Detailed Study of the X-ray Absorption in the ISM

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Special thanks to **Mike Nowak**, **Jörn Wilms** & **Norbert Schulz**

The Universe in High-resolution X-ray Spectra
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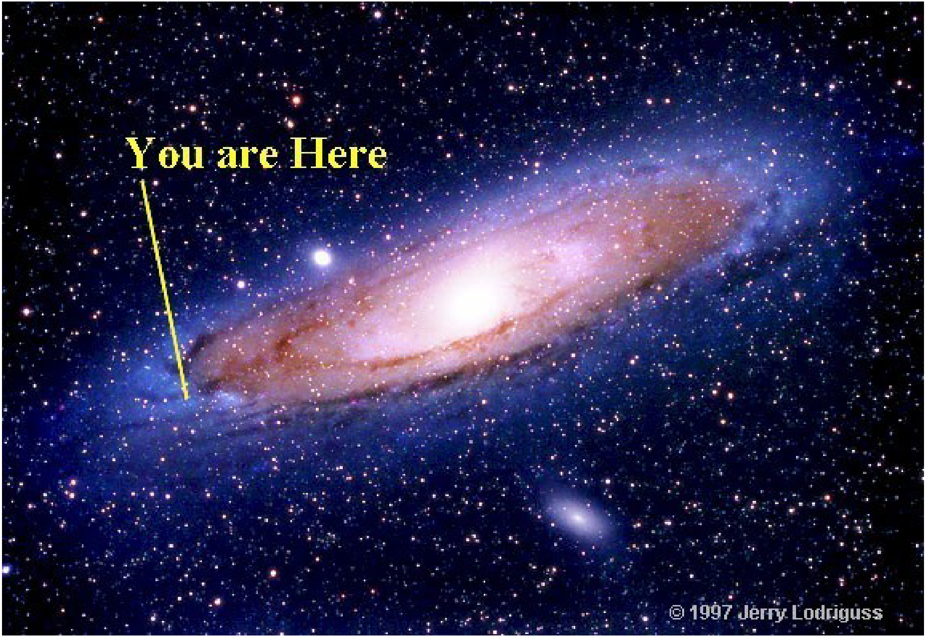
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Motivation

- The study of the physical and chemical properties of the interstellar medium (ISM) provides important information about the formation and evolution of the galaxies.
- High-energy photons interact with the ISM via scattering (by dust and grains) and/or absorption (excitation and ionization of inner K-shell electrons, mainly). Thus, X-ray observations of the ISM provide the opportunity to study the abundances and ionization fractions for a large number of elements.
- Previous studies on ISM absorption features in X-ray binary spectra have only used functional models to fit the spectrum (Paerels+01, Schulz+02, Takei+02, Juett+04, Liao+13)

Interstellar Medium Multiphase Structure

Phase	Component	Temp. (K)	Constituents
	Dust	$\sim 10 - 20$	$MgSiO_3$,...
Cold	Molecules	$\sim 10 - 20$	H_2, CO,...
	Neutral Gas	$\sim 50 - 100$	H I, O I,...
Warm	Neutral Gas	$\lesssim 10^4$	H I, O I,...
	Ionized Gas	$\sim 10^4$	H II, O II-V,...
Hot	Ionized Gas	$\sim 10^6$	O VI-VIII, Ne IX,...

X-ray absorption can provide signatures of the binding of many elements in molecules or solids; the inner-shell electronic transitions are key diagnostics since the ionization state or chemical binding shifts the line energies by a predictable amount (e.g. deVries+Costantini+09, Pinto+10, Costantini+12).

