High Resolution X-Ray Spectroscopy of the multiphase Interstellar Medium (ISM)

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SRON Netherlands Institute for Space Research

Netherlands Organisation for Scientific Research

Motivations

- ISM diagnostic:
    - Temperature structure
    - Chemical analysis
- ISM and Galaxy:
    - Mapping
    - Metallicity gradient
    - Evolution history

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The Multiphase Interstellar-Medium (ISM)

- Multiphase structure: gas, dust and molecules.

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- Accounts for ~ 10-15% of the galactic-disk mass,
  → along the spiral arms in small clouds
  → high inhomogeneity
- Connection with the evolution of the whole Galaxy
  → stellar evolution enriches the ISM with heavy elements
  → ISM acts as source of matter for the star forming regions.

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The Multiphase ISM: constituents

Gas phase	Component	Temp. (K)	n (cm^{-3})	Constituents	Notes
Neutral gas	Cold molecular	~ 10–20	10^2–10^6	CH, CO, H_2 ...	Block off the starlight background
	Cold atomic	~ 50–100	20–50	H I, Ne I, O I ...	H I 21-cm line, UV and other lines
	Warm atomic	≤ 10^4	0.2–0.5	H I, Ne I, O I ...	Absorption edges and lines
Ionized gas	Warm	~ 10^4	0.2–0.5	H II, Ne II, O II ...	Hα and low-ionization lines
	Hot	~ 10^6	$6.5 \cdot 10^{-3}$	O VII, O VIII, Ne IX	Soft X-ray bkg and high-ioniz. Lines

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- The chemical composition is close to that inferred from Solar and disk-stars abundances
- Heavier elements are often "depleted" from the gaseous phase → solid dust grains

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X-ray Spectroscopy: tool for ISM diagnostic

Search for absorption lines in X-ray spectra of background sources

$\rightarrow$ column densities for all relevant ions
of the most abundant elements

Analysis of the chemical abundances in stars and ISM:

- ISM Diagnostic
- Stellar formation and ISM
- Evolution history
- Galaxy and ISM

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Historical background

- First measurement of absorption edges in the X-ray band
  → O I line and O II traces (Schattenburg & Canizares, 1986)

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  (Paerels et al. 2001, Takei et al. 2002, Costantini et al. 2005)
- EXAFS near the O I edge towards Sco X-1 → amorphous ice
  (De Vries & Costantini 2009)

The data

→ The instrument:

XMM-Newton RGS (+ EPIC)

→ Ne, O, Mg K-edge and Fe L-edge

→ Large effective area in 7-35 Å

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Law-Mass X-ray Binary (LMXB) GS 1826-238

F_X ~ 9 x 10^{-10} ergs cm^{-2} s^{-1} (in 0.3-10 keV)

N_H ~ 4 x 10^{21} cm^{-2}

Distance ~ 6-7 kpc, near the center of the Galaxy

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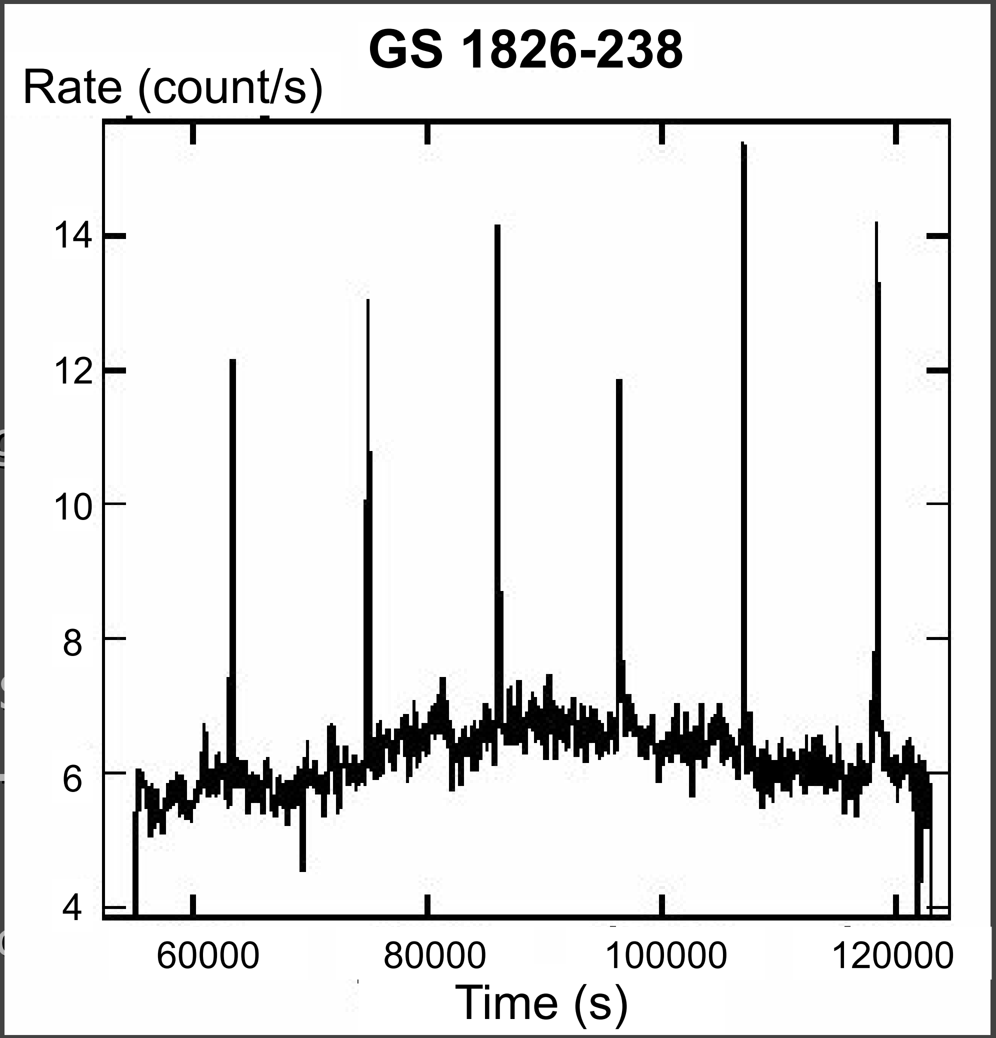

