Friedrich–Alexander–Universität
Erlangen–Nürnberg

X-Ray Astronomy II

Extragalactic X-Ray Astronomy

Jörn Wilms, Matthias Kadler

`http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/xray2/`

Wintersemester 2008/2009

Büro: Dr. Karl Remeis-Sternwarte, Bamberg
Tel.: (0951) 95222-13 / -26
Email: `{joern.wilms,matthias.kadler}@sternwarte.uni-erlangen.de`

Introduction

Schedule

X-Rays in the Galaxy		
13.10.	JW	Introduction, Interstellar Medium
20.10.		**– NO LECTURE –**
27.10.	MK	The Galactic Center / Antrittsvorlesung JW
03.11.	MK	Supernova Remnants, Nucleosynthesis
X-Rays from Normal Galaxies		
10.11.	JW	X-ray Populations in Galaxies
Supermassive Black Holes in Active Galaxies		
17.11.	JW	AGN Taxonomy, Seyfert Galaxies I
24.11.	JW	Seyfert Galaxies, II
01.12.	MK	Radio Galaxies and Blazars, I
08.12.	MK	Radio Galaxies and Blazars, II
Large Scale Structure and Cosmology		
15.12.	JW	Galaxy Clusters
22.12.	JW	γ-ray bursts
12.01.	MK	X-Ray Background and AGN Evolution, I
19.01.	MK	X-Ray Background and AGN Evolution, II
26.01.	JW	X-Ray Background and AGN Evolution, III
02.02.	JW	Summary

Literature

LONGAIR, M.S., 1992, *High Energy Astrophysics, Vol. 1: Particles, Photons, and their Detection*, Cambridge: Cambridge Univ. Press, ~50€

Good introduction to high energy astrophysics, the 1st volume deals extensively with high energy procsses, the 2nd with stars and the Galaxy. The announced 3rd volume has never appeared. Unfortunately, everything is in SI units.

TRÜMPER, J., HASINGER, G. (eds.), 2007, *The Universe in X-rays*, Heidelberg: Springer, 96.25€

Recent book giving an overview of X-ray astronomy written by a group of experts (mainly) from Max Planck Institut für extraterrestrische Physik, the central institute in this area in Germany.

BRADT, H., 2004, *Astronomy Methods: A Physical Approach to Astronomical Observations*, Cambridge: Cambridge Univ. Press, $50

Good general overview book on astronomical observations at all wavelengths.

Literature

CHARLES, P., SEWARD, F., 1995, *Exploring the X-ray Universe*, Cambridge: Cambridge Univ. Press, out of print

Summary of X-ray astronomy, roughly presenting the state of the early 1990s.

ASCHENBACH, B. et al., 1998, *The invisible sky*, New York: Copernicus

Popular “table top” book summarizing the results of the *ROSAT* satellite, with many beautiful pictures.

KROLIK, J., 1999, Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment, Princeton: Princeton Univ. Press, 632pp., $57.50

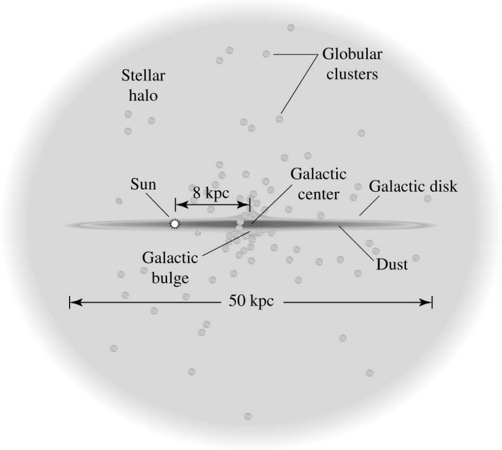
The most comprehensive textbook on AGN available, covers much more material than what is possible here.

KEMBHAVI, A.J. & NARLIKAR, J.V., 1999, Quasars and Active Galactic Nuclei: An Introduction, Cambridge: Cambridge Univ. Press, 476pp., $50

Graduate level textbook, similar to Krolik, but often explains things from a somewhat different point of view.