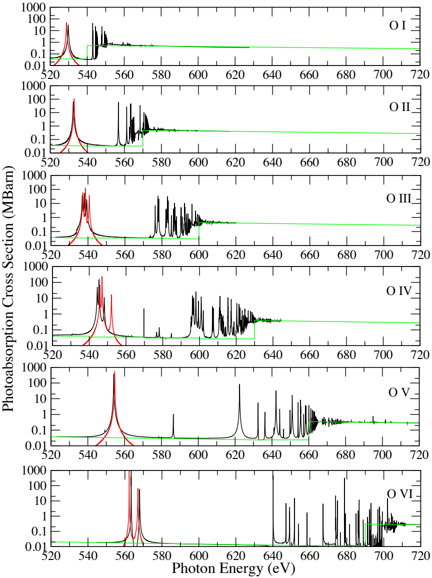
Oxygen Atomic Data

High-energy photoionization cross-sections of O ions showing the structure of the K-edge. In **black** the Breit–Pauli R-Matrix calculation by García+05, in red those by Pradhan+03, and in green by Reilman+Manson79.

The observed flux can be approximated as

$$F(E) = F_0 \exp\left[-N_{\mathrm{O_I}} \sigma_{\mathrm{O_I}}(E)\right]$$

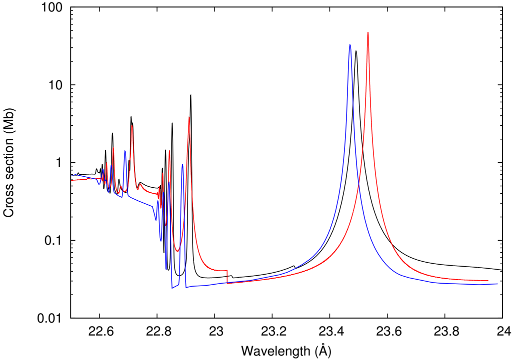
where F_0 is a normalization factor, $N_{\mathrm{O_I}}$ is the oxygen column density, and $\sigma_{\mathrm{O_I}}(E)$ is the photoabsorption cross section for neutral oxygen.



(García+05)

Neutral Oxygen Atomic Data

Photoionization cross sections for neutral oxygen from McLaughlin+Kirby98 (blue curve), Gorczyca+McLaughlin00 (red curve), and García+05 (**black** curve). This spectral region covers both the absorption K-edge and the Kα absorption line (1s-2p) from O I. All the curves have been convoluted with a 0.182 eV FWHM Gaussian.



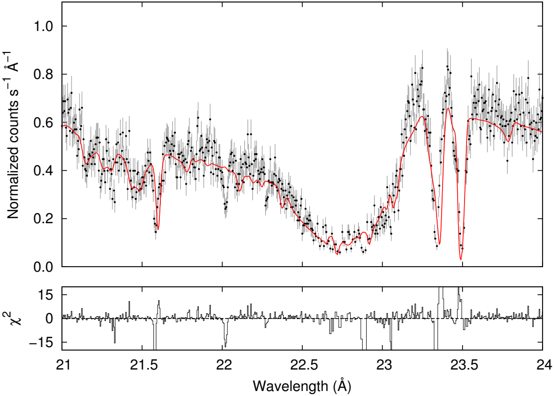
(García+11)

Discrepancies in the Kα position also seen with respect to laboratory data! (Stolte+13, McLaughlin+13, Bizau+15)

See B. McLaughlin's Poster

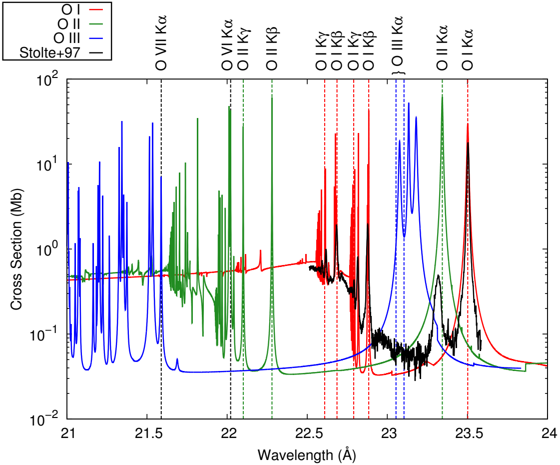
XTE J1817-330 *Chandra* Spectrum

Spectral fit of the *Chandra* MEG observations of XTE J1817-330 in the oxygen absorption region (21–25 Å) using a powerlaw*warmabs physical model.