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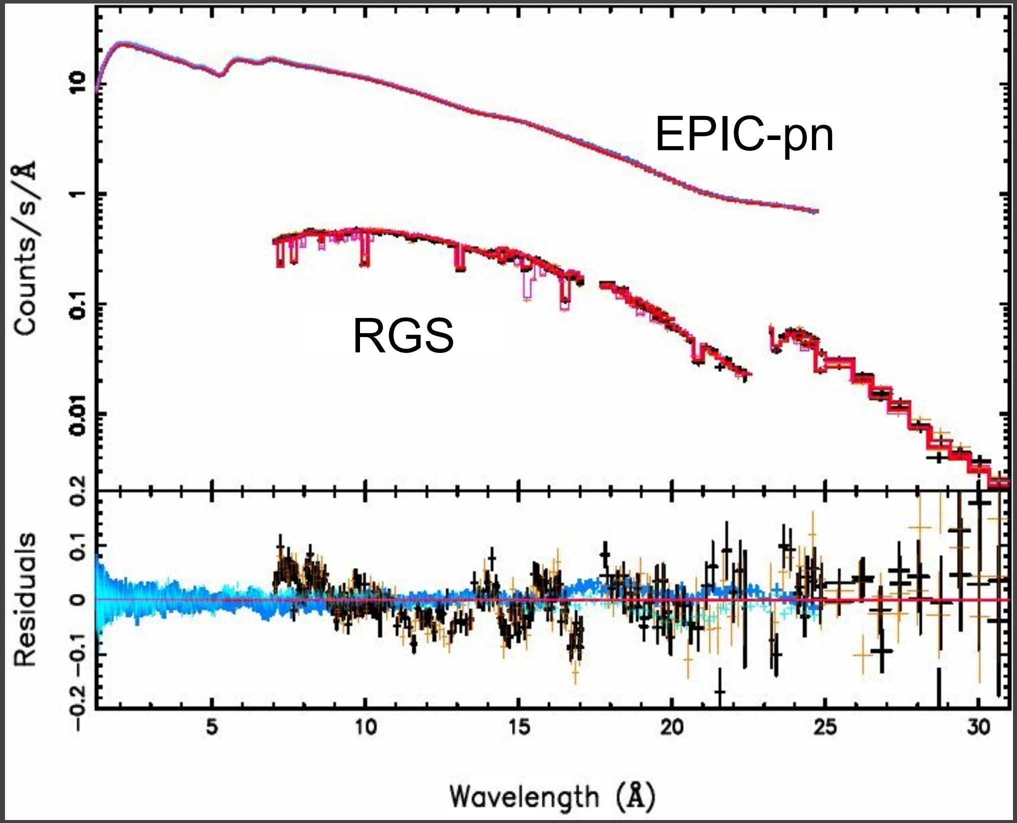
Spectral Modeling: the continuum

Fitting package: SPEX
Kaastra et al. (1996)

- Simultaneous EPIC/RGS fit: 0.5-10 keV EPIC and 0.4-1.77 keV RGS
- Model for the continuum: Black body (*bb*) + 2 comptonization (*comt*)
- Absorption Model A: ISM → cold neutral gas (*hot* model in SPEX)



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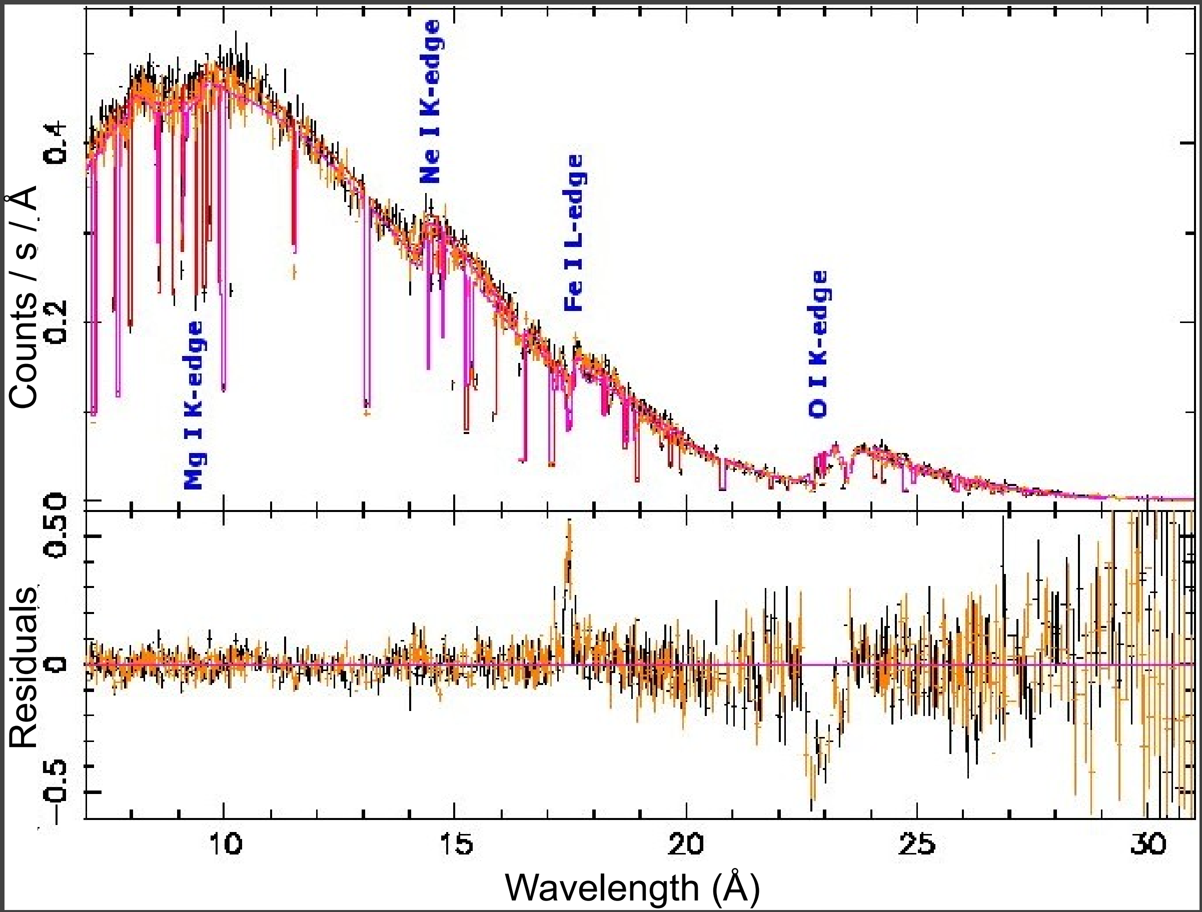
Spectral Modeling: high resolution RGS spectra

