ISM X-ray Astrophysics

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The Interstellar Medium (X-rated)

- Overview
- Phases of the ISM
- X-ray studies of the Hot ISM
- X-ray studies of the Warm/Cold ISM
- X-ray studies of Dust Grains

Overview

- Constituents
  - –Gas: modern ISM has 90% H, 10% He by number
  - –Dust: refractory metals
  - –Cosmic Rays: relativistic e^-, protons, heavy nuclei
  - –Magnetic Fields: interact with CR, ionized gas
- Mass
  - –Milky Way has 10% of baryons in gas
  - –Low surface brightness galaxies can have 90%

ISM: Phases

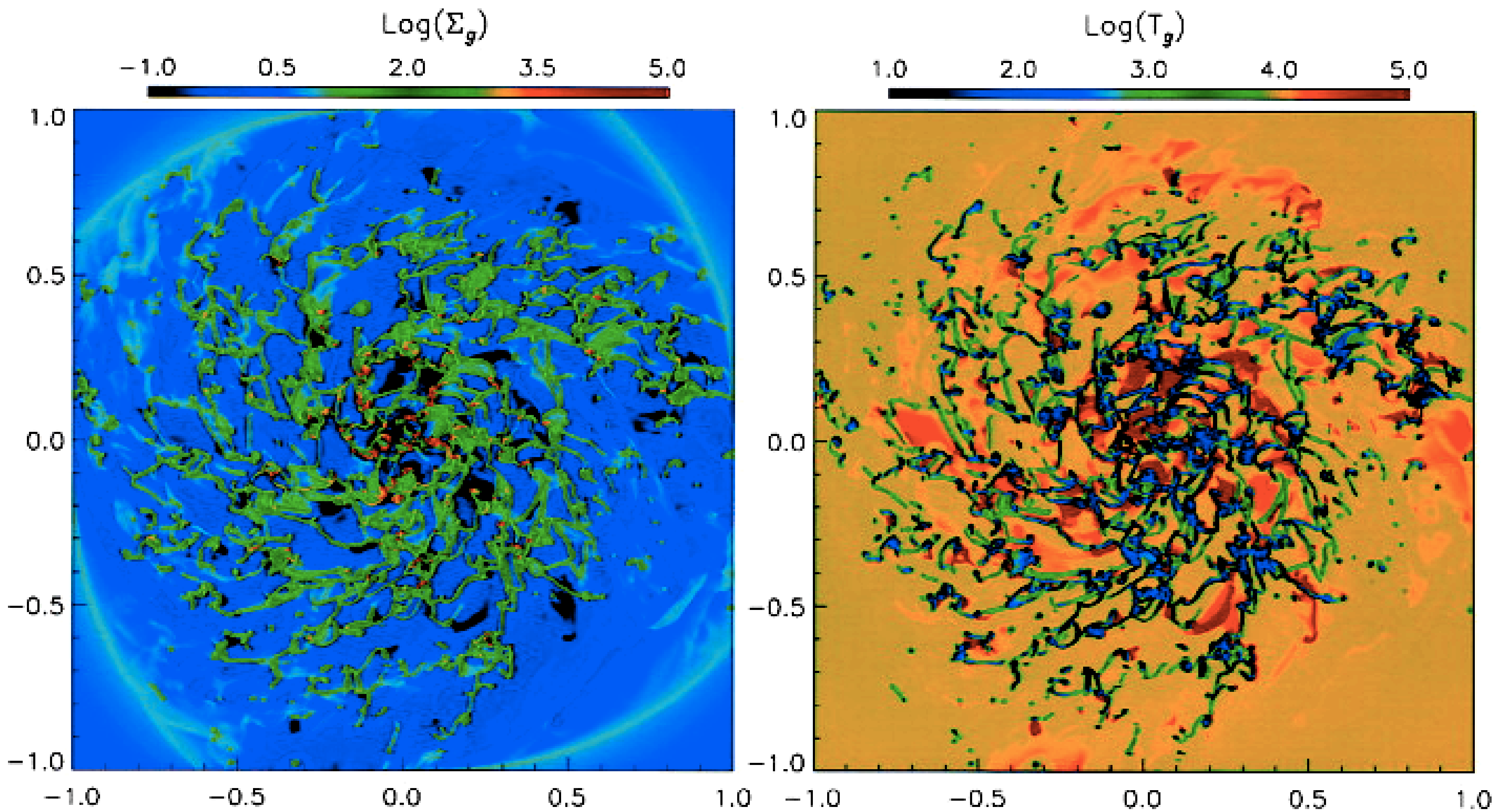
Gas in the ISM has a number of phases:

Cold Neutral Medium: $T \sim 100$ K, $n \sim 100\text{-}10^4$ cm^{-3}
Warm Neutral Medium: $T \sim 1000$ K, $n \sim 1$ cm^{-3}
Warm Ionized Medium: $T \sim 10{,}000$ K, $n \sim 0.1$ cm^{-3}
Hot Interstellar Medium: $T \sim 10^6$ K, $n \sim 0.01$ cm^{-3}

Unsurprisingly, only the hot ISM emits any X-rays, and even these are easily absorbed since they are (mostly) soft.

ISM: Phases

Model surface density and temperature maps of the inner ISM



Wada & Norman 1999

Vertical Distribution

- Cold molecular gas has 100 pc scale height
- HI has composite distribution (~150, 500 pc)
- Reynolds layer of diffuse ionized gas (~1.5 kpc)
- Hot halo extending into local IGM (~*few* kpc)

ISM: Phases

TABLE 1

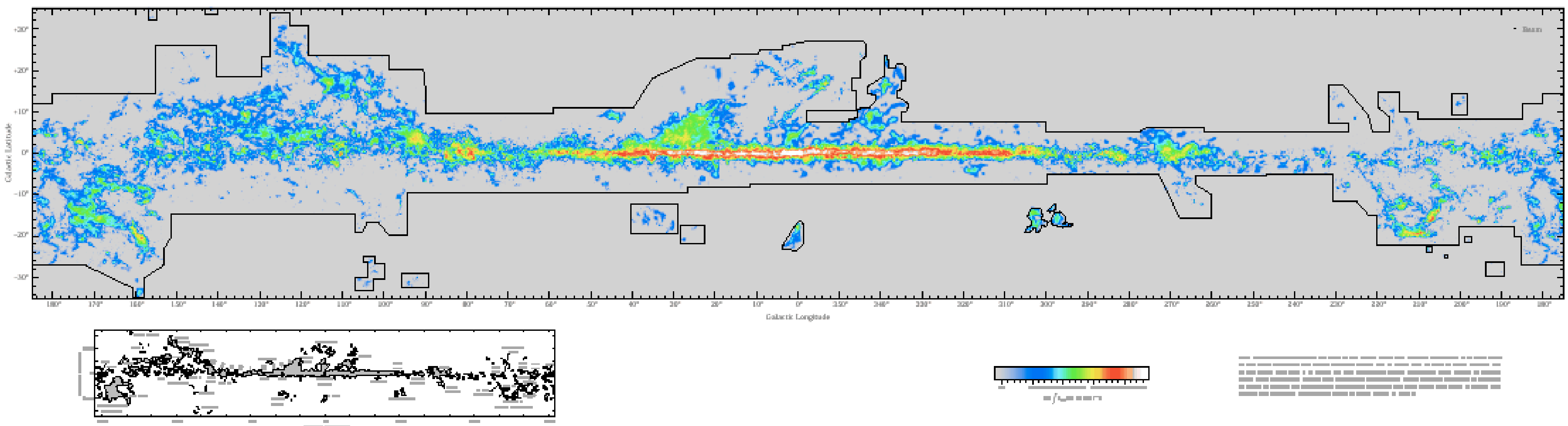
INTERSTELLAR GAS DENSITIES

Component	$n(0)$ (atoms cm^{-3})	$\sqrt{\langle v_z^2 \rangle}$ (km s^{-1})[a]	T (K)[b]	Z_0 (pc)
H_2[c,d]	0.6	5	...	70
Cold H I[c,e]	0.3	6	...	135
Warm H I (clouds)[c,e]	0.07	9	...	135
Warm H I (interclouds)[e,f]	0.10	9(14.3)[i]	...	400
Warm H II (diffuse)[f,g]	0.025	9(20.0)[j]	8000	1500
Warm H II regions[f,g]	0.015	9	8000	70
(H I + H_2)[f,h]	1.15	...	...	160[k]

[a] The velocity dispersion corresponds to turbulent motion only.
[b] Assumed temperature.
[c] The density distribution is Gaussian of the form $\exp(-z^2/2z_0^2)$.
[d] Bloeman *et al.* 1986.
[e] Lockman 1984, adapted by Bloeman 1987.
[f] The density distribution is exponential of the form $\exp(-|z|/z_0)$.
[g] Reynolds 1989.
[h] Savage *et al.* 1977.
[i] Kulkarni and Fich 1985.
[j] Reynolds 1985.
[k] Pandey and Mahri 1987.