Interstellar Medium

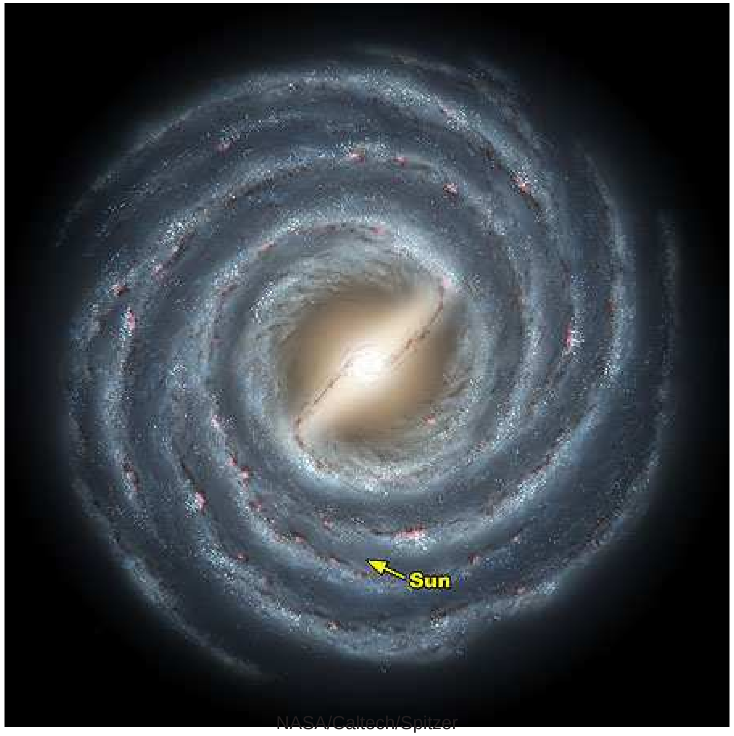
The Milky Way



Carroll & Ostlie, Fig. 24.6

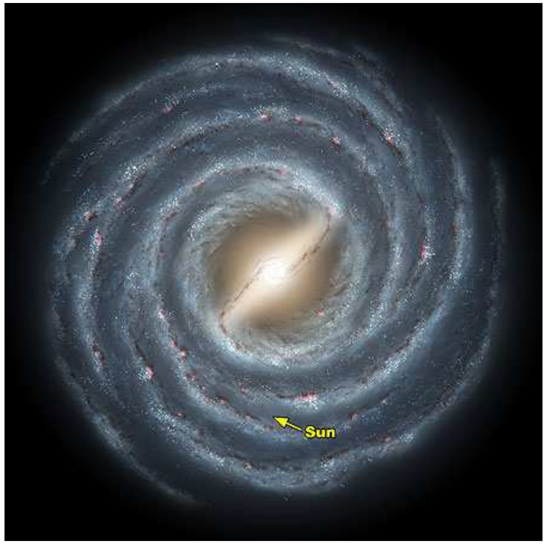
components of the Milky Way:

- Galactic disk:
  - rotating
  - young & old stars, open star clusters
  - gas & dust
- Galactic halo:
  - non-rotating,
  - old stars only, globular clusters
  - no gas, no dust
- Galactic bulge: rigid rotation



NASA/Caltech/Spitzer

The Milky Way



Milkyway is a barred spiral galaxy Luminosity:

$\sim 2 \times 10^{10}\, L_\odot$

Mass: $\sim 10^{11}\, M_\odot$ (radiating)

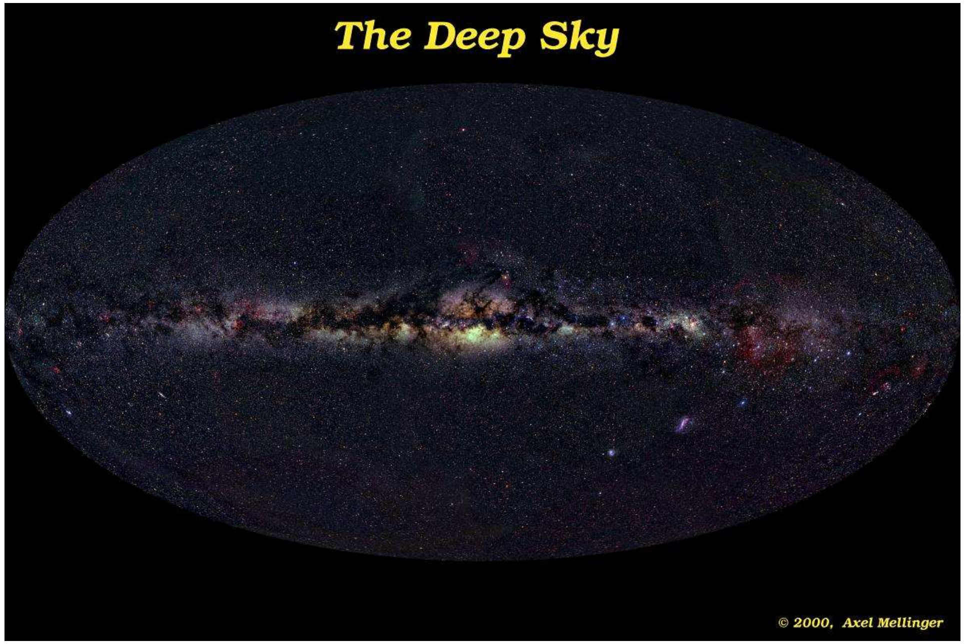
$\sim 10^{12}\, M_\odot$ (total)

Stellar density:

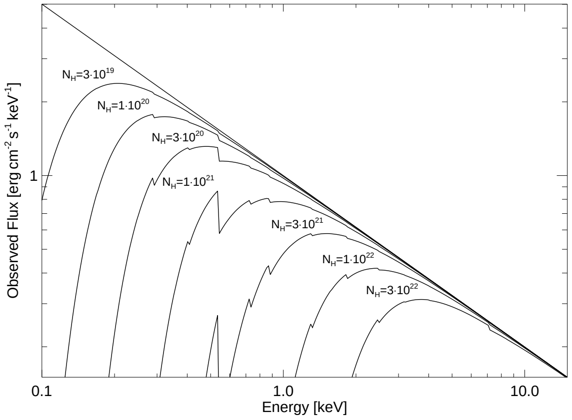
$\sim 0.3\, M_\odot\, \mathrm{pc}^{-3}$

$1\, M_\odot = 2 \times 10^{33}\,\mathrm{g} = 2 \times 10^{30}\,\mathrm{kg}$,

$1\, L_\odot = 4 \times 10^{33}\,\mathrm{erg\,s^{-1}} = 4 \times 10^{26}\,\mathrm{W}$