- Model A: neutral interstellar gas with (~ 7 000 K)
- Abundances of Ne, O, Mg, Fe free to vary
- Temporarily ignored 2 small λ ranges: 17.2-17.7 Å and 22.7:23.2 Å → dust effects



- Large residuals around 23 Å and 17.5 Å (~3σ)
- O II abs line at 23.35 Å
- O VII abs line at 21.6 Å
- All elements show over-abundances with respect to the average Galactic values

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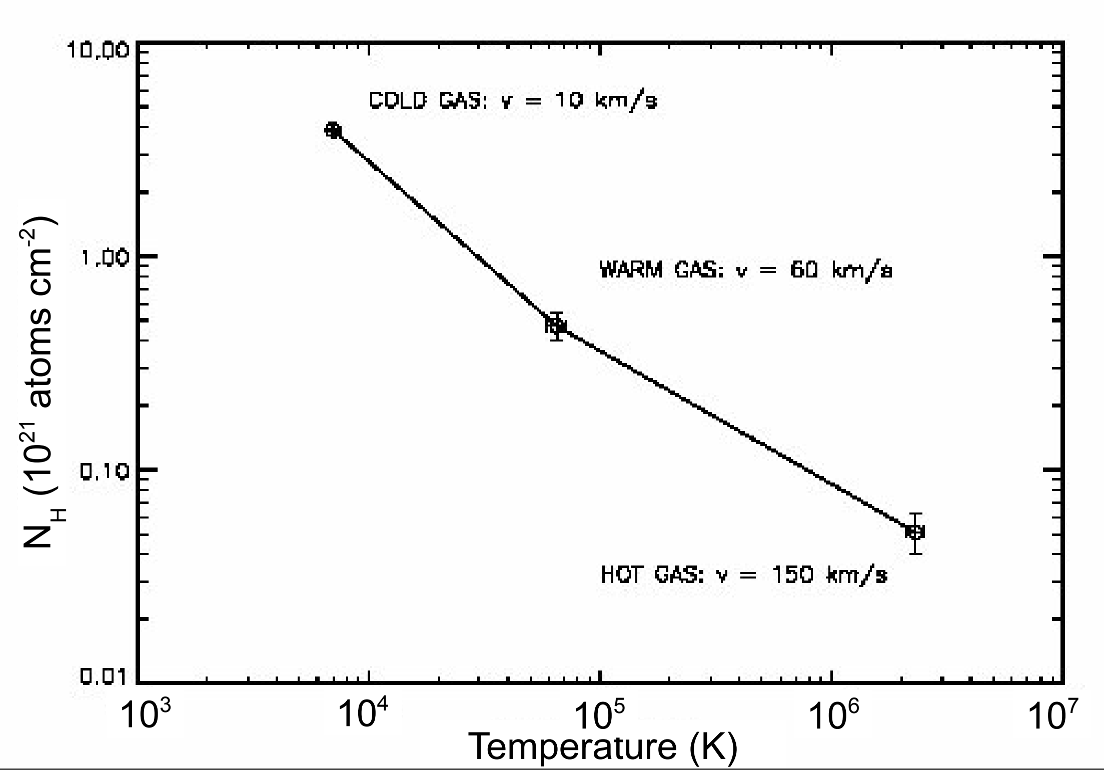
Spectral Modeling: the multi-phase ISM

- Model B: 3-Gas model
- Abundances of:
  Ne, O, Mg, Fe are bound to those of the cold gas
- Presence of ionized gas
- $\Delta \chi^2 \leq 10\ \%$