(Gatuzz+13)

Benchmarking Atomic Data: Oxygen



O I shift: 29 mÅ

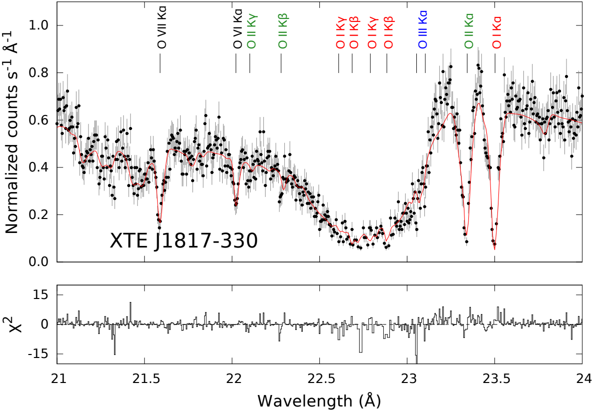
O II shift: 75 mÅ

Lab measurement also needs to be shifted!

Theoretical photoabsorption cross sections for O I (red), O II (green), and O III (blue) computed by García+05 which are implemented in the warmabs model. The **black** solid line is the laboratory measurement by Stolte+97.

(Gatuzz+13)

Benchmarking Atomic Data: Oxygen



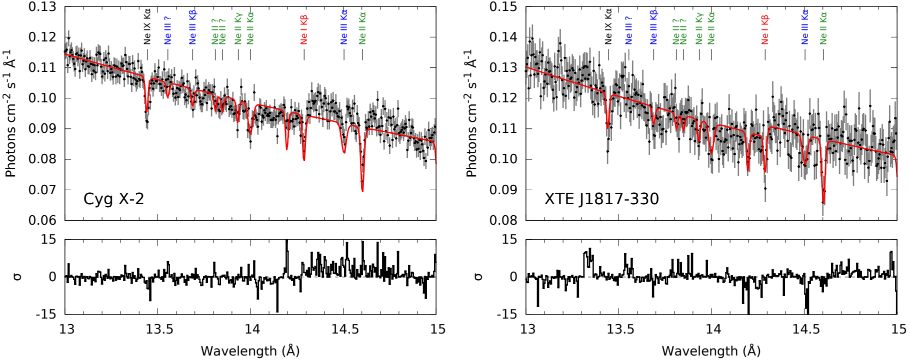
Significant improvement in the fit:
$\chi^2 = 1.77 \rightarrow 1.25$

O VI and O VII are fitted with Gaussian profiles (intrinsic to the source)

Spectral fit of the *Chandra* MEG observations of XTE J1817-330 in the oxygen absorption region (21–25 Å) using the **corrected** `powerlaw*warmabs` physical model.

(Gatuzz+13)

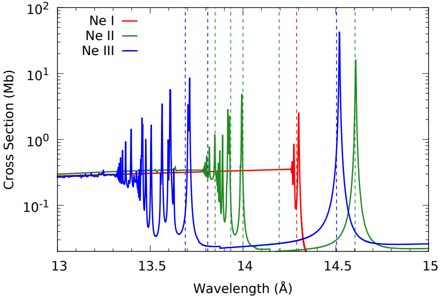
Benchmarking Atomic Data: Neon

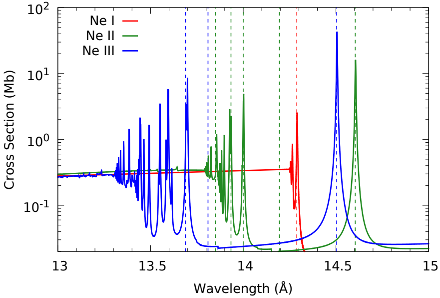


Chandra MEG flux spectra of the X-ray binaries **Cygnus X-2** and **XTE J1817-330** simultaneously fitted with a power-law continuum and several Gaussian profiles.