Absorption in the ISM



Interstellar Medium:

Gas and dust absorbs X-rays

Effect of intermediate medium of Hydrogen column density N_H on observed X-ray spectrum.

$$I_\mathrm{obs}(E) = \mathrm{e}^{-\sigma_\mathrm{ISM}(E)\, N_\mathrm{H}}\, I_\mathrm{src}(E) \quad (2.1)$$

where: N_H: Hydrogen column density (unit: H-atoms cm^{-2}):

$$N_\mathrm{H} = \int_0^d n_\mathrm{H}(\ell)\, d\ell \quad (2.2)$$

where n_H: Hydrogen density (H-atoms cm^{-3})

and where I_src: emitted X-ray spectrum, I_obs: observed X-ray spectrum

History

Papers:

Brown & Gould (1970): First real computations using o.k. cross sections.

Fireman (1974): Include effect of iron, first attempt to describe influence of dust.

Ride & Walker (1977): Dust and phases of ISM. Largely ignored.

Morrison & McCammon (1983): The *de facto* standard (XSPEC: original `model wabs` ...). No dust, fixed abundances.

Bałucińska-Church & McCammon (1992): Better cross sections, based on Henke et al. (1982), newer (and variable) abundances. No dust or molecules. (XSPEC: `model phabs` and `model wabs`...).

Wilms, Allen & McCray (2000): Updated cross sections, includes dust and molecules (XSPEC: `model tbabs` ...).

Absorption Cross Section

$\sigma_{\text{ISM}} =$ sum over contributions of astrophysically relevant elements:

$$\sigma_{\text{ISM}} = \sigma_{\text{gas}} + \sigma_{\text{grains}} + \sigma_{\text{molecules}} \tag{2.3}$$

Gas and Molecules:

$$\sigma_{\text{gas, molecules}} = \sum_{Z,I} A_Z \cdot a_{Z,I} \cdot (1 - \beta_{Z,I}) \cdot \sigma_{\text{bf}}(Z,I) \tag{2.4}$$

where: Z nuclear charge, I: ionization stage

A_Z abundance in number with respect to H

$a_{Z,I}$ ionization fraction

$\beta_{Z,I}$ depletion factor (amount of element in dust)

$\sigma_{\text{bf}}(Z,I)$ photoionization cross section

Dust:

$$\sigma_{\text{grains}} = \sum_{Z,I} A_Z \cdot \beta_{Z,I} f_{Z,I} \cdot \sigma_{\text{bf}}(Z,I) \tag{2.5}$$

where

$f_{Z,I}$: “self blanketing factor” (takes into account shielding of elements in dust grains)

Photoionization cross sections

In X-rays: photon energy $\gg$ binding energy of outer shell electrons

$\Longrightarrow$ relativistic QM effects become important.

X-rays absorbed in inner shells

$\Longrightarrow$ K- and L-shell absorption.

Result of approximate computations: For $E \gg E_{\text{thresh}}$:

$$\boxed{\sigma_{\text{bf}} \propto E^{-3.5}}$$

Experimental measurements are rare.

Compilations of cross sections:

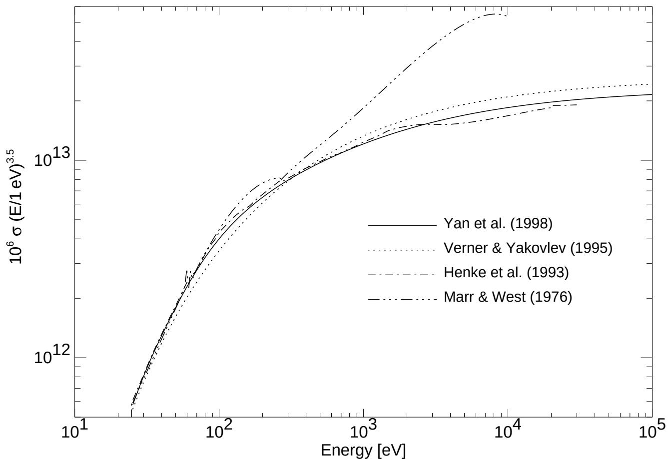
TOPBASE (Seaton et al.): no relativistic effects.

Henke tables (Henke et al., 1982; Henke, Gullikson & Davis, 1993): combination of experimental and theoretical data.

Verner data (Verner et al., 1993; Verner & Yakovlev, 1995): relativistic computations, edge energies adjusted to measured values.