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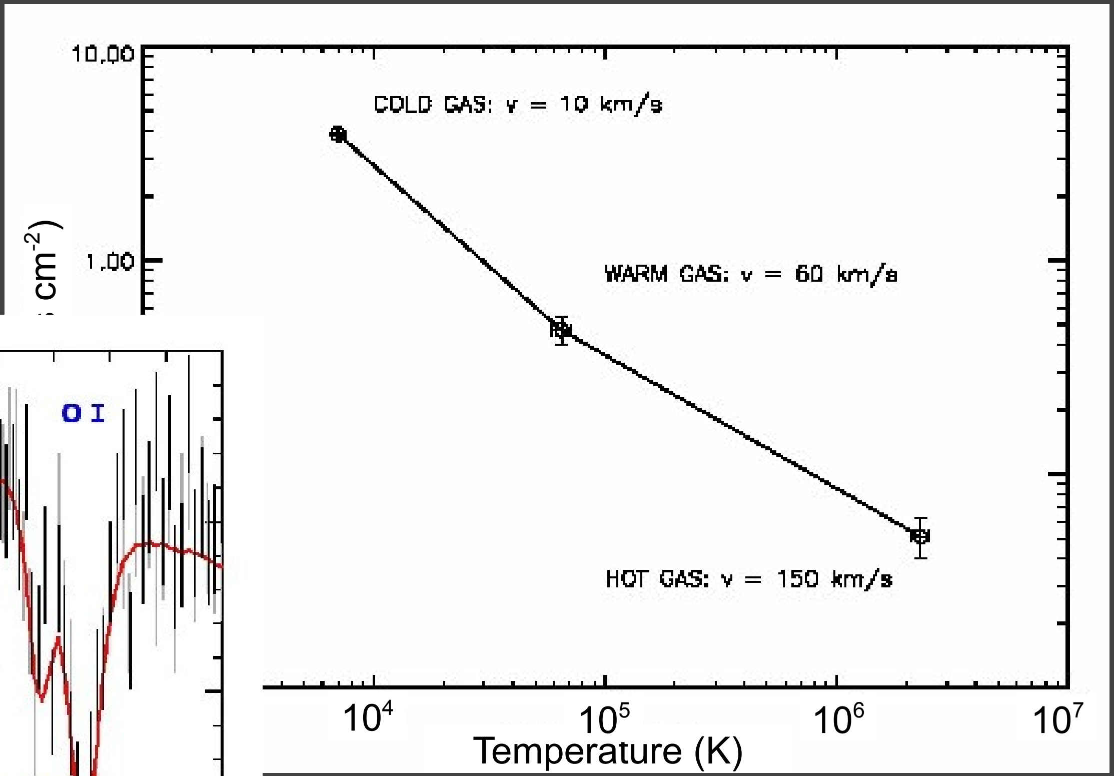

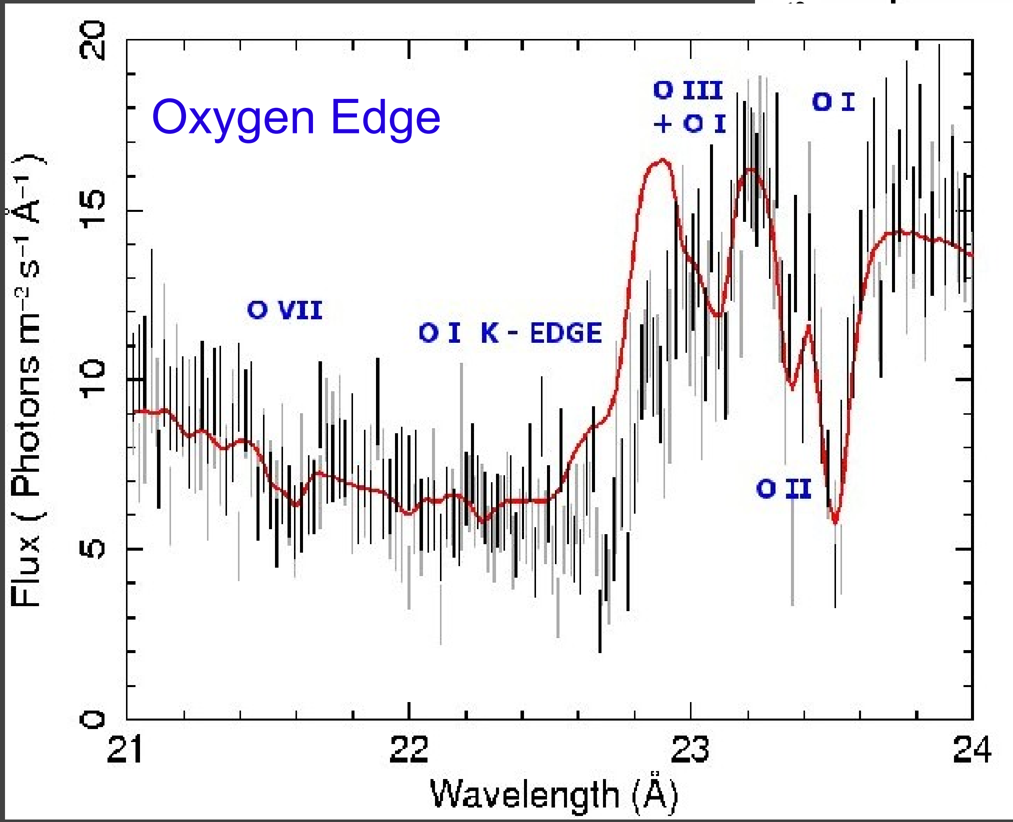

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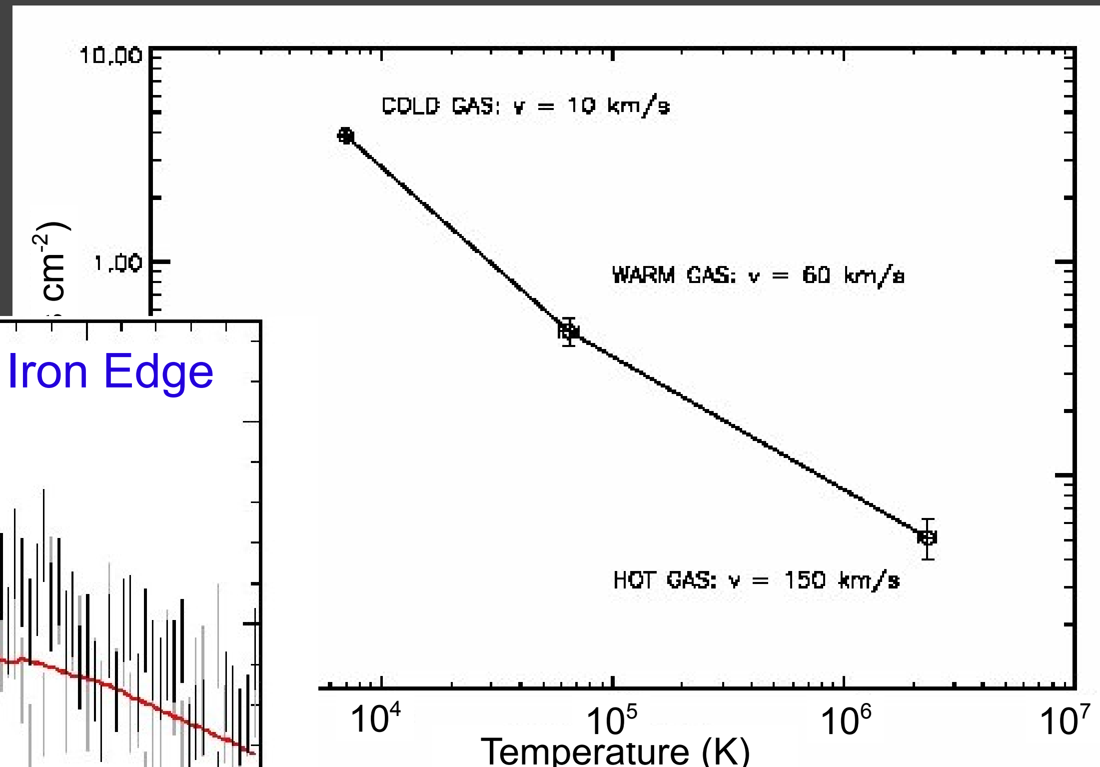