Boulares & Cox 1990

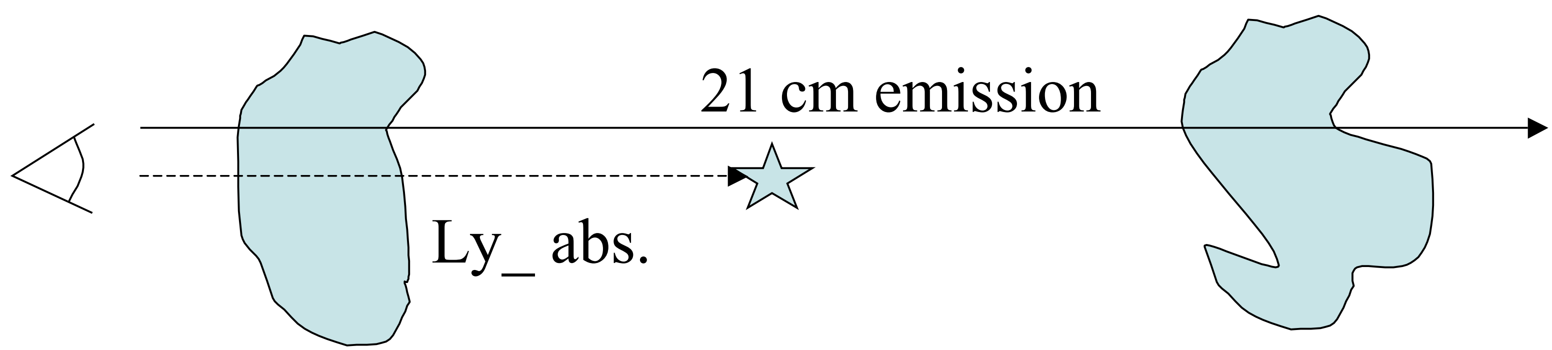
CO distribution in Galaxy



Dame, Hartmann, & Thaddeus 2001

Vertical scale height of Halo HI layer

Measurement of halo HI done by comparing Ly absorption against high-Z stars to 21 cm emission (Lockman, Hobbs, Shull 1986)



Need to watch for stellar contamination, radio beam sidelobes, varying spin temperatures.

Vertical scale height of Halo HI layer

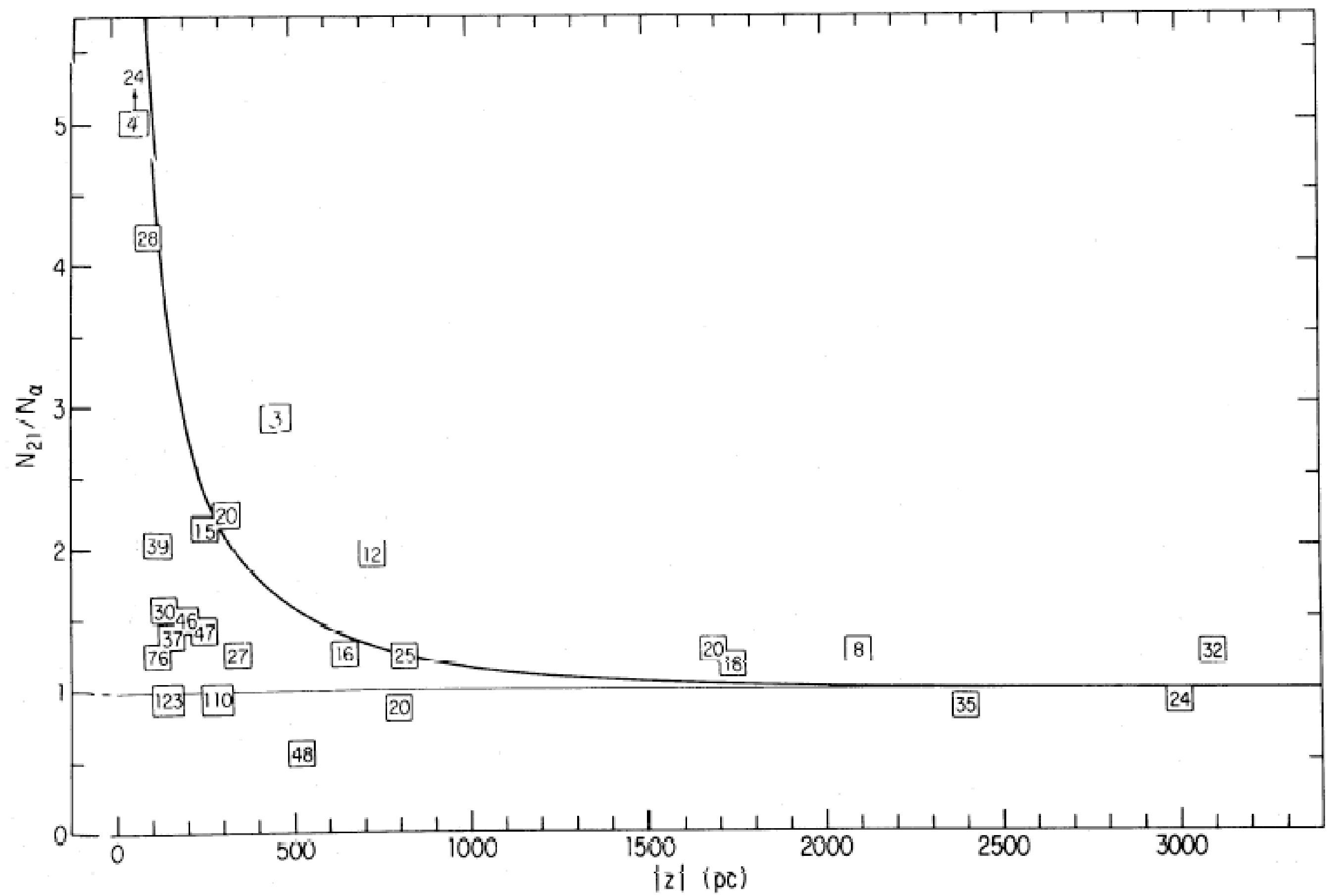
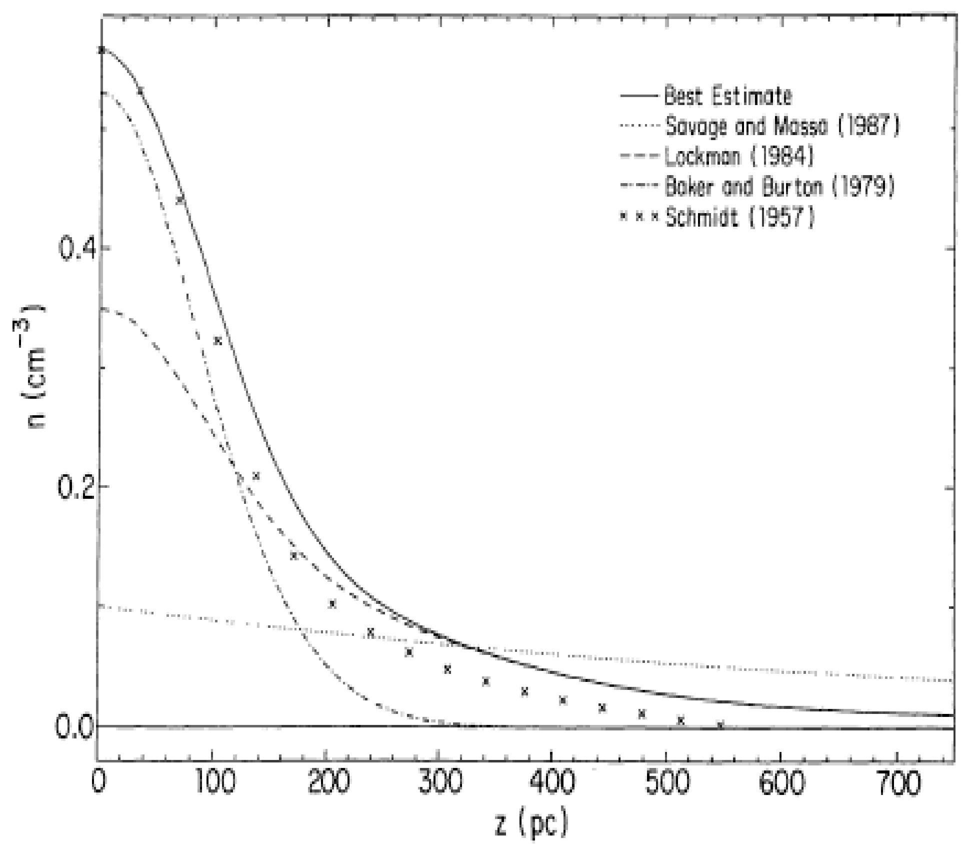


FIG. 3.—The curve shows the ratio N_{21}/N_α expected from a uniform exponential layer with a scale height of 500 pc. The numbers give the average density, $\langle n \rangle$, as efined in the text, in 0.01 cm^{-3}, for the observations.

Lockman, Hobbs, Shull 1986

Vertical scale height of Main HI layer

- Overall density distribution (Dickey & Lockman 1990) at radii 4-8 kpc
- "Lockman layer"
- Disk flares substantially beyond solar circle.



Lockman, Hobbs, Shull 1986

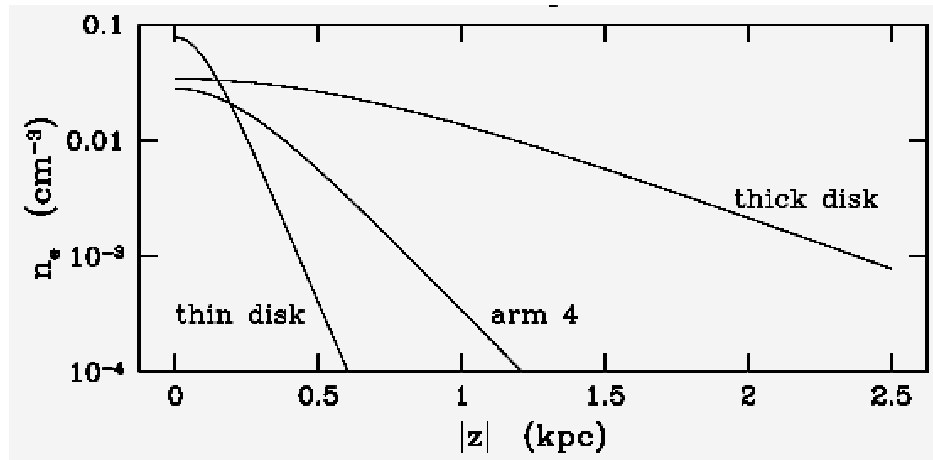
Warm ionized gas in halo

• Diffuse warm ionized gas extends to higher than 1 kpc, seen in H (Reynolds 1985)