EPDL 97 (Cullen, 1998): compilation of measured and theoretical data; falls under export restrictions (US law: International Traffic in Arms Regulations; ITAR)

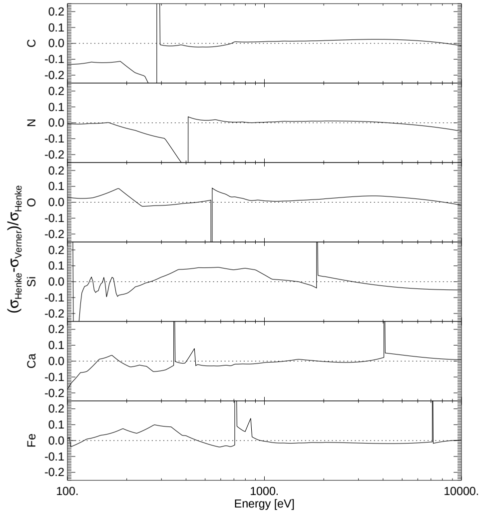
Photoionization cross sections: He



Comparison between four different theories for the He cross section.

For He: Adopt Yan, Sadeghpour & Dalgarno (1998) values.

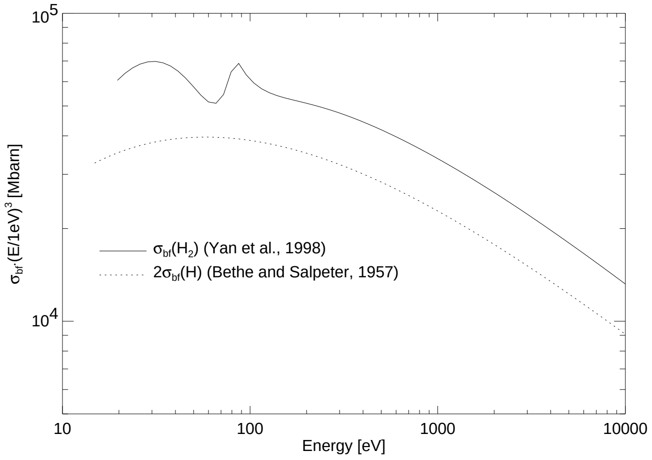
Photoionization cross sections: Metals



Comparison between measurements of Henke, Gullikson & Davis (1993) and theoretical calculations of Verner & Yakovlev (1995)

Currently best available cross sections: Verner & Yakovlev

Photoionization cross sections: H_2



Molecular effects contribute to absorption cross section:

$$\sigma_{\text{bf}}(\text{H}_2) \sim 2.85\sigma_{\text{bf}}(\text{H}) \qquad (2.6)$$

Comparison between classical H cross section and a modern computation of the H_2 cross section.

Abundances, I

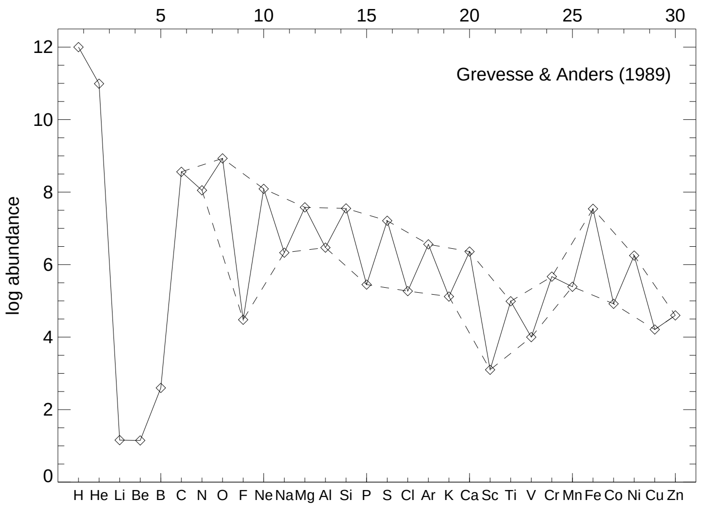
Basic paradigm during last 50 years of astronomy:
abundances are more or less identical throughout the universe.

$\Longrightarrow$ Measurement possible by looking at solar and meteoritic abundances (Anders & Grevesse, 1989).

Recent evidence, mainly from measurements in the UV: ISM abundances are subsolar, dependent on line of sight (Snow & Witt, 1995; Mathis, 1996).

All astronomical work needs the ability to change abundances relative to the adopted (solar) abundances.

Abundances, II

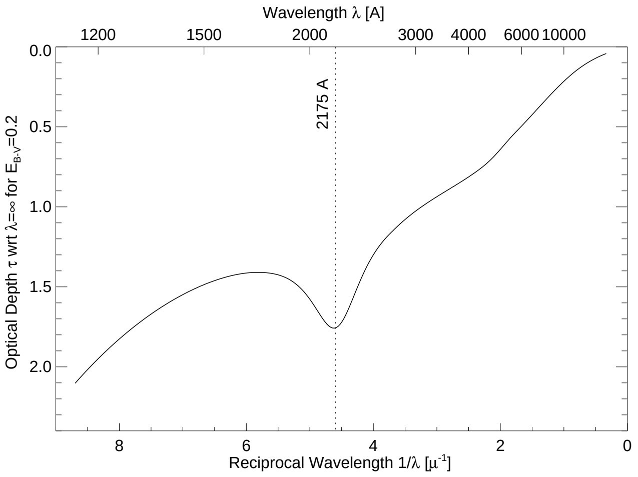


Odd-Even Z variability due to stability of nuclei with paired protons.