Benchmarking Atomic Data: Neon

Shifts to the Kα Resonances: Ne II $= -3.2$ mÅ, Ne III $= -15.7$ mÅ



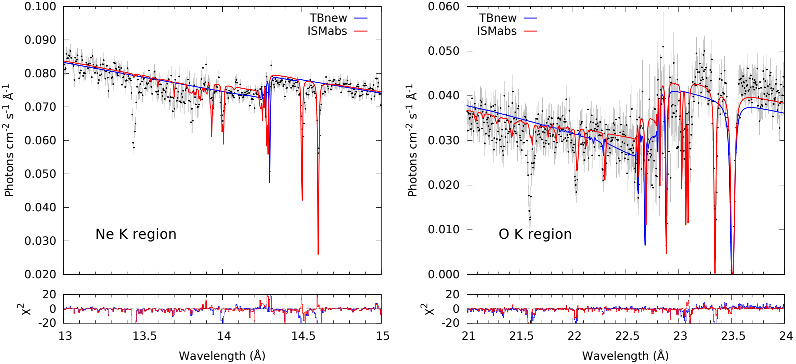


Shifts to the Cross Sections:
Ne I $=-11$ mÅ, Ne II $= +7.6$ mÅ, Ne III $= -14.7$ mÅ

ISMabs: An X-ray Interstellar Absorption Model

$$I(E)_{Obs} = I(E)_{source} \exp(-\tau)$$

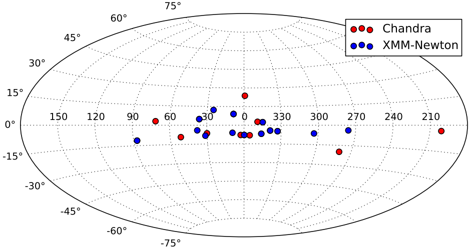
$\tau = \sum_i \sigma_i(E) N_i$, where $\sigma_i(E)$: Photoelectric Cross Section and N_i: Column Density of $i-$th ion.

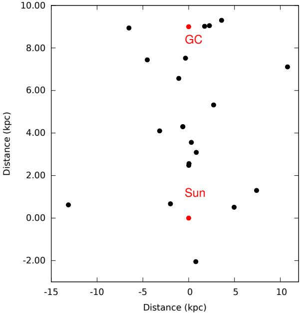


https://heasarc.gsfc.nasa.gov/xanadu/xspec/models/ismabs.html

(Gatuzz, García et al. 2015)

Analysis of All Available Sources

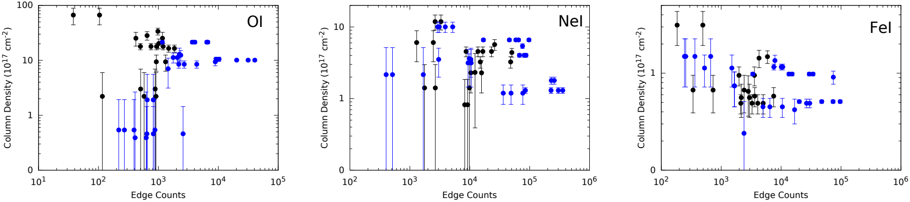




Selection of **24 bright sources**, 17 from *Chandra* and 15 from *XMM-Newton*. A total of 84 single observations were analyzed. In the case of *Chandra*, 20 observations were taken in TE-mode, and 29 in CC-mode.