•"Reynolds layer",

• **W**arm **I**onized **M**edium, or

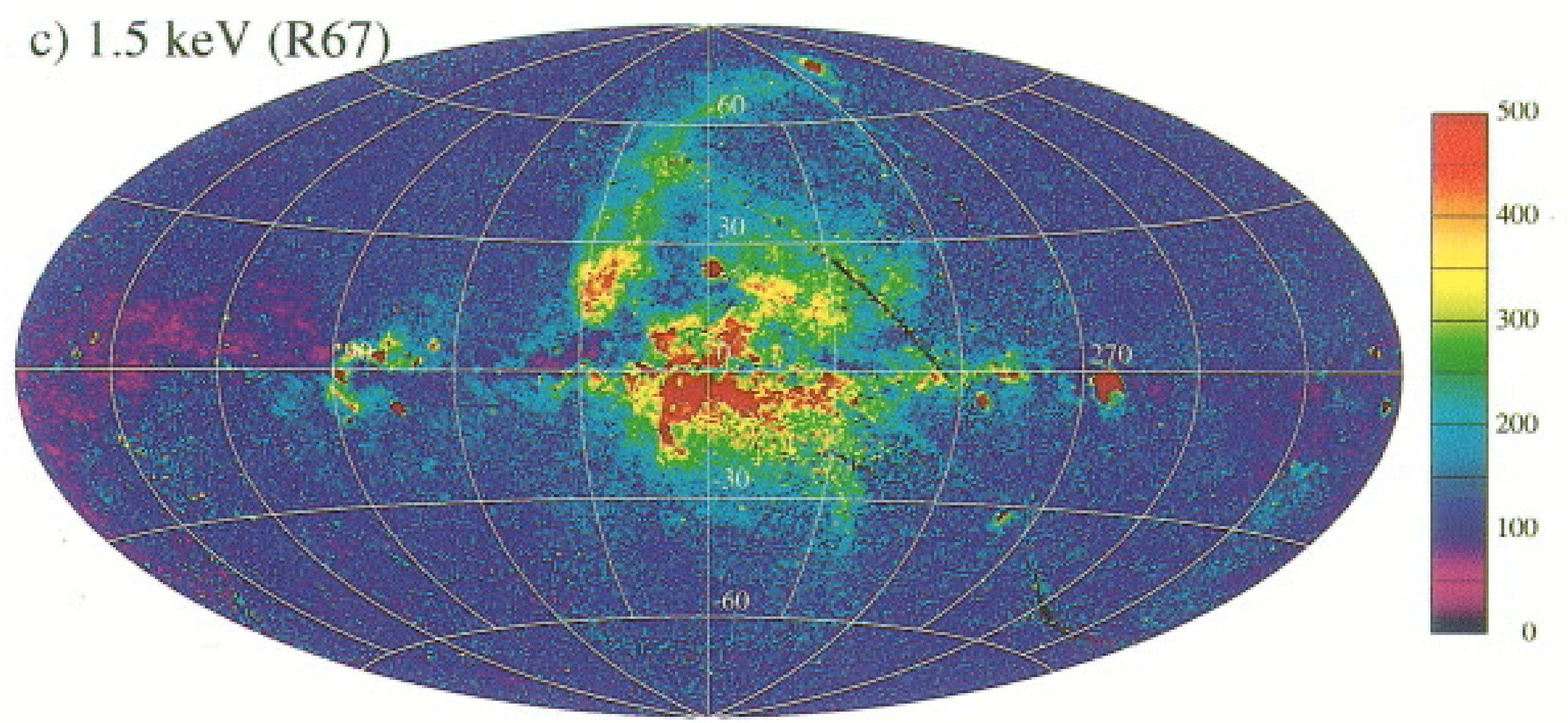
• **D**iffuse **I**onized **G**as



- Dispersion measures and distances of pulsars in globular clusters show scale height of 1.5 kpc (Reynolds 1989). Revision using all pulsars by Taylor & Cordes (1993), Cordes & Lazio (2002 astro-ph)

ISM: Phases

ROSAT made an all-sky survey in soft X-rays (0.1-2.2 keV); these results, after removing point sources, are from Snowden *et al*. 1997:



Interstellar Pressure

- Thermal pressures are very low:

$$P_T \sim 10^3 k_B = 1.4 \times 10^{-13} \text{ erg cm}^{-3}.$$

(Perhaps reaches $3000 k_B$ in plane)

- Magnetic pressures with $B = 3\text{-}6\,\mu G$ reach

$$P_B \sim 0.4\text{-}1.4 \times 10^{-12} \text{ erg cm}^{-3}.$$

- Cosmic rays also exert a pressure:

$$P_{CR} \sim 0.8\text{-}1.6 \times 10^{-12} \text{ erg cm}^{-3}.$$

- Turbulent motions of up to 20 km/s contribute:

$$P_{turb} \sim 10^{-12} \text{ erg cm}^{-3}.$$

- Boulares & Cox (1990) show that total weight may require as much as 5×10^{-12} erg cm^{-3} to support.

ISM: Local

Interestingly, we do not appear to be in a "normal" region of the Galaxy. Partial proof of this may be seen this evening:

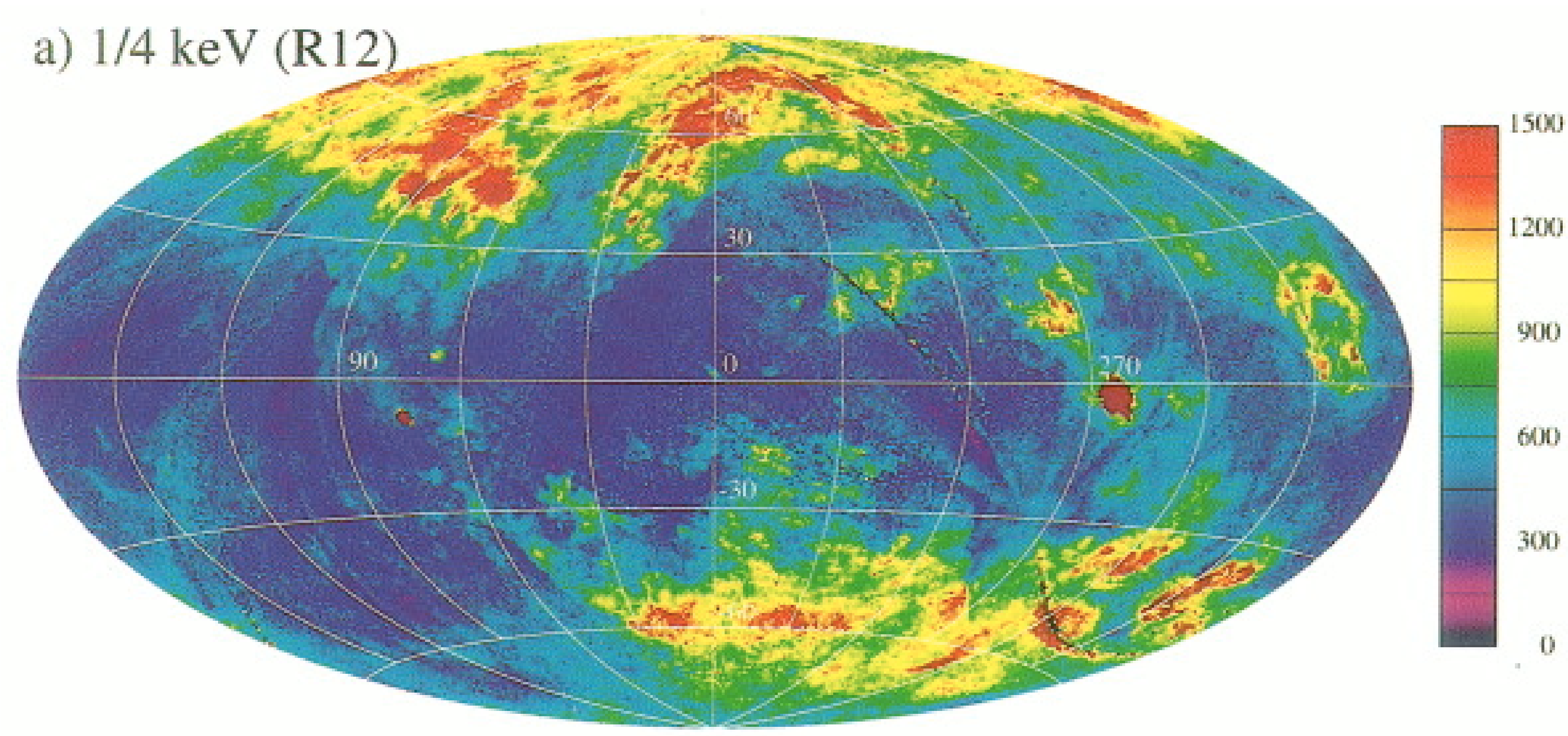
There are frequently stars visible in the night sky

If we lived in or near a molecular cloud, all of much of the night sky would be dark to visible light. In fact, we can even see (from orbit) quite a few sources in the extreme ultraviolet (EUV) when a single "normal ISM" cloud would completely absorb them.

Clearly, nearby space is not filled with dense ($n > 1\ cm^{-3}$) gas.
What is it filled with?

ISM: Local

Besides absorption studies of nearby (D ~ 100 pc) stars (used to quantify how little gas there is in our neighborhood), we can also see the material that fills our locale, in soft X-rays:



ISM: Local

Based on this evidence, it is believed that we live inside a "Local (Hot) Bubble" with average radius 100 pc, which happens to be right next to another bubble, Loop I. The Local Bubble is filled with hot (T ~ 10^6 K), diffuse (n ~ 0.01 cm^{-3}) gas, and radiates primarily below 0.25 keV.