Horsehead Nebula in Orion (R. Steinberg/A. Block/NOAO/AURA/NSF)

Milky Way contains a lot of dust

Dust, II



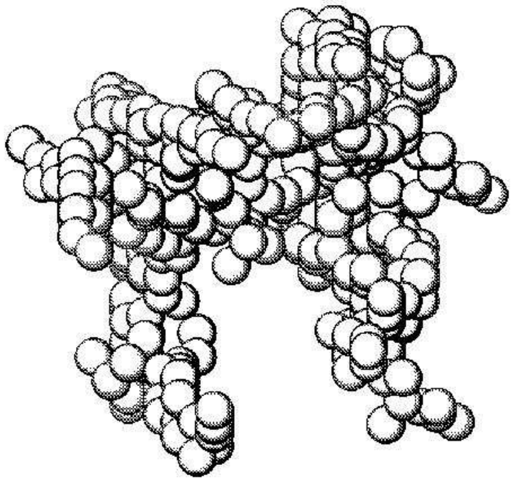
Interstellar reddening curve (Fitzpatrick, 1999).

Interstellar Reddening is λ-dependent: 2175 Å bump generally interpreted as evidence for absorption through dust.

Mathis, Rumpl & Nordsieck (1977, MRN): dust mainly graphite and silicate grains with a power law size distribution, $P(a) \propto a^{-3.5}$, radii ranging from 0.025 μm to 0.25 μm and density $\sim 1\,\mathrm{g\,cm^{-3}}$.

(similar to smoke from cigarettes)

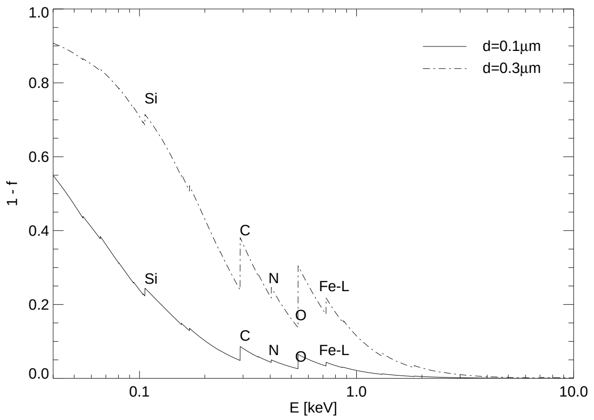
Dust, III



Observational evidence and theoretical motivation favor porous grains composed of silicates, graphite, and oxides (Mathis & Whiffen, 1989; Fogel & Leung, 1998)

$\Longrightarrow$ Density of grains is probably smaller than $1\,\mathrm{g\,cm^{-3}}$.

Effect of Grains on X-ray Absorption



Energy dependent shielding factor for grains of sizes 0.1 μm and 0.3 μm.

X-rays: Metals are "depleted" in grains

$\Longrightarrow$ less metals in gas phase.

Outer skin of grains absorbs most X-rays

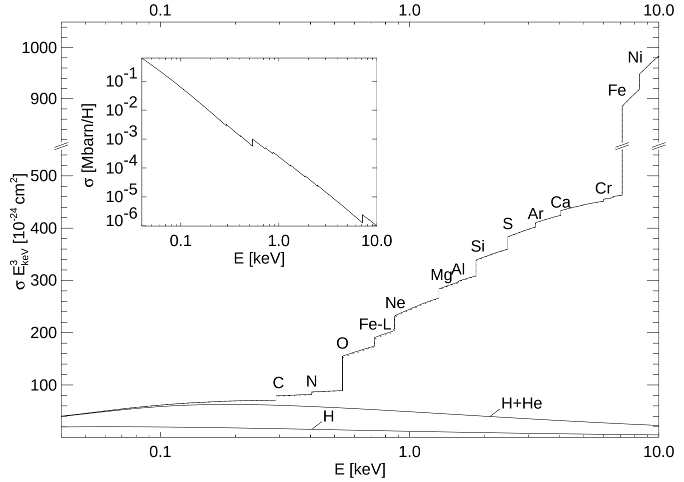
$\Longrightarrow$ we do not see atoms embedded in the inner part of grains

$\Longrightarrow$ "shielding"

Calculations show:

Grains do not have influence above $\sim$3 keV.