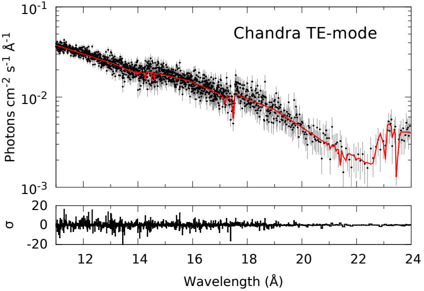
TE- and CC-Modes in Chandra

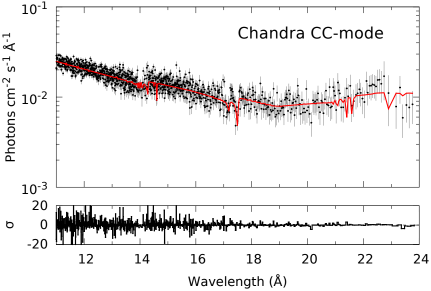
ISMabs column densities for Chandra observations versus number of counts. The **CC-mode data** shows large discrepancies when counts are low compared to the TE-mode data (**black points**).

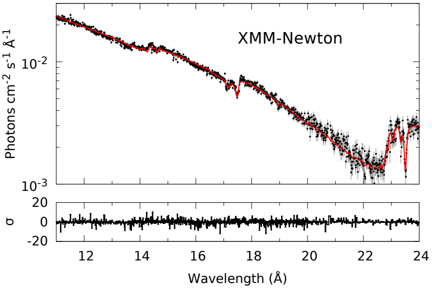


Oxygen columns from **CC-mode** data with less than 10^3 counts are **unreliable**