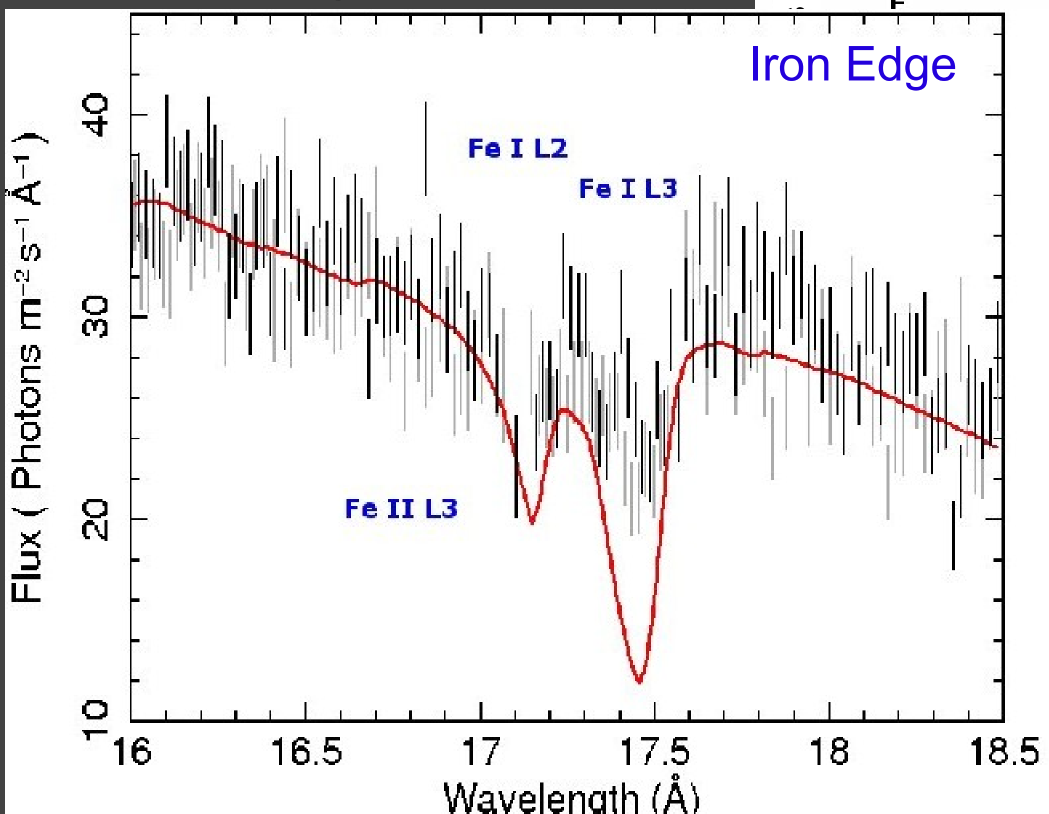

- Pure-gas models are not completely satisfactory

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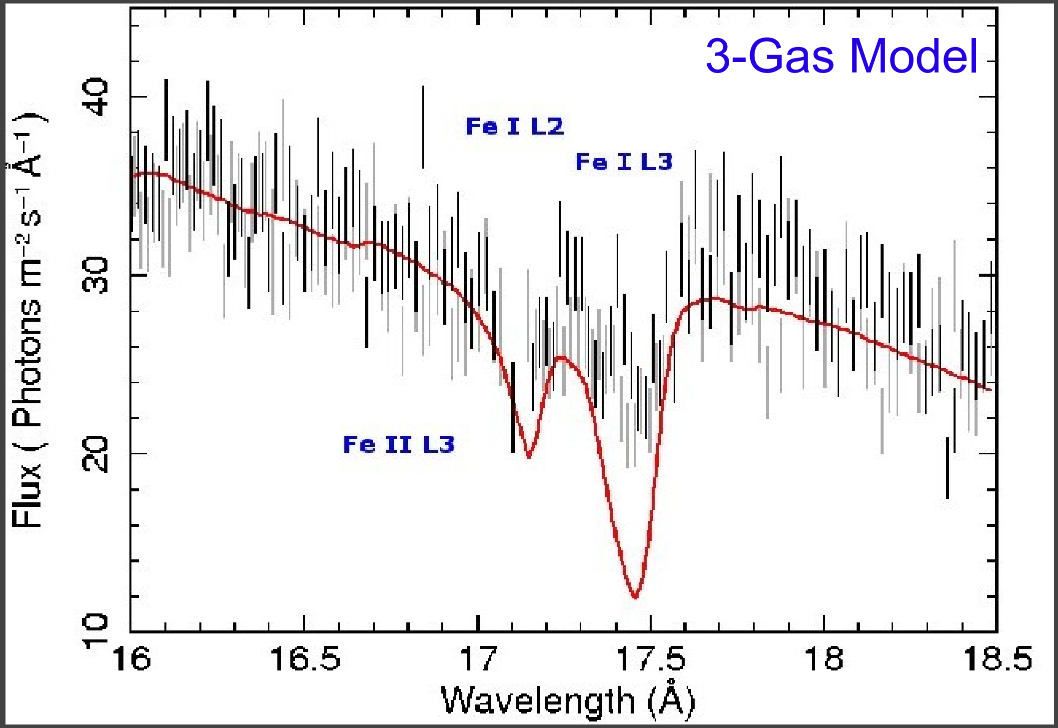
Spectral Modeling: dust and molecules → iron edge