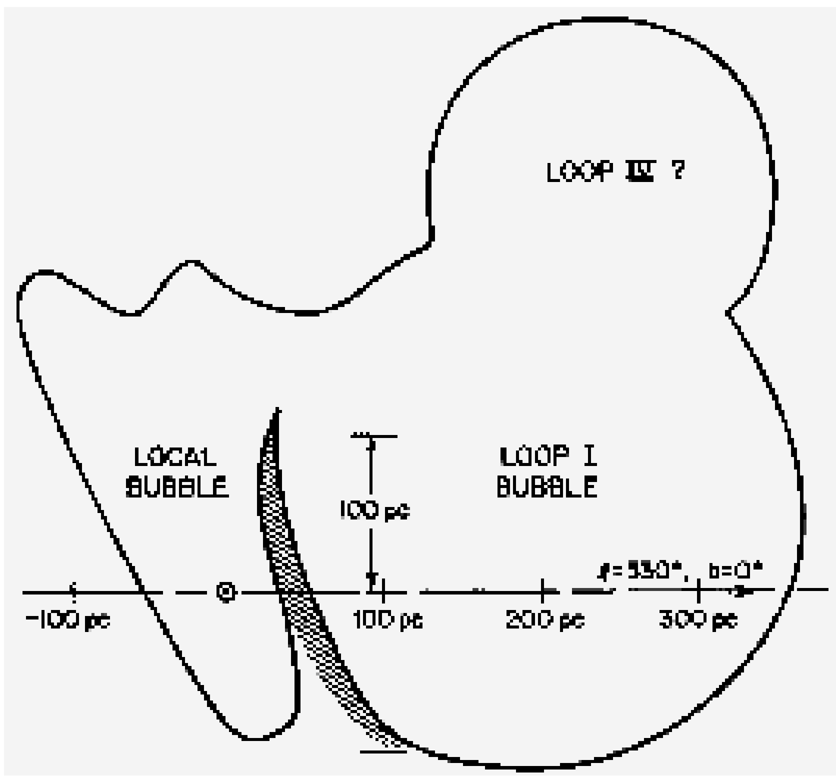
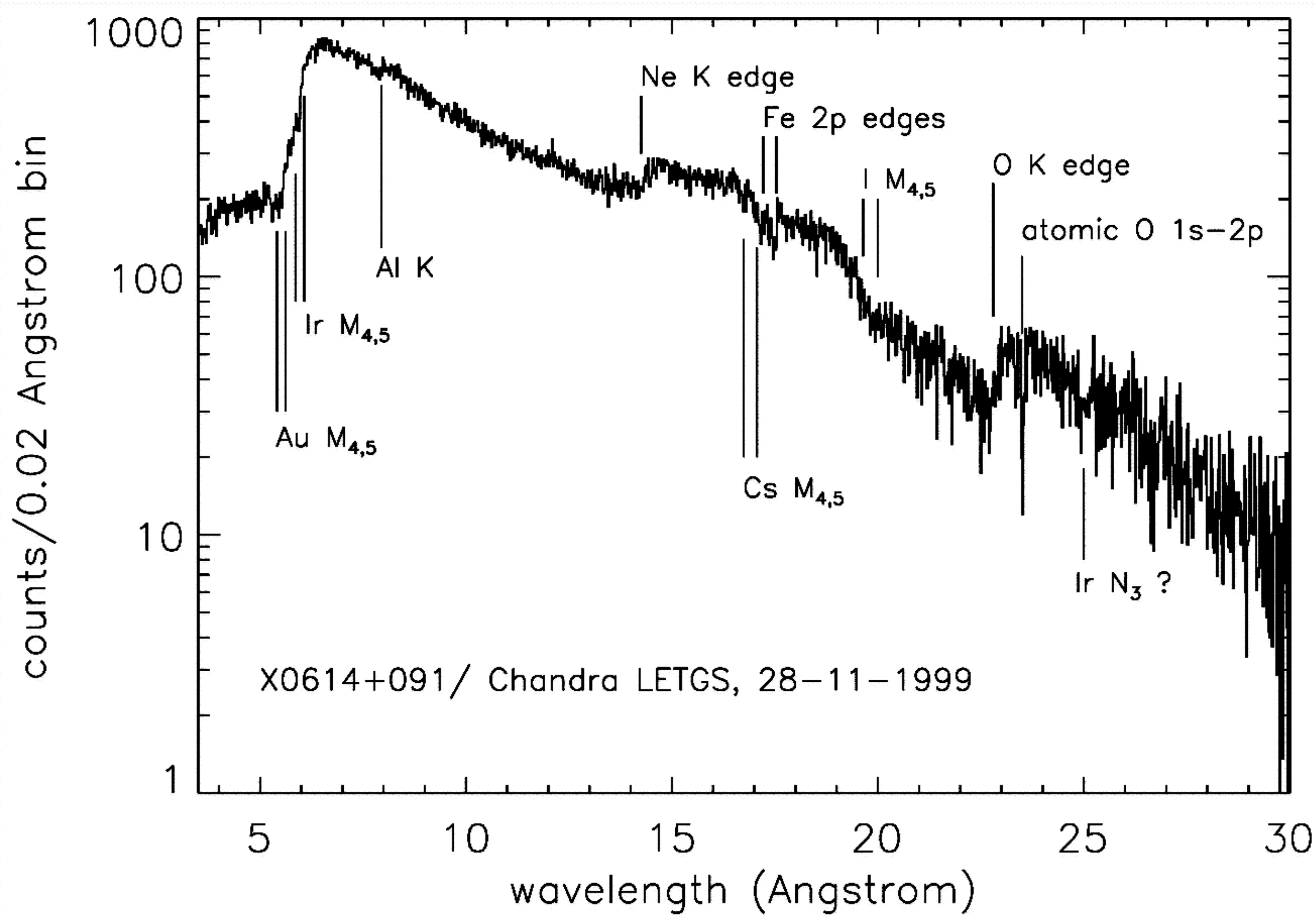


Diagram of LB from Cox & Reynolds (1990)

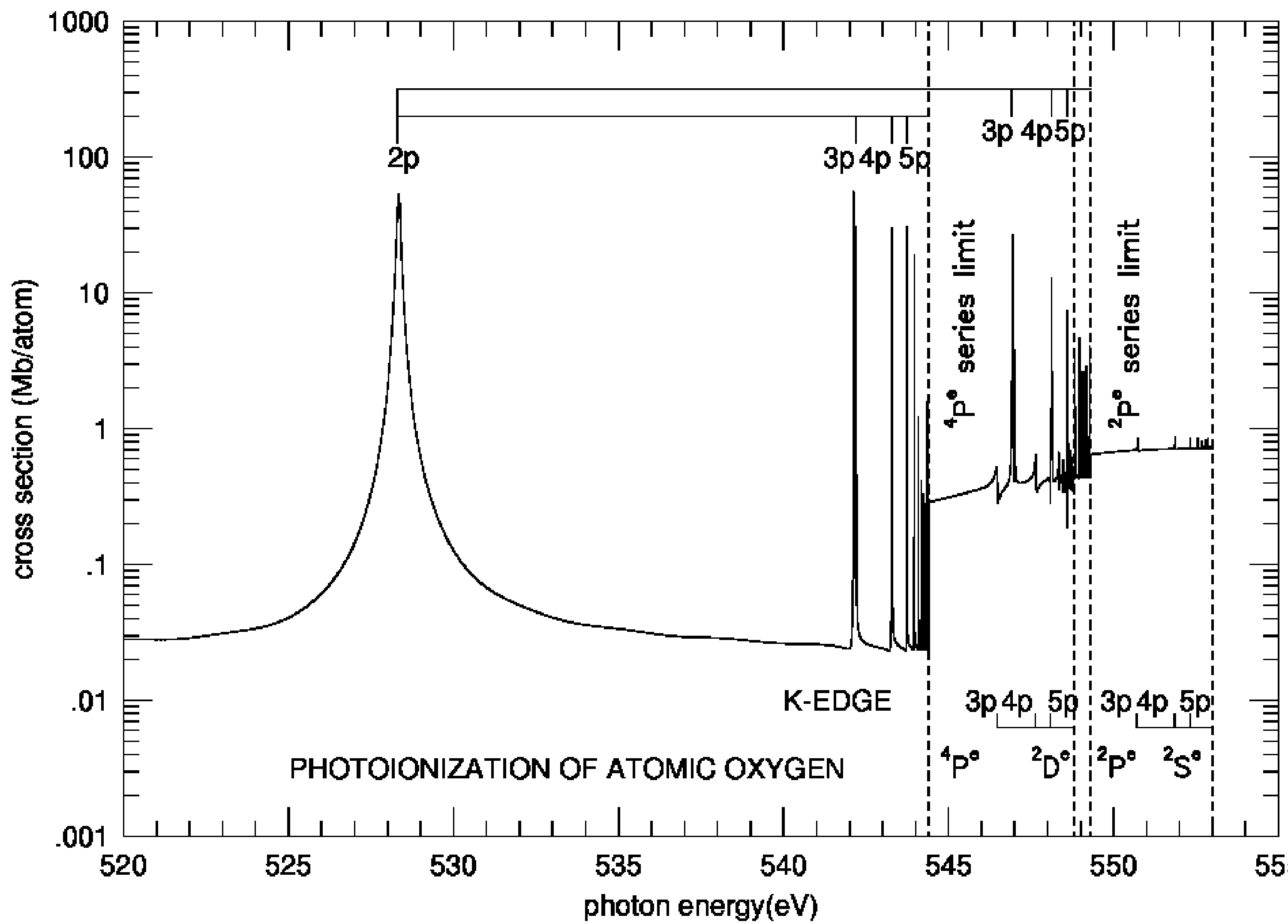
ISM: Absorption

All the phases of the ISM can be studied using absorption spectroscopy. Simply find a bright (ideally continuum) source, and look for absorption features:



LMXB X0614+091 observed with Chandra LETG by Paerels *et al.* 2001

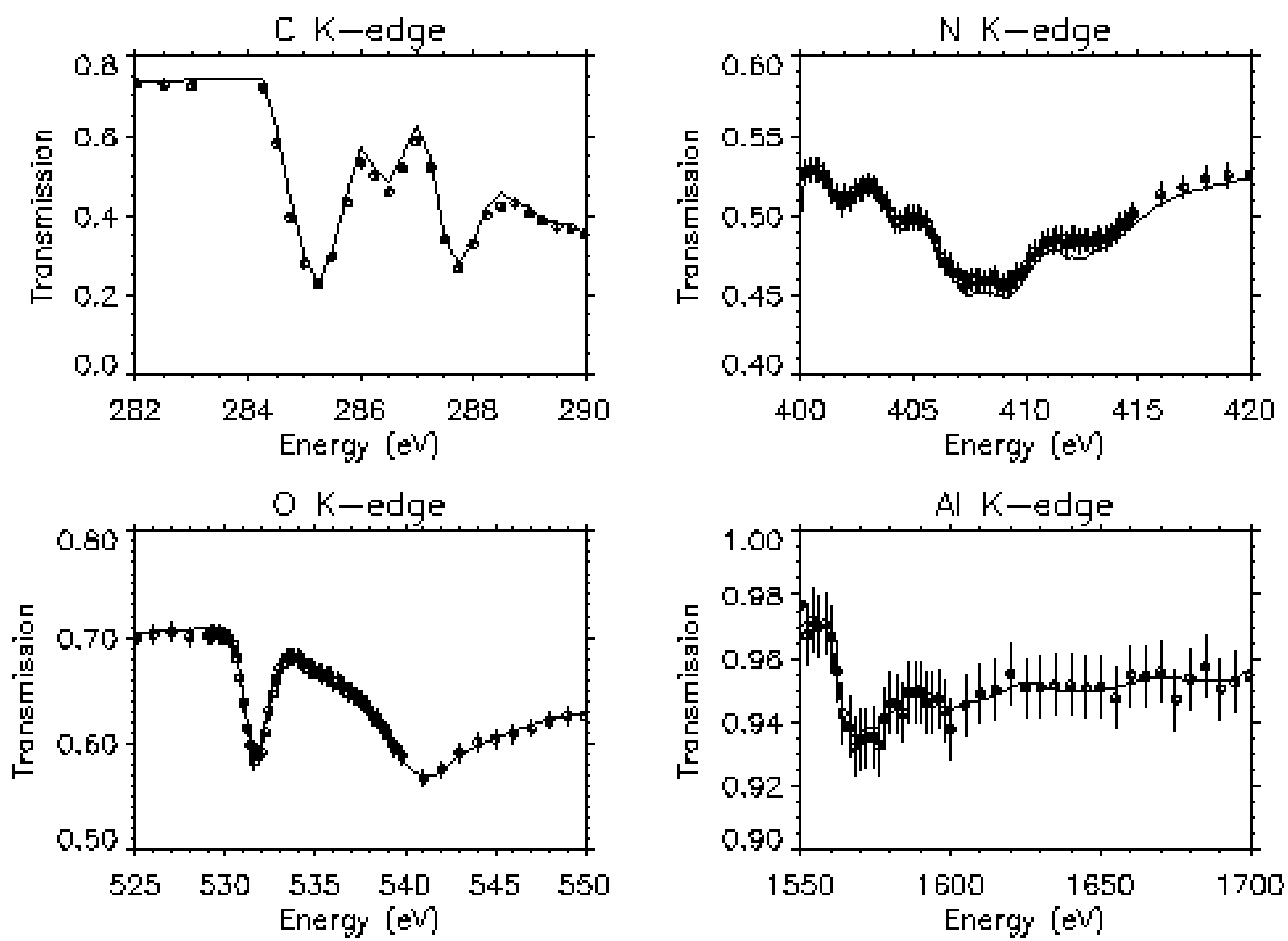
ISM: Absorption



McLaughlin & Kirby 1998

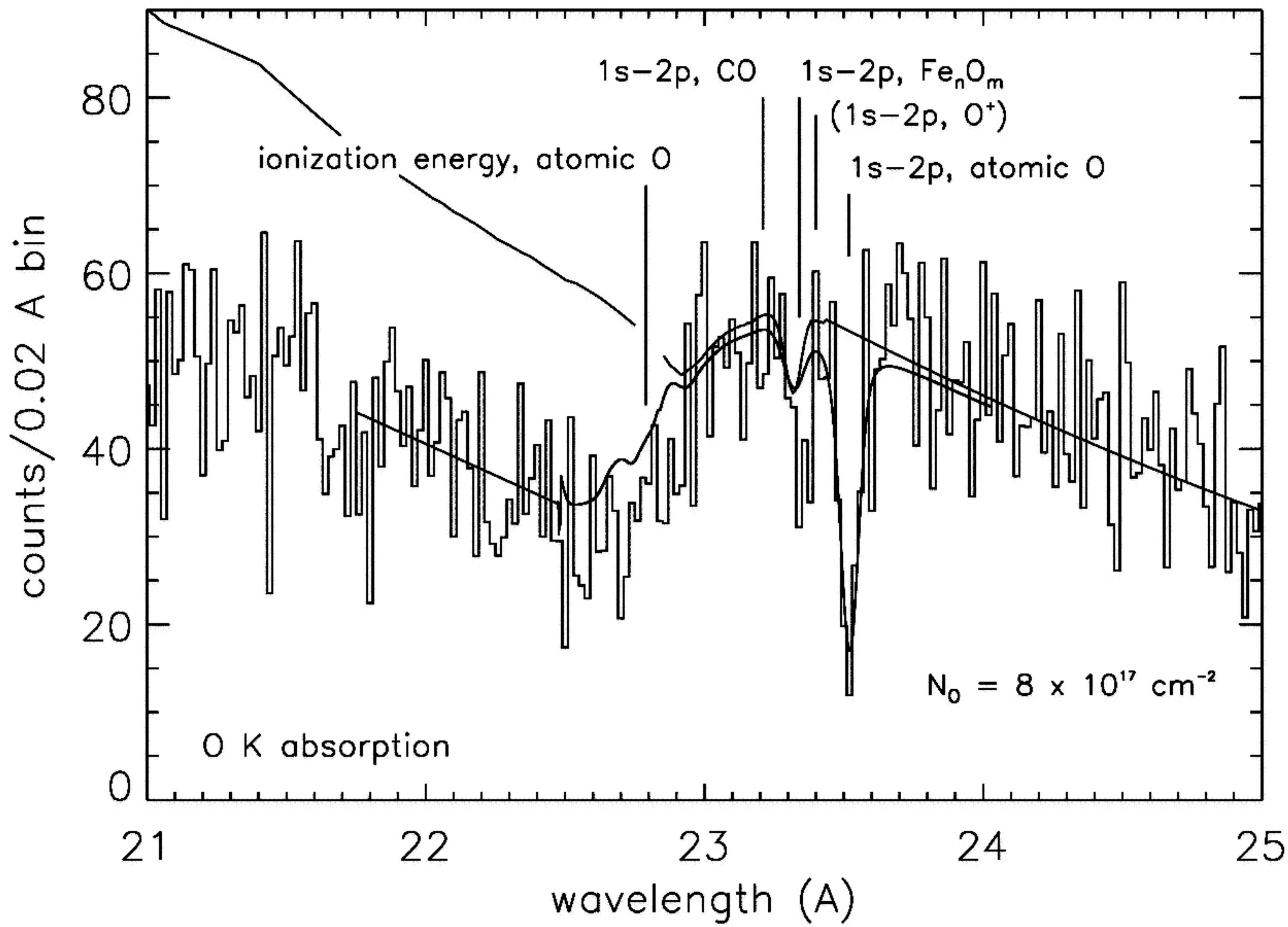
ISM: Absorption

Of course, one must also worry about calibration:



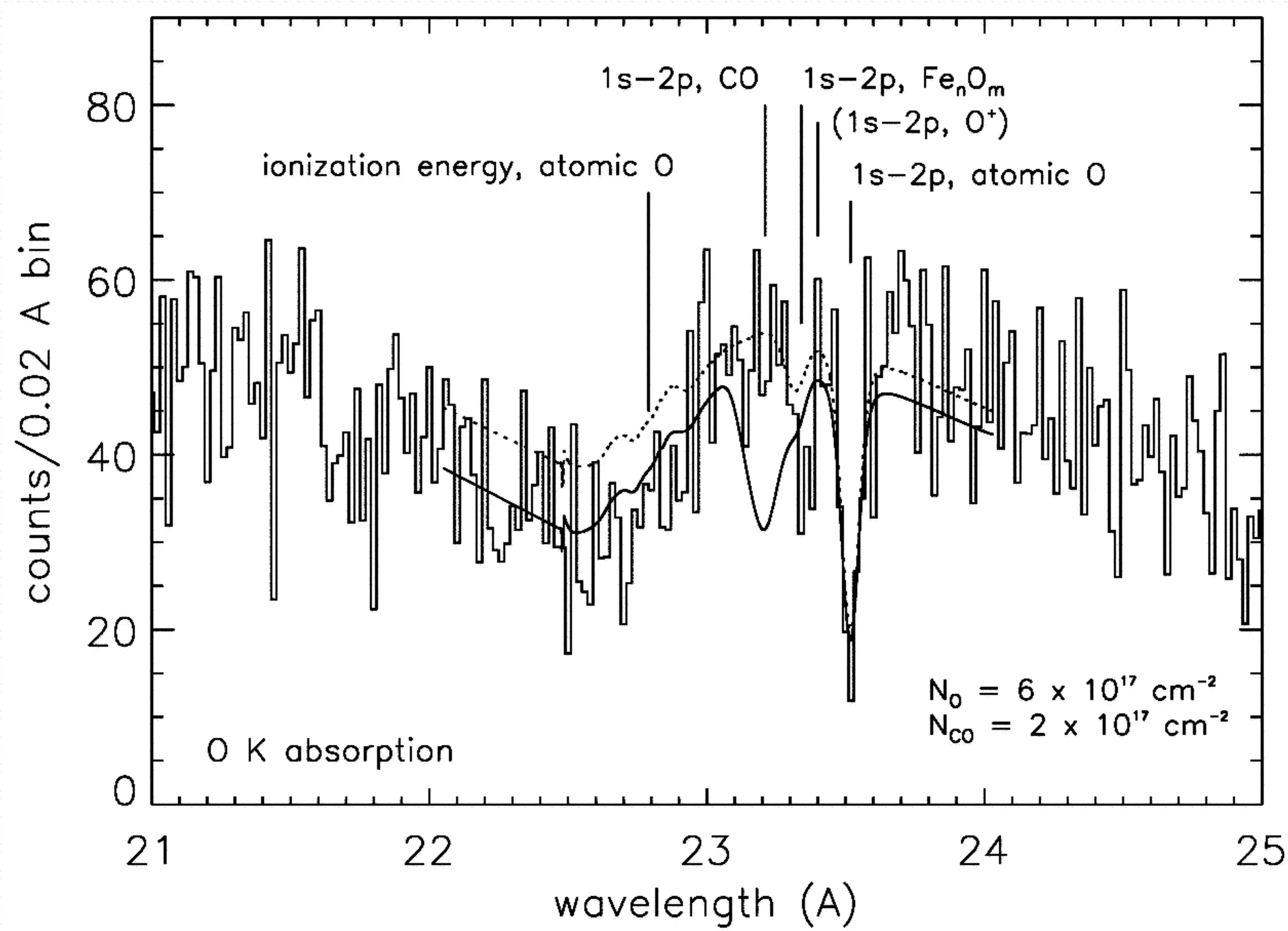
ISM: Absorption

However, good results are available:



ISM: Absorption

Clear limits can be placed on CO absorption:

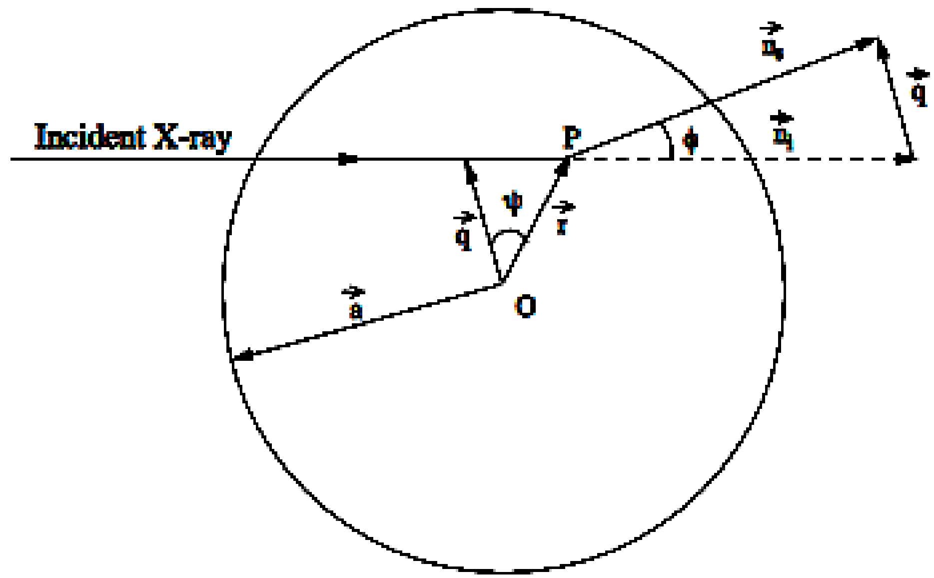


ISM: Dust Grains

The counterpart to absorption studies is normally emission (*e.g.* radio 21 cm/H). However, there is very little ISM gas with temperatures higher than 10^6 K, so neither Chandra nor XMM/Newton is much use.

Surprisingly, however, X-rays can also probe IS dust grains.

When an X-ray interacts with a dense cloud of electrons (such as are found in a dust grain), the electrons may vibrate coherently, scattering the X-ray slightly.



ISM: Dust Grains

The dust scattering cross section is

$$\left(\frac{d\sigma}{d\Omega}\right)(E, a, \phi) \approx 1.1\left(\frac{\rho}{3\ \mathrm{g\ cm^{-3}}}\right)^2 a_{\mu m}^6 E_{keV}^{-2} \exp\left(-\frac{\phi^2}{2\sigma^2}\right)\ \mathrm{cm^2\ sr^{-1}}$$

where $\sigma \approx 62.4'' E_{keV}^{-1} a_{\mu m}^{-1}$.

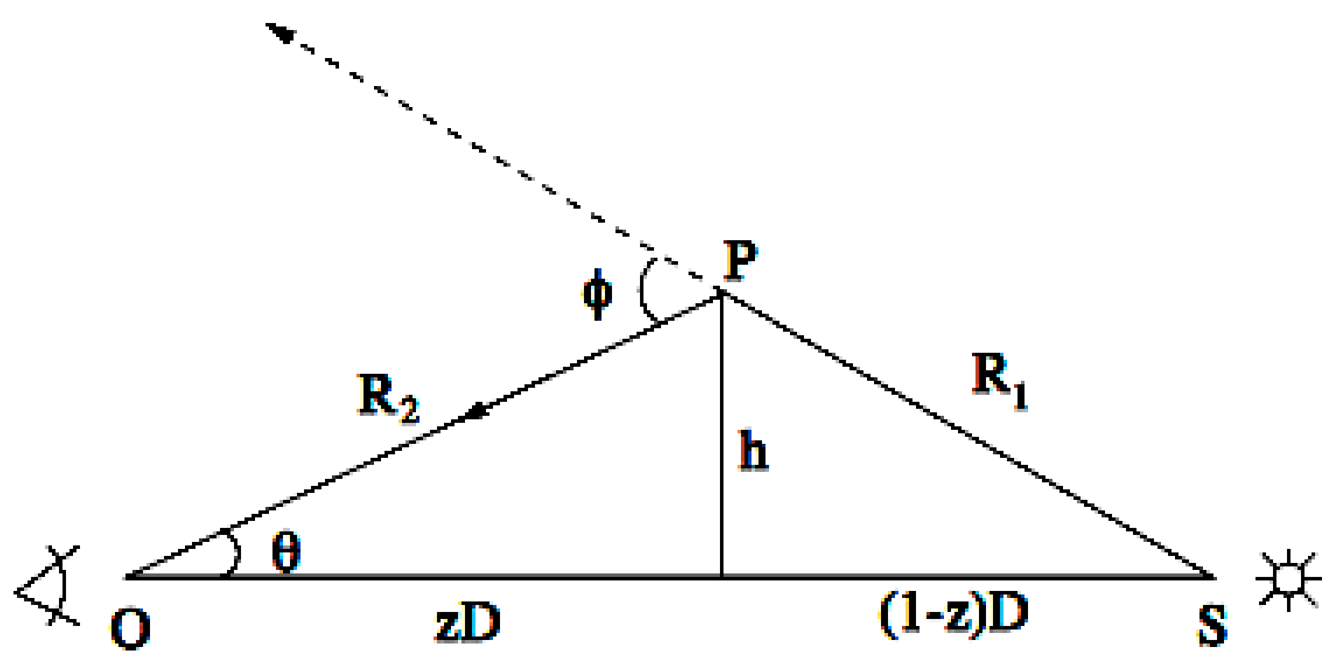
So what does this mean?

Of course, we don't observe single dust grains; we must integrate over a distribution of dust grains, and along the light of sight to a bright source.