TE- and CC-Modes in Chandra: **4U 1636-53**

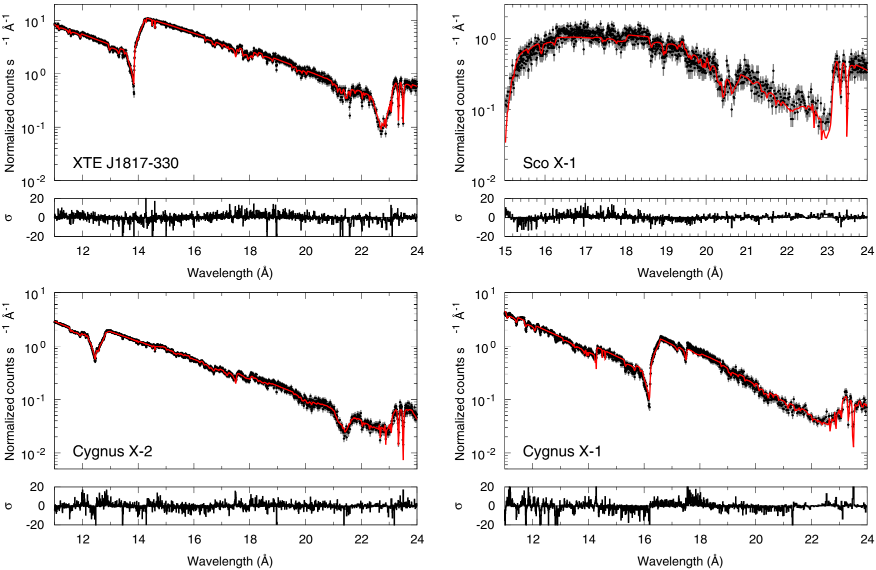




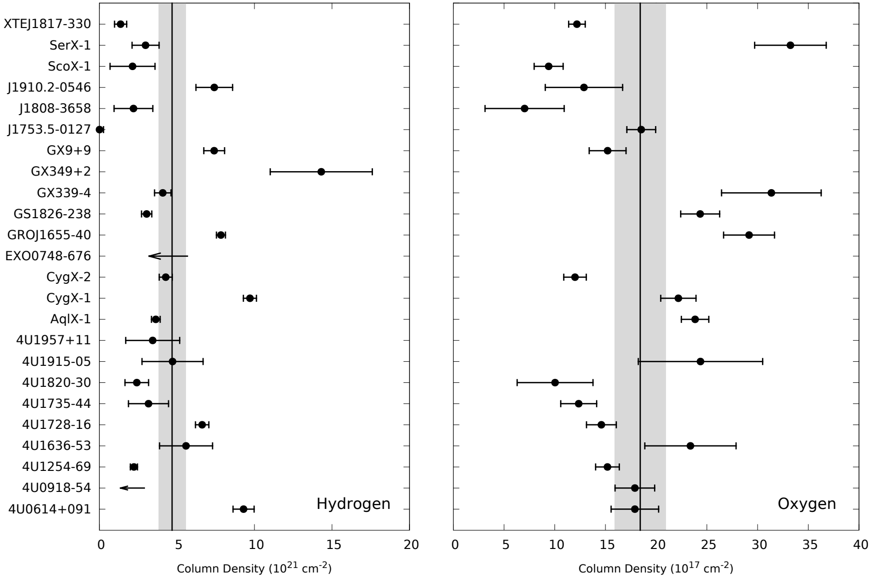


Possible **Background** contamination at the **O-K edge!**

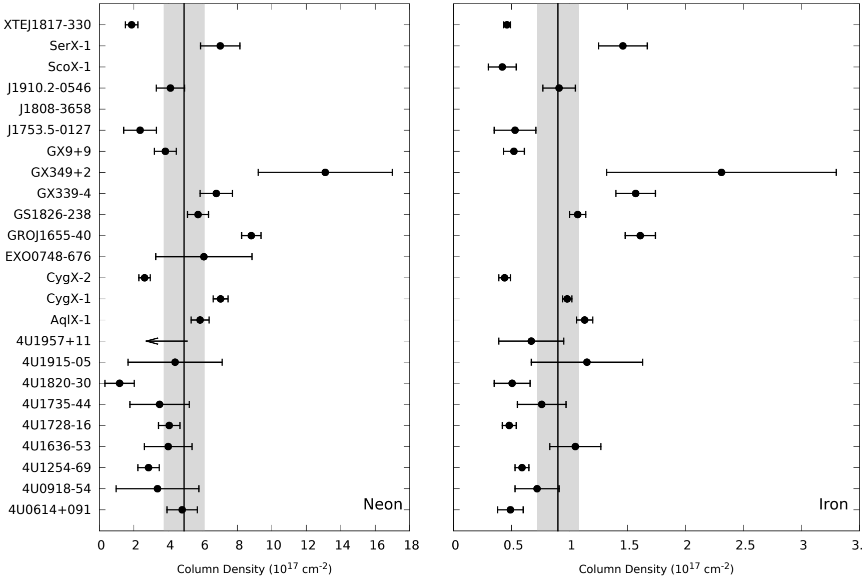
Fits to the Brightest Sources



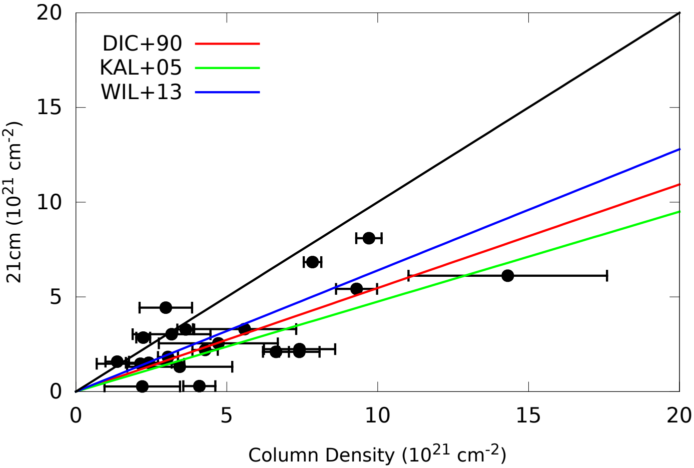
Derived Column Densities: Hydrogen and Oxygen



