the dispersed spectra. This reduces the count rate and has to be modelled:

\[ C'(i) = \exp(-\beta \cdot C_{\text{tot}}(i)) \cdot C(i) \]

(non-linear pile-up model of Nowak et al., slightly modified by myself)

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with Chandra
Pile-up of photons in the CCD detector

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\[ C'(i) = \exp \left( -\beta \cdot C_{\text{tot}}(i) \right) \cdot C(i) \]

(non-linear pile-up model of Nowak et al., slightly modified by myself)

The High Energy Gratings, which operate at shorter wavelengths, have a stronger dispersion; the photons are thus spread over more pixels.

The HEG spectra are thus not so strongly affected by pile-up.

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High-resolution spectroscopy

After the continuum has been described properly...

The residuals of the high-resolution spectra reveal absorption lines of highly ionized ions:

- **Lyman series of H-like ions**: $1s \rightarrow np$
  - O $^\text{VIII}$, Ne $^\text{X}$, Mg $^\text{XII}$, Al $^\text{XIII}$, Si $^\text{XIV}$, S $^\text{XVI}$, Ar $^\text{XVIII}$

- **Absorption lines of He-like ions**: $1s^2 \rightarrow 1s np$
  - O $^\text{VII}$, Ne $^\text{IX}$, Mg $^\text{XI}$, Al $^\text{XII}$, Si $^\text{XIII}$, S $^\text{XV}$, Ar $^\text{XVII}$

- **Lots of iron L-shell transitions** ([$1s^2 X \rightarrow [1s^2 X']$] of
  - Fe $^\text{XVII}$, Fe $^\text{XVIII}$, Fe $^\text{XIX}$, Fe $^\text{XX}$, Fe $^\text{XXI}$, Fe $^\text{XXII}$, Fe $^\text{XIII}$, Fe $^\text{XVI}$

  – which overlap, of course, to make the identification more challenging...
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The ‘non-dip’ Cygnus X-1 spectrum

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Wavelength [Å]
The ‘non-dip’ Cygnus X-1 spectrum

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with Chandra
From a comparison with the theoretical absorption line profile
\[ e^{-\tau_{i\rightarrow j}(\lambda)} = \exp \left( -N_i \cdot f_{ij} \frac{\pi e^2}{mc} \phi(\lambda) \right), \]
not only \textbf{wavelength shifts} (wind velocities!) can be inferred, but also \textbf{column densities} \( N_i \) along the line of sight – even if the line profiles are not fully resolved.

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with \textit{Chandra}
From a comparison with the theoretical absorption line profile

\[ e^{-\tau_{i\rightarrow j}(\lambda)} = \exp \left( -N_i \cdot f_{ij} \frac{\pi e^2}{mc} \phi(\lambda) \right), \]

not only wavelength shifts (wind velocities!) can be inferred, but also column densities \( N_i \) along the line of sight – even if the line profiles are not fully resolved.

This allows to determine the properties and composition of the stellar wind.

More details on the non-dip spectrum will be given in a publication in the Astrophysical Journal: Hanke et al. (2008), to be submitted. The dips will be described in a second one.
Summary

- Black holes, X-ray binaries and Cygnus X-1
• **Black holes, X-ray binaries and Cygnus X-1**

• **X-ray Astronomy, with Chandra**
• Black holes, X-ray binaries and Cygnus X-1

• X-ray Astronomy, with Chandra

• A *Chandra* observation of Cygnus X-1 at $\phi \approx 0$
  absorption dips, (pile-up), high-resolution spectroscopy: line analysis to investigate the focused stellar wind
new observation of Cygnus X-1 (PI: Jörn Wilms) in April 2008 at superior conjunction of the black hole ($\phi = 0$)

with *Chandra* (for the high-resolution spectra)