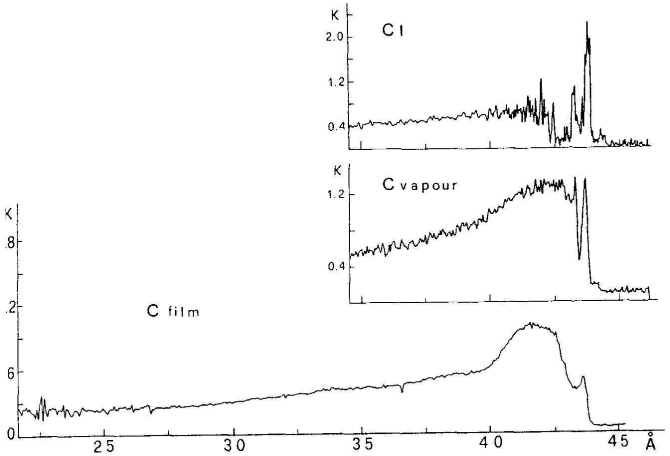
Result: Total Absorptivity



$\sigma_{\mathrm{ISM}} \cdot E^3$ as function of energy for pure gas and for gas with grains with MRN distribution.

Note comparably small influence of grains.

XAFS

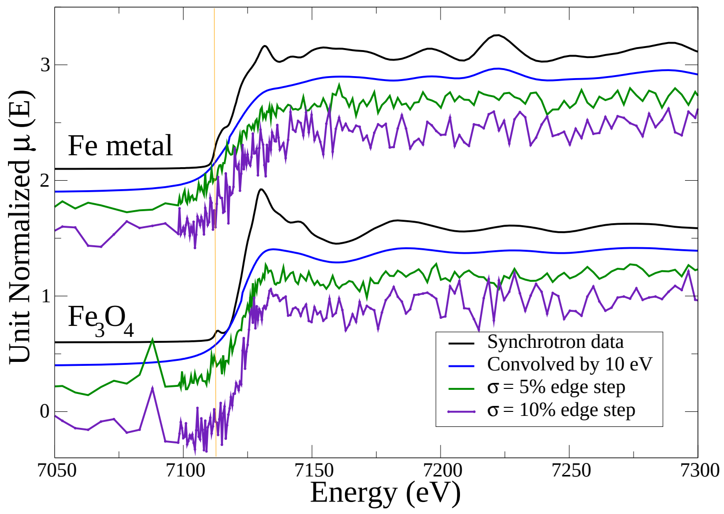


Nicolosi, Jannitti & Tondello (1991)

Around absorption edges: X-ray cross section is strongly influenced by environment of absorbing atom

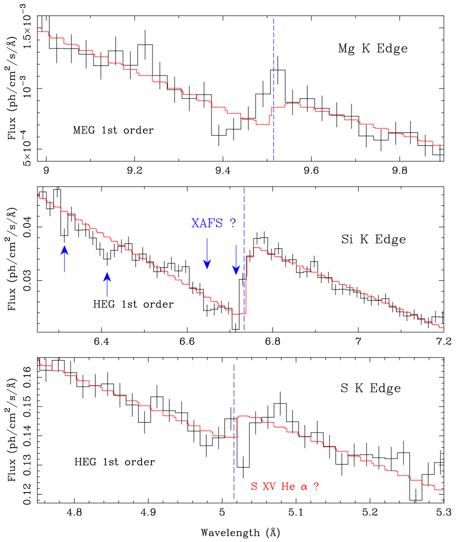
⟹ X-ray Absorption Fine Structure (XAFS)

XAFS



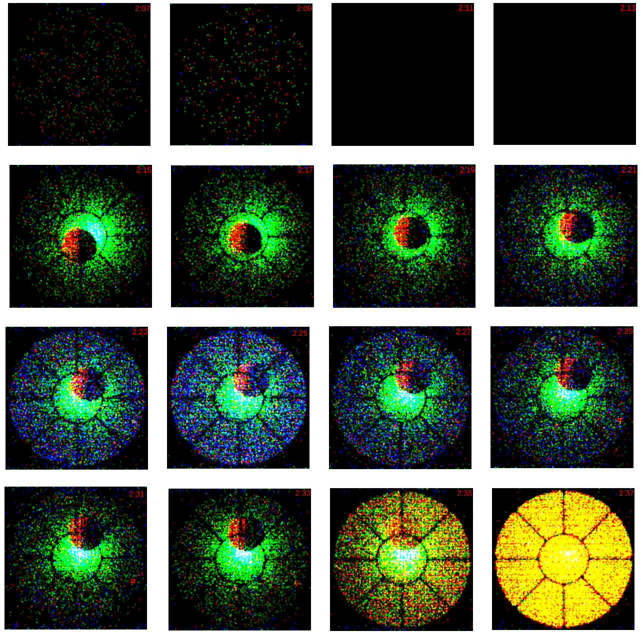
Absorptivity of metallic Fe and of rust (Lee & Ravel, 2005)

XAFS



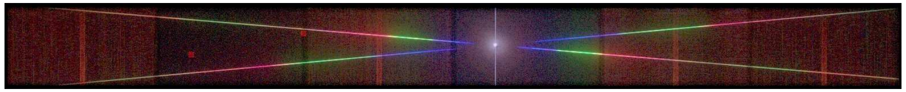
Possibly XAFS has already been detected with the *Chandra*-HETGS in the Black Hole Candidate GRS 1915+105

(Lee et al., 2002, Fig. 2)

