Laboratory astrophysics:
Investigating the mystery of low charge states of Si in the HMXB Cyg X-1

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The High Mass X-ray Binary Cygnus X-1

HDE 226868: O9.7 supergiant
\[ M_\star = 18M_\odot \]
\[ L_\star = 250\ 000L_\odot \]
\[ R_\star = 17R_\odot \]
fills \( \approx 90\% \) of Roche lobe volume
wind mass loss \( \dot{M}_\star = 3 \cdot 10^{-6}M_\odot \)

Cyg X-1: black hole
\[ M_{BH} = 10M_\odot \]
\[ L_X \approx 10\ 000L_\odot \]

- binary separation \( a = 41R_\odot \)
- orbital period \( P = 5.6d \)
- inclination \( i \approx 35^\circ \)
- distance \( d = 6000\ \text{ly} \)
Chandra:  
- launched in 1999  
- energy range 0.1-10 keV  
- HETG: High Energy Transmission Grating

ObsID 3814:  
- 19/20 April 2003  
- 48 kilo seconds  
- phase -0.08 - 0.03

http://www-xray.ast.cam.ac.uk/xray_introduction/Chandra.html
Low charge states of Si

![Graph](attachment:image.png)

Time since MJD 52748.700 [ks]

\( \frac{(0.5-1.5 \text{ keV})}{(3-10 \text{ keV})} \)
Low charge states of Si

(0.5−1.5 keV)/(3−10 keV) vs Time since MJD 52748.700 [ks]

Chandra−HETGS [photons/s/cm²/Å] Si XIV Si XIII Si XII Si XI Si X Si IX Si VIII Si VII
Low charge states of Si

![Graph showing time vs. ratio of 0.5-1.5 keV to 3-10 keV emissions over time since MJD 52748.700 [ks].](image)

![Graph showing energy vs. Chandra-HETGS photon's/s/cm²/Å for Si XIV, Si XIII, Si XII, Si XI, Si X, Si IX, Si VIII, and Si VII wavelengths.](image)
Low charge states of Si

lower charge states of Si with increasing dipping!
Low charge states of Si

large difference between Si line centers in Cyg X-1 and theoretical values ⇒ Doppler shifts or atomic physics?
The Electron Beam Ion Trap (EBIT)

https://ebit.llnl.gov/overviewEBIT.html
EBIT-I @ LLNL

[Image of a nuclear reactor]

https://ebit.llnl.gov/EBITPhotoGallery.html

high energy variant, SuperEBIT, can produce bare Uranium (U^{92+})

https://ebit.llnl.gov/
Principle of a microcalorimeter

Absorber: low heat capacity
Thermistor: electrical resistance strong function of temperature
Heat sink: Adiabatic Demagnetization Refrigerator: $T < 0.1\, \text{K}$

- X-ray photon knocks electron loose
- photoelectron rattles in absorber $\rightarrow$ rise in temperature
  $\Delta T \sim E_{\text{photon}}$ (few mK!)
- wait for thermal equilibrium $\rightarrow$ measure resistance
The ECS Instrumet

The ECS instrument uses a 32-pixel x-ray calorimeter array developed at NASA/GSFC for the Suzaku/XRS sounding rocket program and in our XRS program. Each pixel is a thermal x-ray detector with some important improvements to increase the gain stability and energy resolution. Specifically, we have improved the readout circuit by introducing infrared absorbing materials into the detector housing to decrease the sensitivity to infrared radiation. The cryogen-free version is entirely transparent to the user. The cryogen-free version of the ECS refrigerator to cool the detector array to 0.05 K for over 65 h and requires only a 4.2 K interface, has no moving parts, and has no external plumbing. The ECS cryogenics package contains a Chase refrigerator to cool the cryogenics package to 50 mK and have a cryogen-free version. Every 21 days. Otherwise the operation of the spectrometer requires no servicing. A liquid nitrogen shielded liquid helium dewar, running on a commercial pulse-tube mechanical cooler and using no cryogens, cools the calorimeter detector array to 0.05 K for over 65 h and requires only a 4.2 K interface, requiring no external plumbing and no moving parts.

The ECS detector array, shown in Fig. 1, is divided into two subarrays: a midband array covering from 0.1 keV to 10 keV and 625 \( \times \) 625 \( \mu \text{m}^2 \), 8 \( \mu \text{m} \) thick HgTe absorbers giving a quantum efficiency of 95% at 6 keV. The high-energy array is similar to several MeV. In the ECS, the absorber material is HgTe, providing extraordinary performance with resolving over the bandpass, fast thermalization, and low heat capacity. For example, with the right choice of materials and careful design, extraordinary performance can be achieved with resolving over 3000 and a very large bandpass from a few eV to over 100 keV. The midband array consists of 625 \( \times \) 625 HgTe pixels:

- 18 mid energy: 0.1-10 keV
  - 625 \( \times \) 625 \( \mu \text{m}^2 \), 8 \( \mu \text{m} \) thick

- 14 high energy: 0.5-100 keV
  - 625 \( \times \) 500 \( \mu \text{m}^2 \), 100 \( \mu \text{m} \) thick

The 36 pixel ECS microcalorimeter array. The left side of the array includes the 624 energies, 32% at 60 keV.
The Spectrum

resolution: 4.47 eV FWHM
line w: fit: 1864.801 eV theory: 1864.9995 eV (Drake’88)
Ly $\alpha$: fit: 2005.64 eV theory: 2005.49 eV (Garcia’65)
colored sticks: output of the Flexible Atomic Code (FAC; M. F. Gu 2004)

compare theoretical predictions with fits to help the line identification
much better agreement of Cyg X-1 with laboratory spectrum than with theory

Doppler shifts of the order of few ten to \( \sim 100 \) km/s