Manfred Hanke: High-resolution X-ray Spectroscopy of the Black Hole Cygnus X-1 with *Chandra*
new observation of Cygnus X-1 (PI: Jörn Wilms) in April 2008 at superior conjunction of the black hole ($\phi = 0$)

with Chandra
(for the high-resolution spectra)

and jointly with XMM-Newton
(for better sensitivity around 6.4 keV, i.e. at higher energies)
new observation of Cygnus X-1 (PI: Jörn Wilms) in April 2008 at superior conjunction of the black hole ($\phi = 0$) with \textit{Chandra}
(for the high-resolution spectra)
and jointly with \textit{XMM-Newton}
(for better sensitivity around 6.4 keV, i.e. at higher energies)
and jointly with \textit{RXTE}
(for the broad band continuum)
new observation of Cygnus X-1 (PI: Jörn Wilms) in April 2008
at superior conjunction of the black hole ($\phi = 0$)

with *Chandra*
(for the high-resolution spectra)

and jointly with *XMM-Newton*
(for better sensitivity around 6.4 keV, i.e. at higher energies)

and jointly with *RXTE*
(for the broad band continuum)

and jointly with *Integral*???
(for the very hard X-rays / $\gamma$-rays)

and jointly with *Suzaku*???
(for a better resolution at higher X-ray energies)
new observation of Cygnus X-1 (PI: Jörn Wilms) in April 2008 at superior conjunction of the black hole ($\phi = 0$) with Chandra (for the high-resolution spectra) and jointly with XMM-Newton (for better sensitivity around 6.4 keV, i.e. at higher energies) and jointly with RXTE (for the broad band continuum) and jointly with Integral (for the very hard X-rays / $\gamma$-rays) and jointly with Suzaku (for a better resolution at higher X-ray energies)

There is enough work for my PhD... but presumably a lot to find out about one of the most interesting sources of the X-ray sky as well!
References


Thank you very much for your attention!

For further contact:

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Appendix

- The analysis of X-ray spectra
- The dynamically constrained mass of Cygnus X-1
- The X-ray spectrum of Cygnus X-1
- The ASM light curve of Cygnus X-1

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A direct measurement of the flux spectrum $S_E(E)$ is not possible.
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**Alternative approach:**

Model spectra $S_{\text{model}}$ are folded through the detector response,

$$C_{\text{model}}(i) = B(i) + t_{\text{exp}} \cdot \int R(i, E) \cdot A(E) \cdot S_{E}^{\text{model}}(E) \, dE,$$
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$$C_{\text{model}}(i) = B(i) + t_{\text{exp}} \cdot \int R(i, E) \cdot A(E) \cdot S_E^{\text{model}}(E) \, dE,$$

and compared with the measured count rate $C_{\text{measured}}$, e.g., via

$$\chi^2 = \sum_i \left( \frac{C_{\text{measured}}(i) - C_{\text{model}}(i)}{\sigma(i)} \right)^2 \equiv \text{min}.$$

→ $\chi^2$-fitting for model parameters and confidence levels
A traditional detector’s response matrix

RXTE-PCA

Photon Energy [keV]

PHA Channel Energy [keV]

PHA channel energies can originate from several photon energies.

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Wilms, 1998, Fig. 4.4

• broad diagonal
  ⇒ not invertible

• secondary peaks
  \( E_{\text{ph}} = E_{\text{det}} + \text{const.} \)
  from escaping K\( \alpha \), K\( \beta \)
or L\( \alpha \) photons of the Xe gas proportional counter array (PCA)
orbital period: $P = 5.6$ d, $V_r$-semi-amplitude $K = v \sin i = 75.7$ km/s

(Brockopp et al., 1999, Fig. 1)
Mass-function of Cygnus X-1 / HDE 226868

\[ f(M_*, M_{\text{comp}}) = \frac{P K^3}{2\pi G} = 0.252 \, M_\odot = \frac{(M_{\text{comp}} \sin i)^3}{(M_* + \dot{M}_{\text{comp}})^2} \]

\( M_{\text{comp}} \gg 3 \, M_\odot \Rightarrow \text{The compact object has to be a black hole!} \)

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The X-ray spectrum of Cygnus X-1

**States:**

**high/soft:** (2003-01-10)
- high luminosity
- thermal (soft) emission from an accretion disk
- Fe Kα fluorescence

**low/hard:** (2003-07-29)
- flatter (harder) spectrum
- far less disk-contributions

(Wilms et al., 2006, Fig. 12)

The hard power law component can be explained by Compton-upscattered soft photons in a corona of hot electrons.

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Long term RXTE/ASM light curve of Cygnus X-1

The All Sky Monitor is a good indicator for the state:

Observation of Cygnus X-1 in low/hard state before high/soft state in summer 2003.

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