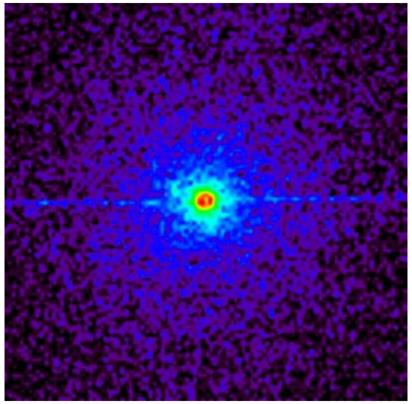


1998 Feb 20: *ROSAT* observation of lunar occultation of Sco X-1
⟹ X-ray dust scattering halo

Dust Scattering Halos, II



(Cyg X-1, *Chandra*-HETGS; Hanke et al., 2008)



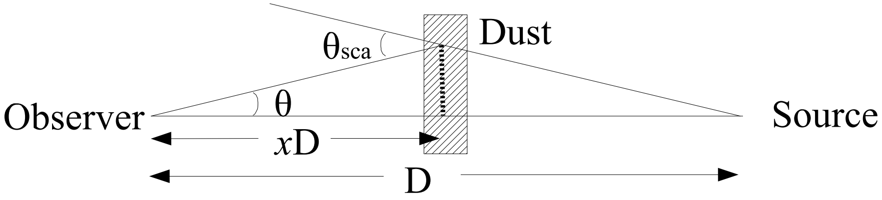
Because of dust scattering, X-ray point sources at larger N_H do not appear point-like

$\Longrightarrow$ X-ray Scattering Halos

(Trümper & Schönfelder, 1973; Predehl & Schmitt, 1995; Predehl & Klose, 1995)

Cyg X-3 (*Chandra*-HETGS)

Dust Scattering Halos, III



(Xiang, Lee & Nowak, 2007, Fig. 1)

Rayleigh-Gans approximation gives scattering cross section:

$$\frac{d\sigma_{\mathrm{sca}}(a,E,\theta_{\mathrm{sca}})}{d\Omega} \sim \exp\left(-0.46E^2a^2\frac{\theta^2}{(1-x)^2}\right) \tag{2.7}$$

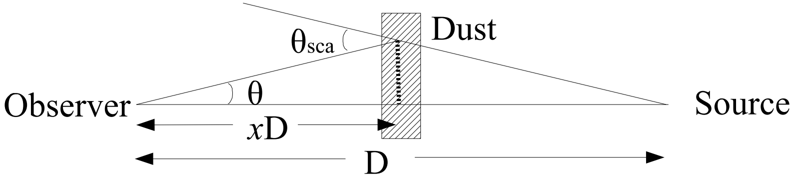
θ in arcmin, a in μm, E in keV; see Predehl et al. (2000) and Xiang, Lee & Nowak (2007)

Total scattering cross section:

$$\sigma_{\mathrm{sca}} \sim E^{-2} \tag{2.8}$$

$\Longrightarrow$ Scattering halos are soft

Geometrical Distance Estimation



(Xiang, Lee & Nowak, 2007, Fig. 1)

Typical scattering angle (from $d\sigma/d\Omega$):

$$\theta_{\mathrm{sca}} = \frac{\lambda}{\pi}a \propto E^{-1} \tag{2.9}$$

Small angle approximation gives size of halo (note $\theta_{\mathrm{sca}} = \theta + \alpha$):

$$\theta = (1-x)\theta_{\mathrm{sca}} \tag{2.10}$$

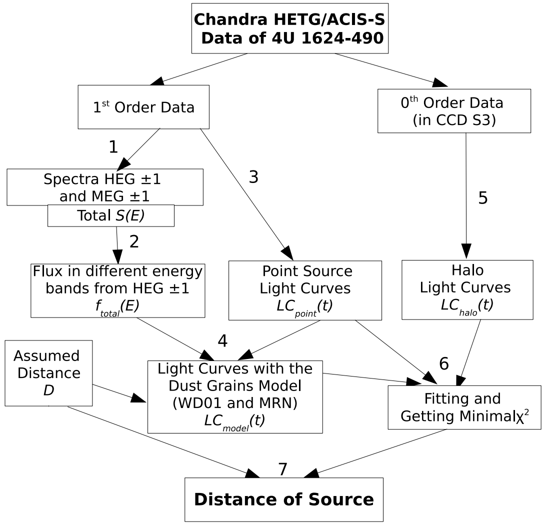
Time delay:

$$c\Delta t = \frac{x\theta^2}{1-x}D \quad\Longrightarrow\quad \Delta t = 1.15\,\mathrm{h}\cdot\frac{D}{1\,\mathrm{kpc}}\left(\frac{\theta}{1\,\mathrm{arcmin}}\right)^2\frac{x}{1-x} \tag{2.11}$$

$\Longrightarrow$ Time delay measurement gives D!
First used by Predehl et al. (2000): distance of Cyg X-3 is ~9 kpc