- Important improvements 1: a dust component (*dabs* model in SPEX)
- → shielding of X-ray photons by dust grains with radii of 0.025-0.25 μm
- More than 90 % of Fe appears to be bound in dust grains

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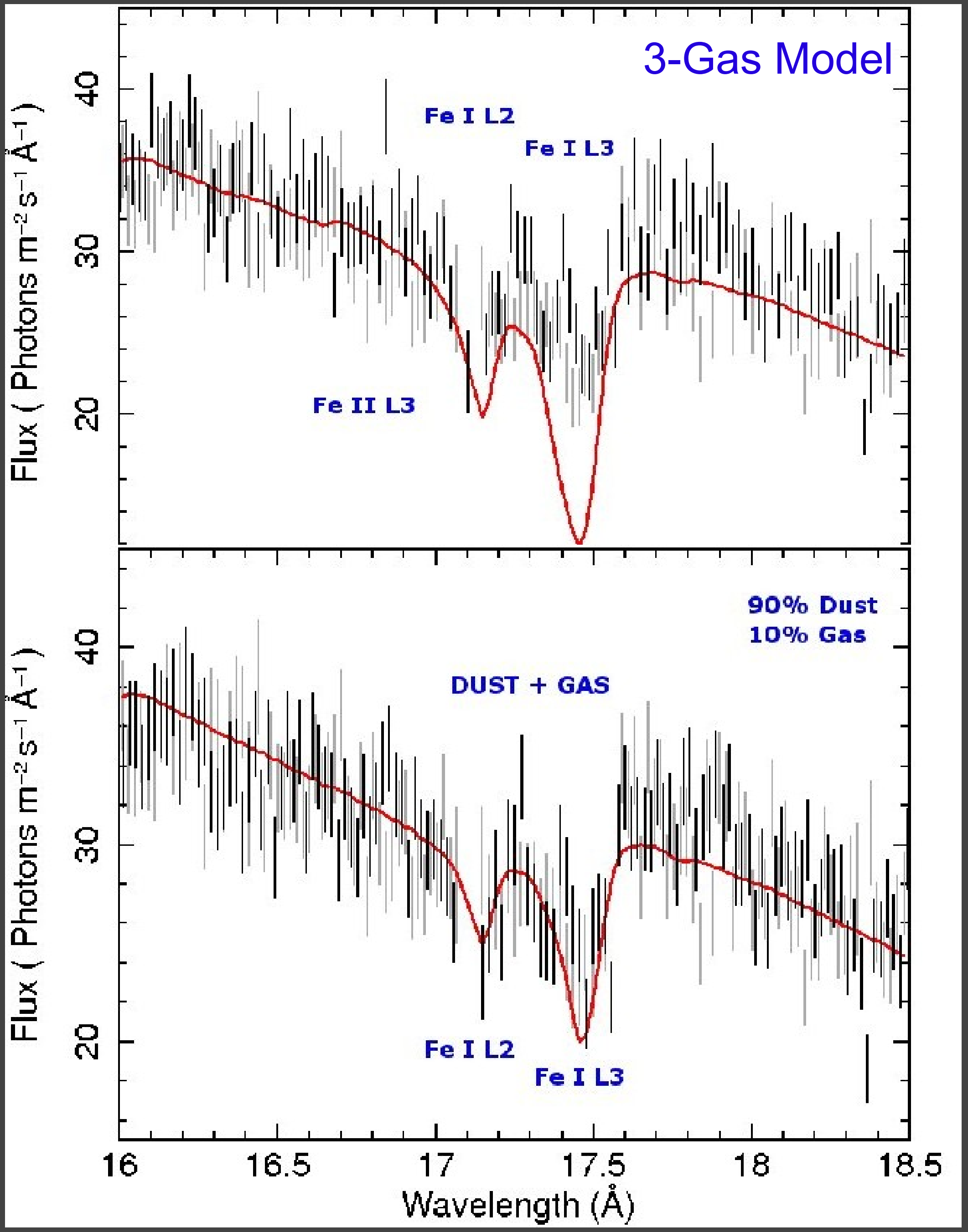