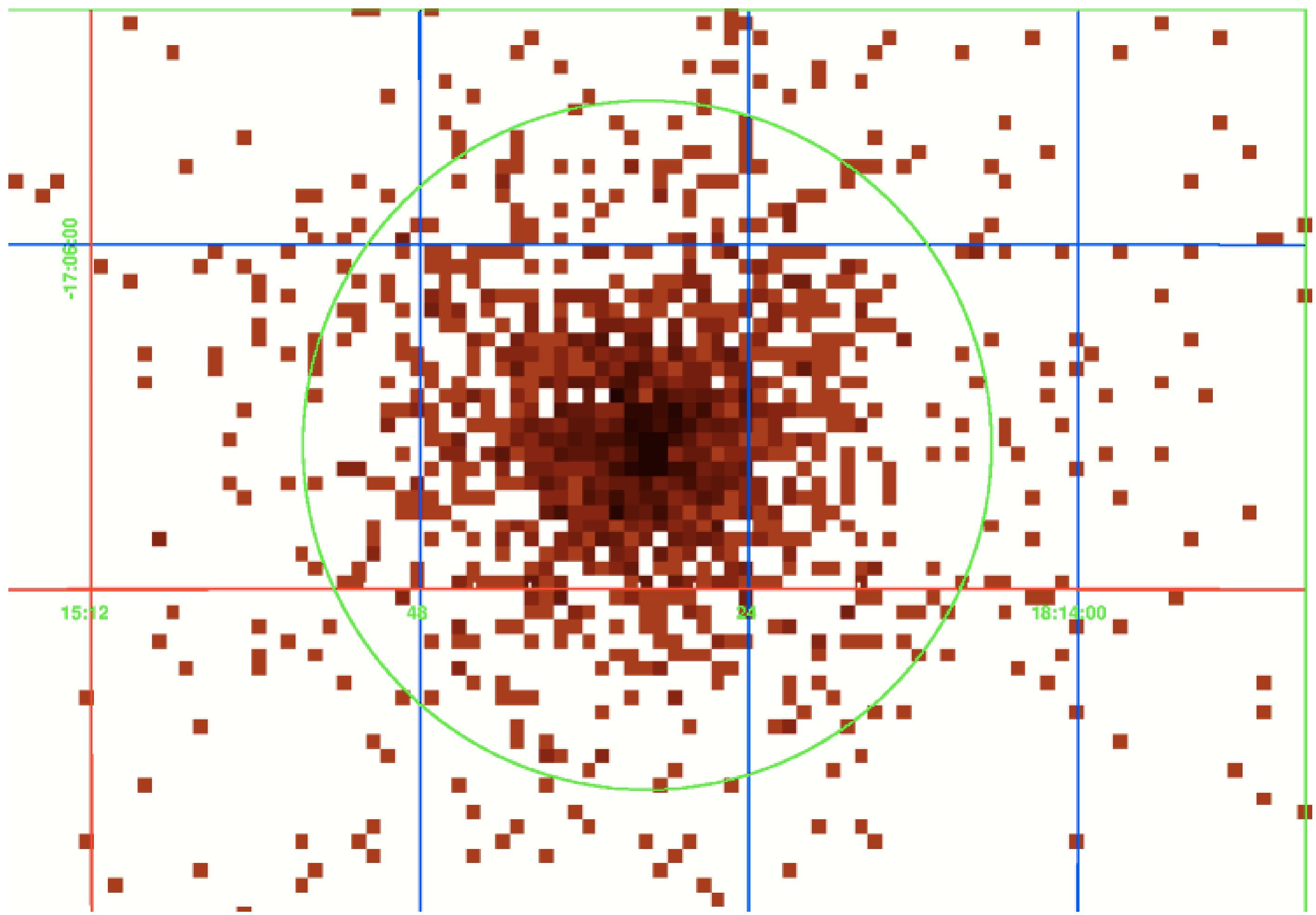
ISM: Dust Grains

So the observed surface brightness at position from the source is:

$$I_{sca}(\theta) = N_H F_X \int dE\, S(E) \int da\, n(a) \int \frac{f(z)}{(1-z)^2} \frac{d\sigma}{d\Omega}(E, a, \frac{\theta}{1-z}) dz$$

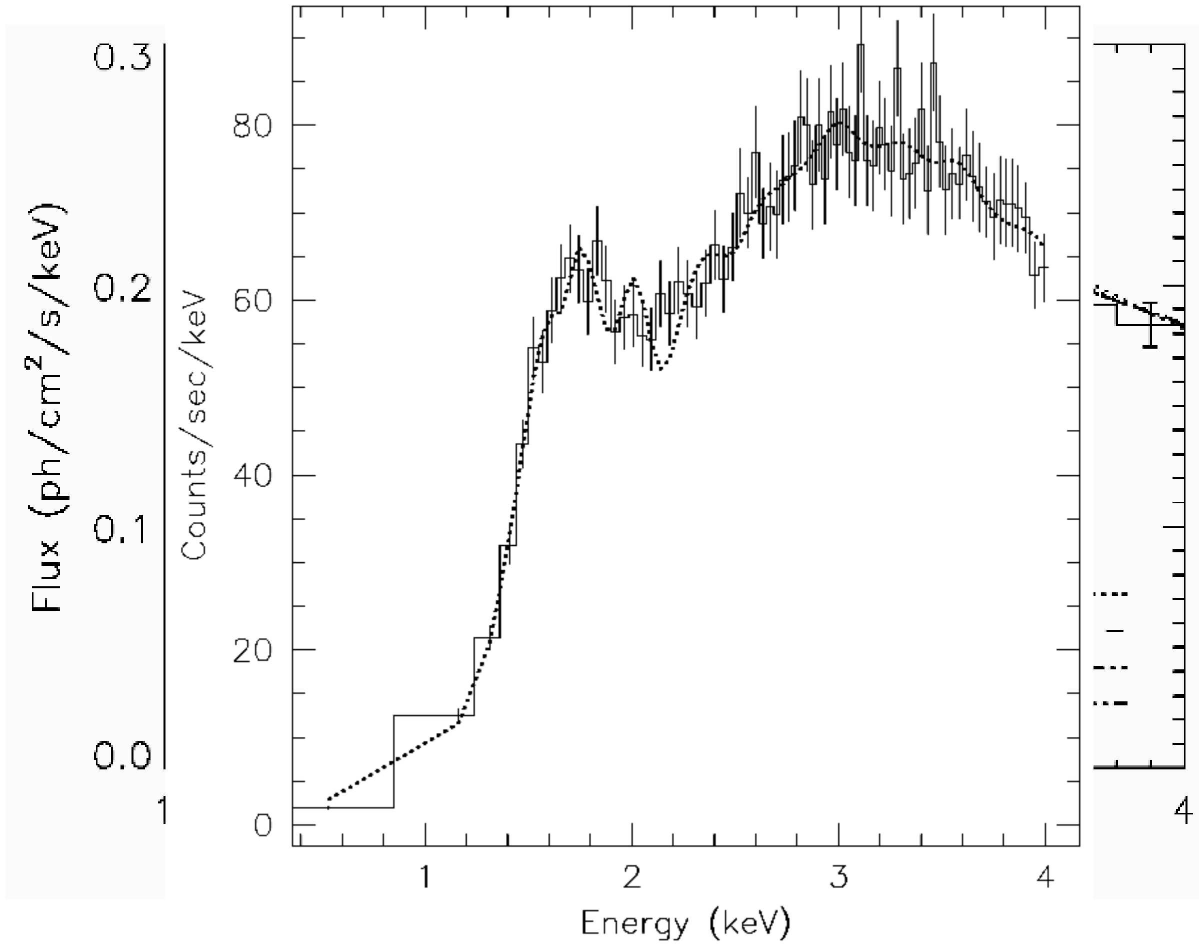


ISM: Dust Grains



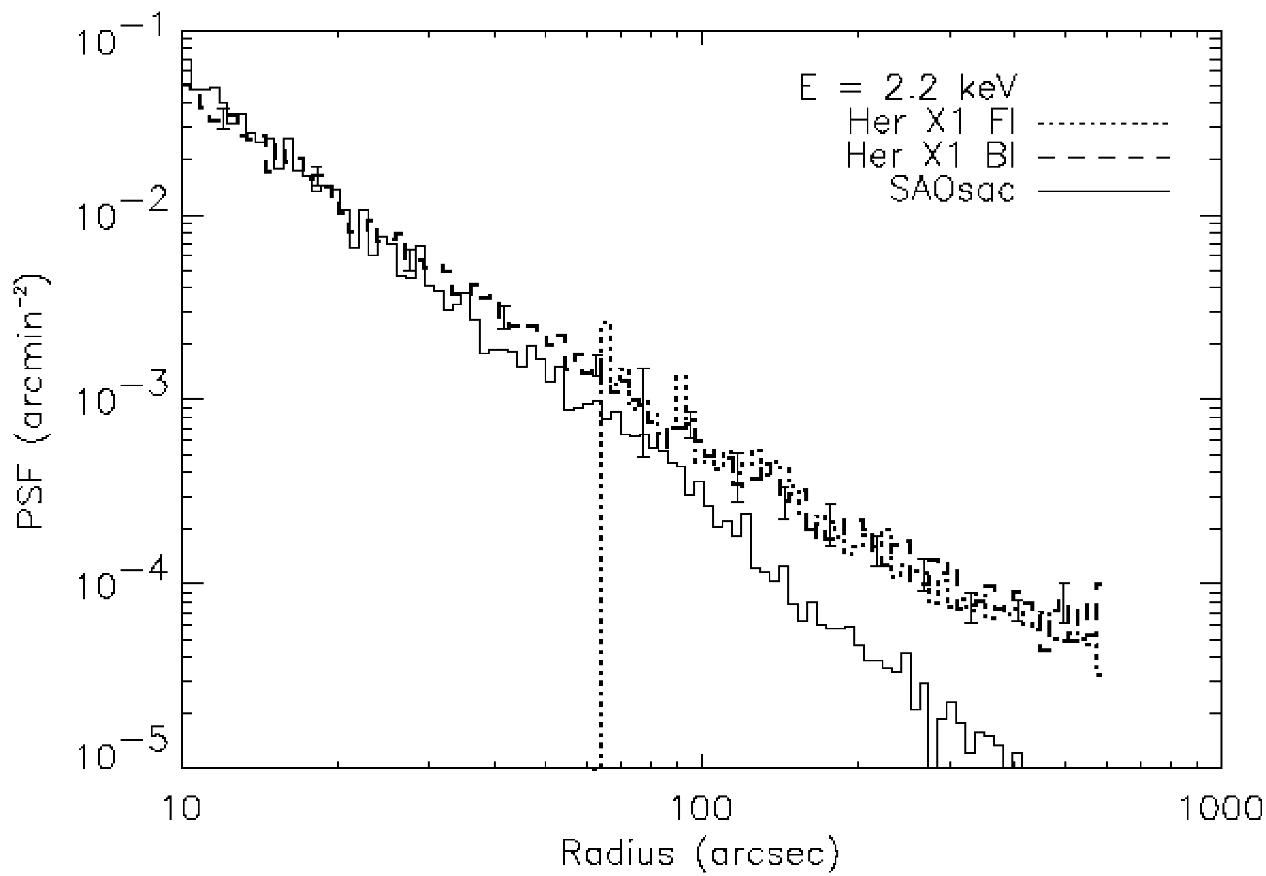
ISM: Dust Grains

In order to properly measure the halo, the spectrum must be measured:



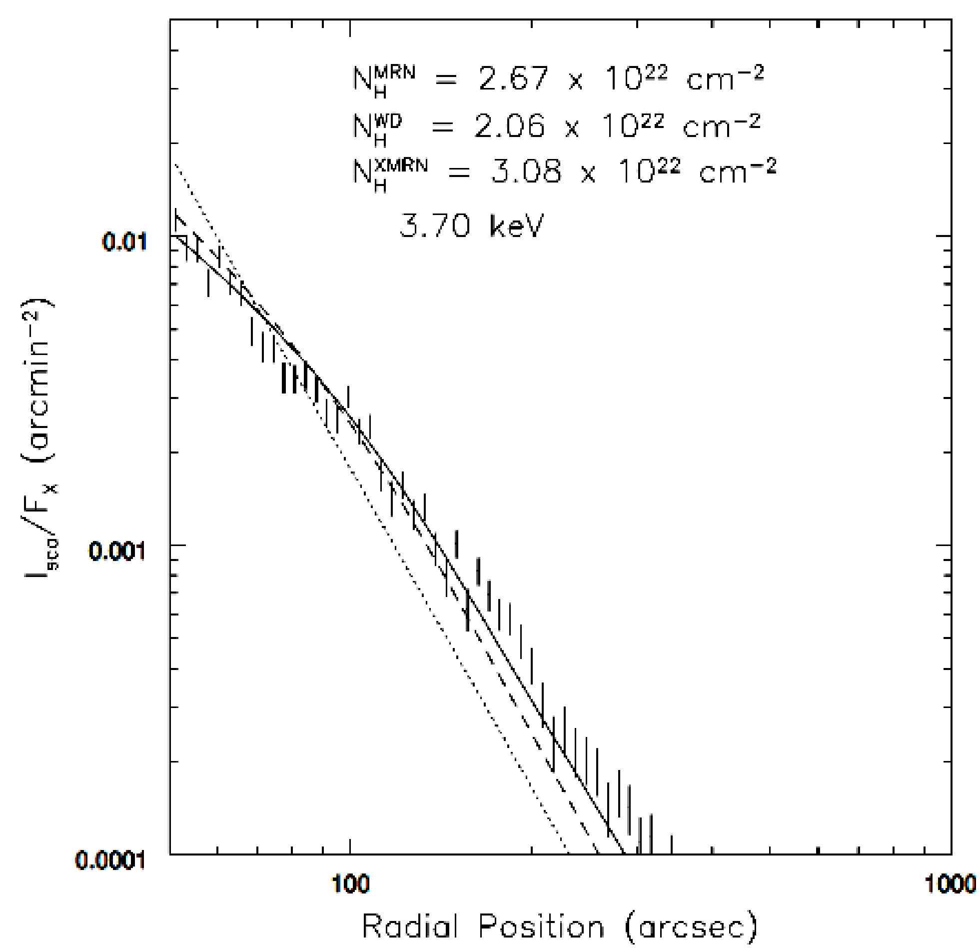
ISM: Dust Grains

In addition, we need to know the PSF of the telescope, as this must be subtracted to get the actual scattered halo:



ISM: Dust Grains

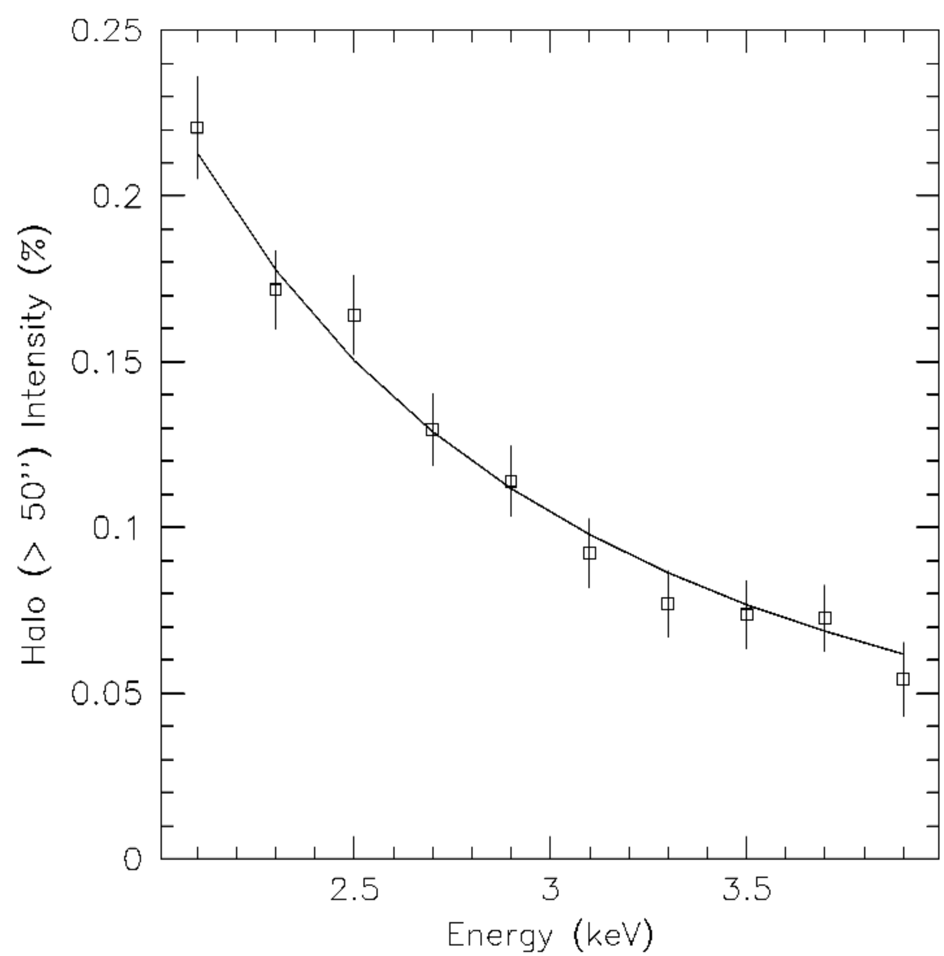
So here are some results from the LMXB GX13+1, at 3 different energies. The only free parameter is N_H.



Smith, Edgar, & Shafer (2001)

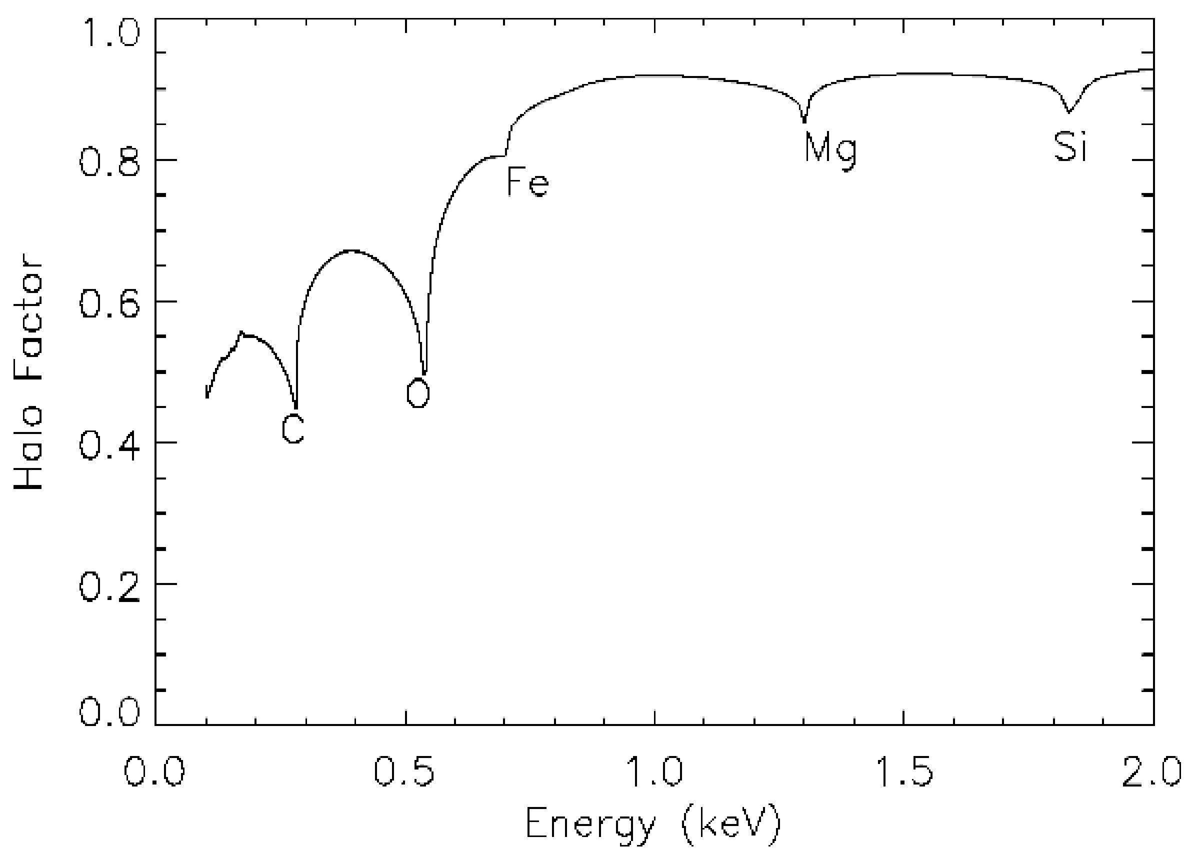
ISM: Dust Grains

Integrating the total surface brightness (relative to the source flux) gives a result proportional to E^{-2}. The constant term can be easily related to any dust model.



ISM: Dust Grains

What does the future hold? With sufficient energy resolution and effective area, it will be possible to diagnose dust abundances directly:



Conclusions

Studying the ISM in X-rays is a relatively new field.

- Detailed absorption studies can only be done with high-resolution telescopes. However, since X-rays penetrate all the way to the Galactic center, they open a new window on ISM studies.
- It is possible (albeit very difficult) to study the IGM as well with deep observations.
- Emission from the ISM in X-rays is dominated by very soft X-rays, mostly local.
- The study of IS dust grains, especially the largest dust grains, can be done in a unique way with X-rays.