---

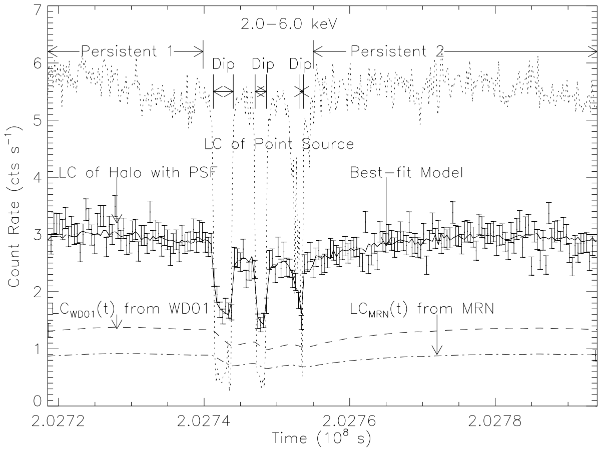
Geometrical Distance Estimation



Practical measurement of D is complicated because of cross-talk between source variability and halo variability, because of point spread function of telescope mirrors.

(Xiang, Lee & Nowak, 2007, Fig. 2)

Geometrical Distance Estimation



(Xiang, Lee & Nowak, 2007, Fig. 4)

For 4U1624−490: Delay Halo vs. Source is 1.6 ksec

Anders, E., & Grevesse, N., 1989, Geochim. Cosmochim. Acta, 53, 197

Bałucińska-Church, M., & McCammon, D., 1992, ApJ, 400, 699

Brown, R. L., & Gould, R. J., 1970, Phys. Rev. D, 1, 2252

Cullen, D. E., 1998, Photon and Electron Data for Use in Accelerator Applications, UCRL-JC 133079, LLNL)

Fireman, E. L., 1974, ApJ, 187, 57

Fitzpatrick, E. L., 1999, PASP, 111, 63

Fogel, M. E., & Leung, C. M., 1998, ApJ, 501, 175

Hanke, M., Wilms, J., Nowak, M. A., Pottschmidt, K., & Lee, J. C., 2008, ApJ, in press

Henke, B. L., Gullikson, E. M., & Davis, J. C., 1993, Atomic Data Nucl. Data Tables, 54, 181, available at `http://cindy.lbl.gov/optical_constants/`

Henke, B. L., Lee, P., Tanaka, T. J., Shimabukuro, R. L., & Fujikawa, B. K., 1982, Atomic Data Nucl. Data Tables, 27, 1

Lee, J. C., & Ravel, B., 2005, ApJ, 622, 970

Lee, J. C., Reynolds, C. S., Remillard, R., Schulz, N. S., Blackman, E. G., & Fabian, A. C., 2002, ApJ, 567, 1102

Mathis, J. S., 1996, ApJ, 472, 643

Mathis, J. S., Rumpl, W., & Nordsieck, K. H., 1977, ApJ, 217, 425

Mathis, J. S., & Whiffen, G., 1989, ApJ, 341, 808

Morrison, R., & McCammon, D., 1983, ApJ, 270, 119

Nicolosi, F., Jannitti, E., & Tondello, G., 1991, J. Physique IV, C1, 89

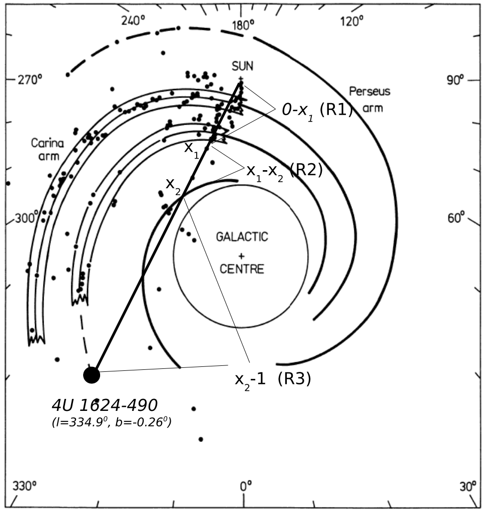
Predehl, P., Burwitz, V., Paerels, F., & Trümper, J., 2000, A&A, 357, L25

Predehl, P., & Klose, S., 1995, A&A, 306, 283

Predehl, P., & Schmitt, J. H. M. M., 1995, A&A, 293, 889

Ride, S. K., & Walker, Jr., A. B. C., 1977, A&A, 61, 339

Geometrical Distance Estimation



4U1624−490 has distance of $10.2^{+2.4}_{-1.4}$ kpc (assuming MRN and $a_{\rm max} = 0.25\,\mu$m)

(Xiang, Lee & Nowak, 2007, Fig. 8)

Snow, T. P., & Witt, A. N., 1995, Sci, 270, 1455

Trümper, J., & Schönfelder, V., 1973, A&A, 25, 445

Verner, D. A., & Yakovlev, D. G., 1995, A&AS, 109, 125

Verner, D. A., Yakovlev, D. G., Band, I. M., & Trzhaskovskaya, M. B., 1993, Atomic Data Nucl. Data Tables, 55, 233

Wilms, J., Allen, A., & McCray, R., 2000, ApJ, 542, 914

Xiang, J., Lee, J. C., & Nowak, M. A., 2007, ApJ, 660, 1309

Yan, M., Sadeghpour, H. R., & Dalgarno, A., 1998, ApJ, 496, 1044