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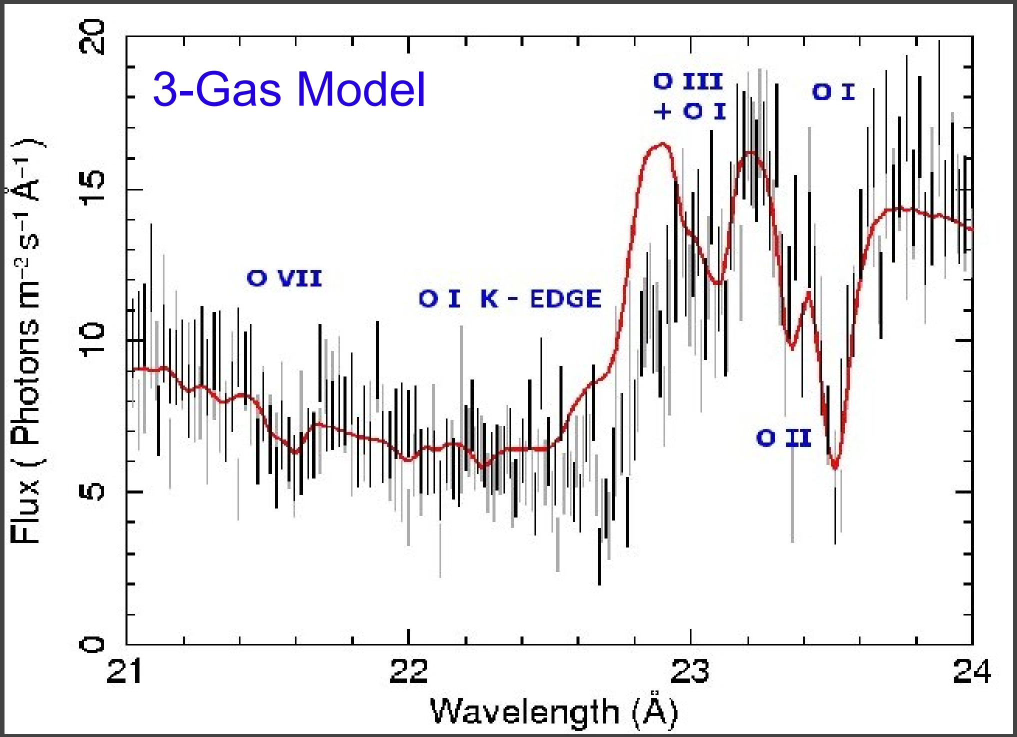
Spectral Modeling: dust and molecules → oxygen edge



- Important improvements 2:
  a dust-molecular component (*amol* model in SPEX)
- → modified edge structure around the O K-edge of various oxygen compounds: CO, H_20 ice O_2 and silicates, ...
- At least 10 % of oxygen appears to be bound in compounds: silicates are the best candidate

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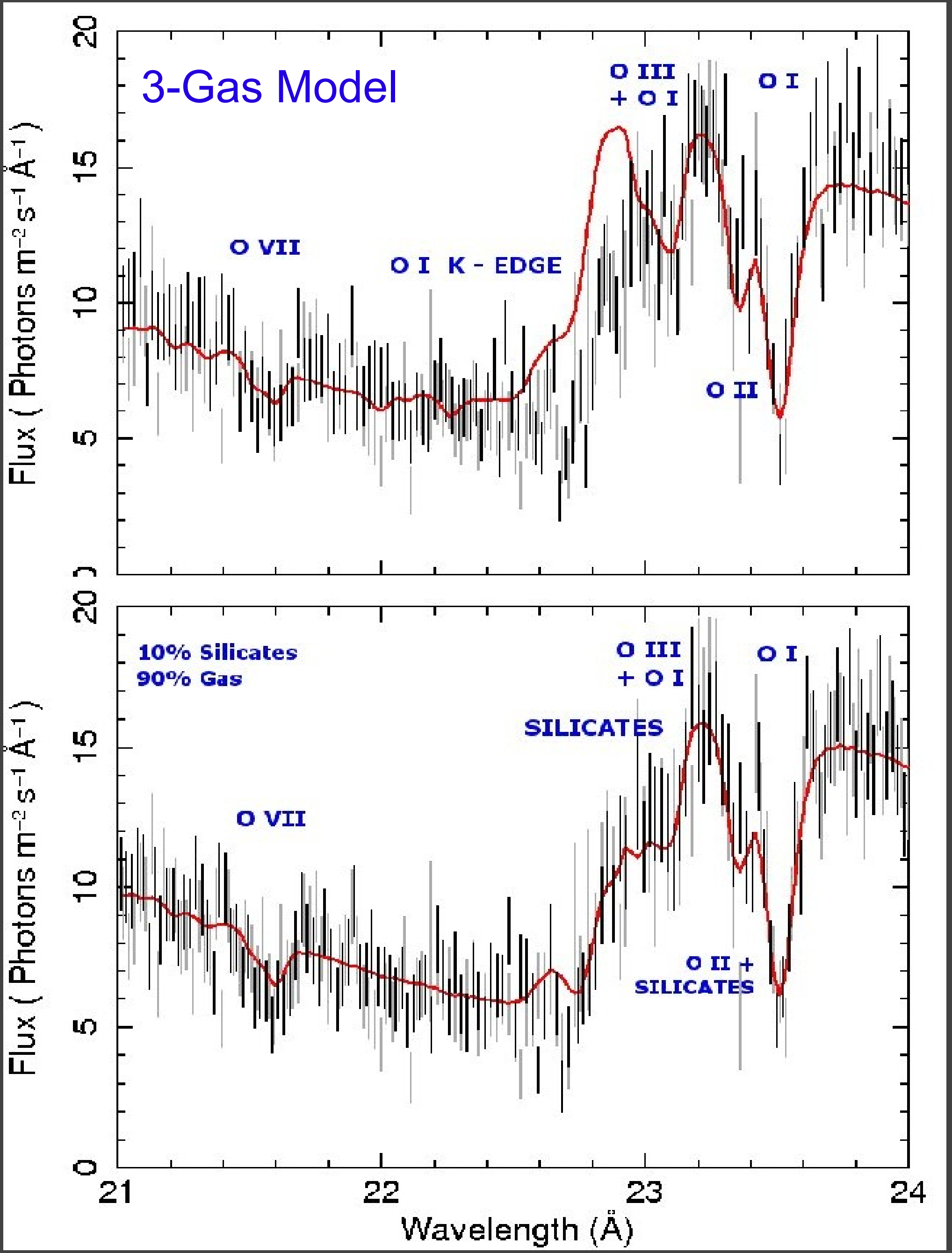