Derived Column Densities: Neon and Iron

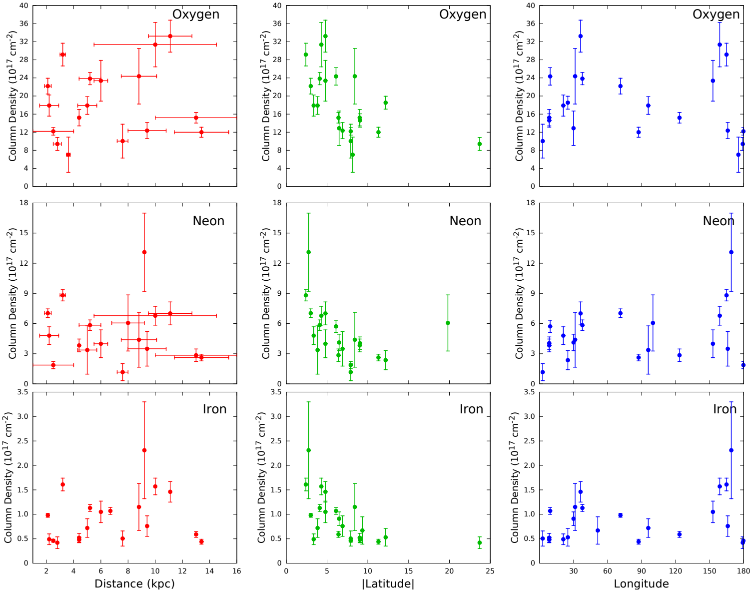


Hydrogen Column Densities

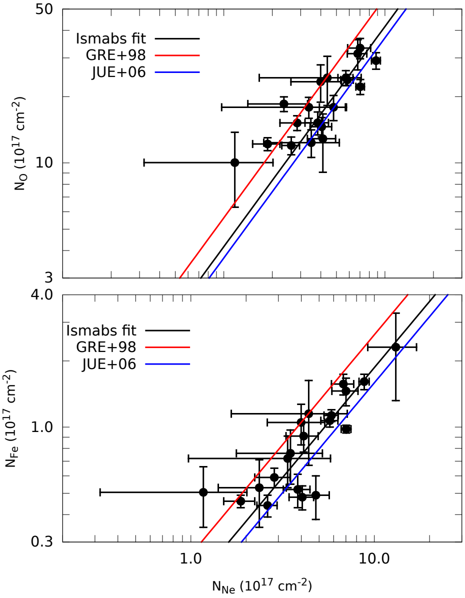


ISMabs H columns systematically larger than the 21-cm measurements by Dickey & Lockman (1990) and Kalberla et al. (2005). Better agreement with Willingale et al. (2013). **But continuum modeling influences this trend!**