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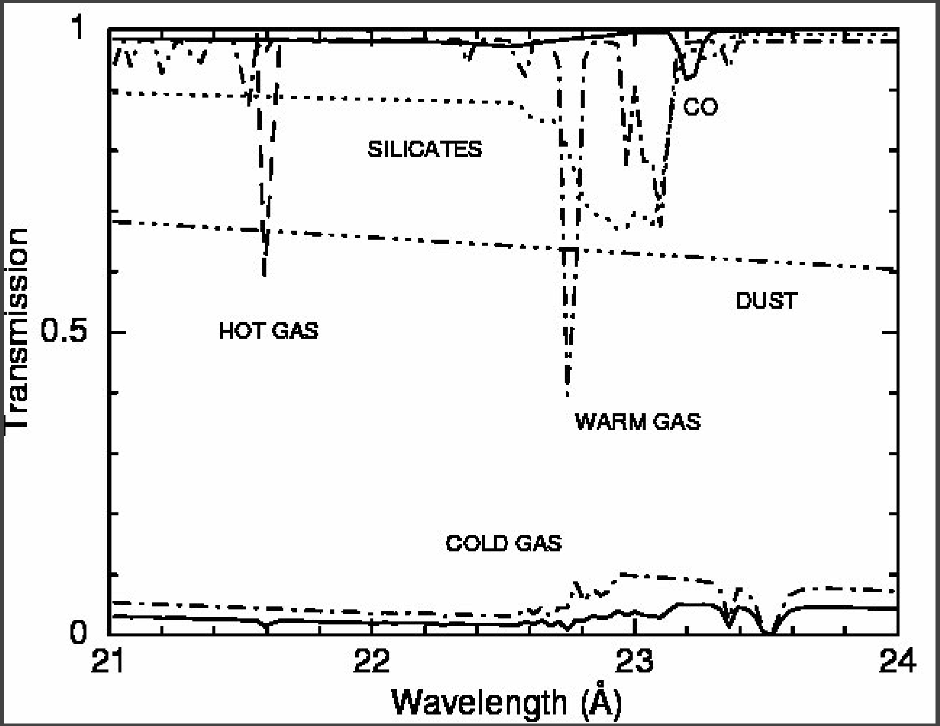
ISM diagnostic - oxygen

- Most of the absorption is due to the cold neutral gas
- Dust and ionized gas give distinct local contributions



Phase	Constituents	% N_O in phase	% of N_O
	O I	94	
Gas	O II, O III, O IV	4	90
	O VII, O VIII	2	
Dust	Silicates	85 - 100	8
	Other Oxides	0 - 15	
Molecules	H_2O ice	~ 65	0 - 2
	CO	~ 35	

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ISM diagnostic – chemical abundances

- Abundances → sum of all the phases
- Nitrogen abundance (*) is fitted by extending the fit to 7-33 Å
- GS 1826-238 is towards the Galactic center at ~ 6-7 kpc

Crab → Kaastra et al. (2009)
Cyg X-2 → Yao & Wang (2006)
4U 1820-303 → Yao et al. (2009)

Abundances are referred to the proto-Solar value of Lodders (2003)

X	Pure Gas	Gas + Dust	Crab	Cyg X-2	4U 1820
N*	2.5 ± 0.7	2.4 ± 0.7	1.01 ± 0.09	-	-
O	1.29 ± 0.02	1.23 ± 0.05	1.03 ± 0.02	~ 0.67	~ 0.6
Ne	2.19 ± 0.10	1.75 ± 0.11	1.72 ± 0.11	~ 0.94	~ 1.3
Mg	1.93 ± 0.15	2.45 ± 0.35	0.85 ± 0.21	~ 0.84	-
Fe	1.65 ± 0.08	1.37 ± 0.17	0.78 ± 0.05	-	-

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ISM diagnostic – abundances gradient

- All elements show over-abundances
- Abundances appear to be related to the line of sight
- O ~ 1.23 → change in (O/H) ~ - 0.04 kpc^{-1} (Esteban et al. 2005)
- Fe ~ 1.37 → change in (Fe/H) ~ - 0.06 kpc^{-1} (Pedicelli et al. 2009)
- Different gradients trace different composition in the ISM

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ISM towards GS 1826-238: consistencies

- Complex multi-phase structure:
  media with different ionization state and composition (Ferrière 2001)

- About 95% of absorption is due to a gas with ~ 7 000 K

- About 5% of the gas is ionized: T_{warm} ~ 70 000 K, T_{hot} ~ 2 x 10^6 K
  → agrees with 4U 1820-303 (Yao & Wang 2006)

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ISM towards GS 1826-238: consistencies

- 90% of iron and 10% of oxygen are bound in dust
  $\rightarrow$ agrees with Crab (Kaastra et al 2009 and Wilms et al. 2000)

- The bulk of dust is represented by silicates (olivine, andradite)
  (Paerels at al. 2001, Takei et al. 2002, Costantini et al. 2005)

- Dust presence is also confirmed by IR observations

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ISM towards GS 1826-238: news

- The total N_H = (4.14 ± 0.07) 10^{21} cm^{-2} is higher than other estimates

  → (3.19 ± 0.01) 10^{21} cm^{-2} by Thompson et al. ('08)

  → expected if we are considering contributions from all the phases

- The $(dust/gas)_{Fe}$ is among the highest measured

  → dense regions near the G. center

  → forming dust from gas particles (Williams & Taylor '96)

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  → dense regions near the G. center
  → forming dust from gas particles (Williams & Taylor '96)
- Over-abundances:
  → edges better fitted with the complete model
  → all main phases contributing
- The metallicity gradient is a trace of evolutionary effects:
  → supernovae explosions enrich the ISM with heavy elements
  → crucial in high-density region like towards the Galactic center

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Conclusion and future

- X-ray spectroscopy is a powerful tool to investigate the ISM
- Detailed chemical analysis and charge states study of the gas
- Constrain some ISM constituents that at other wavelengths (e.g. optical) could be prohibitive, such as dust

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- The analysis can be extended to several sources in different directions of the Galaxy $\rightarrow$ complete mapping of the ISM
- We need to: larger lab. data,
  higher S/N data,
  better resolution (e.g. to distinguish among the compounds)
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Thanks for your attention !

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