Spatial Variations of the Columns



Oxygen and Iron Depletion

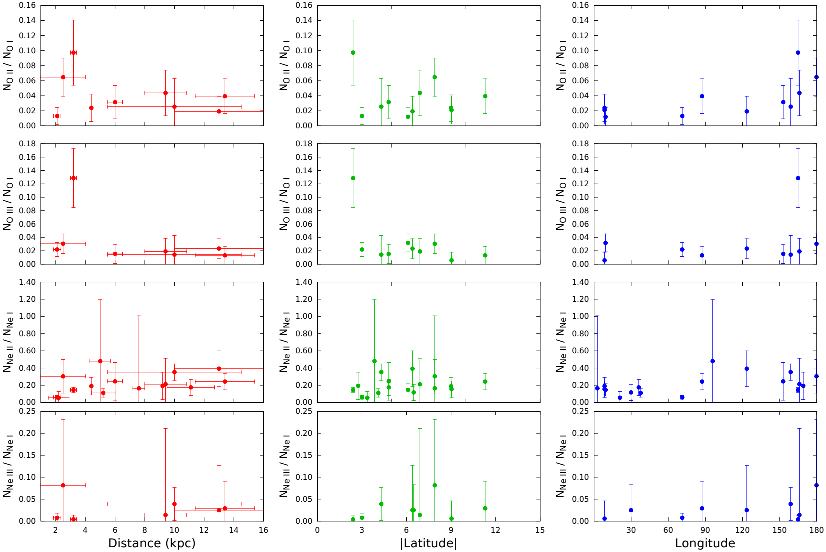


$$N_O = \left(\frac{A_O}{A_{Ne}}\right) N_{Ne}$$

$$N_{Fe} = \left(\frac{A_{Fe}}{A_{Ne}}\right) N_{Ne}$$

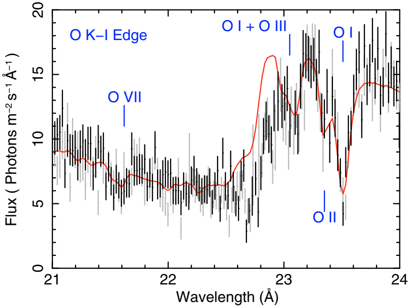
- `ISMabs` columns agree with those from Juett et al. (2006)
- Neon does not combine (noble gas)
- Depletion of oxygen and iron with respect to the Solar values of Grevesse & Sauval (1998)

Ion Fractions

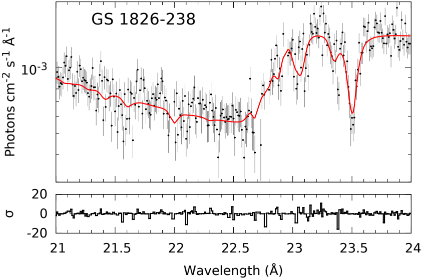


What about the Compounds?

We don't see dust or molecules, but we are not really looking for them yet.
→ But see next talk by **E. Costantini**



(Pinto+10)

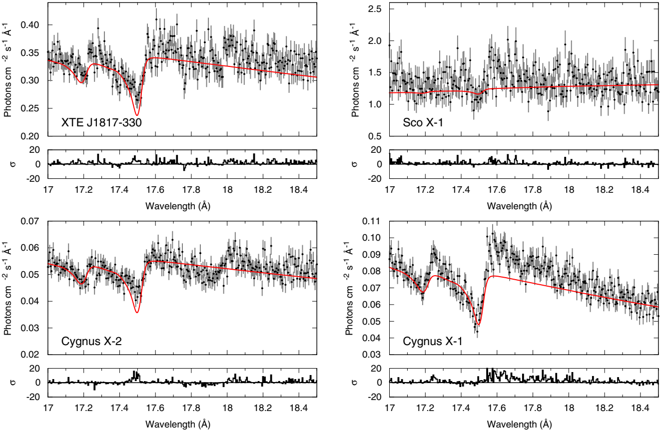


(Gatuzz+García+15)

Accurate atomic data is an important step toward robust detection of **compounds**.

Fe L-shell Absorption

Only the experimental cross section for metallic Fe is included (Kortright+Kim00)



Accurate atomic data is an important step toward robust detection of **compounds**.

Final Remarks

- The superior spectral resolution of **Chandra-HETG** allowed us to benchmark theoretical cross sections, which in turn are used for detailed studies of the ISM absorption. These models are particularly relevant for **Astro-H** and **Athena** science.
- Our analysis of **24 bright low-mass X-ray binaries** revealed absorption that includes both neutral and ionized gas, detecting for first time Kα, Kβ, and Kγ resonances from some species.
- The X-ray **H column densities** are systematically larger than those from **21-cm** measurements. However, these trends can depend on the continuum model.
- Depletion of **O** and **Fe** is also detected.
- **Accurate** atomic data is the first necessary step for robust detection of **compounds**.
- A rather **large discrepancy** between several astrophysical measurements and the latest laboratory experiments still remains and needs to be solved.