Solid state astrophysics using the techniques of X-ray Absorption Spectroscopy

Bruce Ravel
Biosciences Division
Argonne National Laboratory

Julia C. Lee
Center for Astrophysics
Harvard University

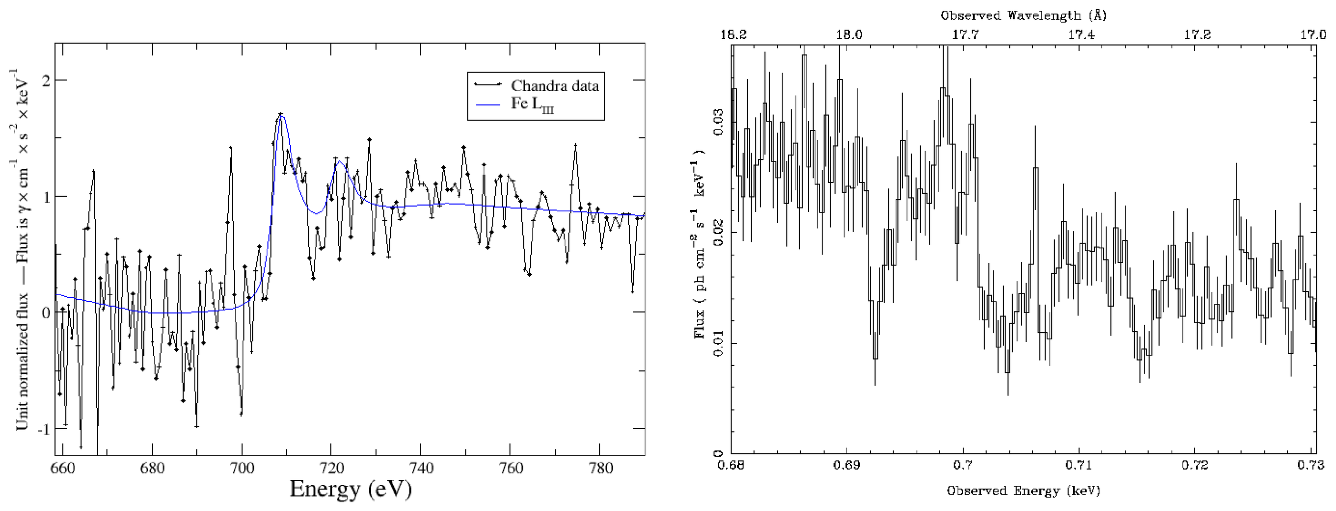
Abstract

The compositional make-up of interstellar dust and relative abundances of chemical elements in astrophysical environments are not well understood. Since dust is a primary repository of the interstellar medium and responsible for the chemical evolution of stars, planets and life, it has a profound effect on many areas of astrophysical research from cosmology to star and planet formation. To date, astrophysical studies of dust fall to wavebands other then X-rays, with a strong concentration in the IR where polyaromatic hydrocarbons (PAHs), graphites and certain silicates can be probed. These however, account for less than 5 percent of the interstellar dust. The X-ray space mission Chandra with spectroscopic capabilities of $dE/E \approx 10^3$ and an energy range of about 400 - 10,000 eV may allow a more direct probe of astrophysical dust through application of solid state techniques to astrophysical environments. From the perspective of the synchrotron spectroscopist, this work involves the use of an improbable and highly imperfect "beam line". The source is a bright astrophysical compact object such as a black hole, a neutron star, or a pulsar system. The transmission detector is a grating flying on a satellite orbiting the earth. The sample – optically thick absorbing clouds in interstellar space – is ill-characterized and dispersed over astronomical distances. Worse yet, the measurement is severely count rate limited. In this poster, we show data from the Chandra X-Ray Observatory and discuss certain features of the measured spectrum in the context of X-ray absorption spectroscopy. We then discuss the requirements needed of future satellite observatories to make feasible the application of methods developed for synchrotron X-ray absorption spectroscopy to observational, space-based X-ray data.

Data from Chandra

The left is a snippet of the 120 kiloseconds (about 1¼ days) of continuous observation of the supermassive (~10^6 – 10^7 solar mass) black hole MCG-6-30-15 at ~110 million light years. The signal around the Fe L3,2 edges just above 700 eV is plotted with an artificially broadened iron foil spectrum. Each point represents about 25 counts. The right is a subsequent 540 kilosecond (about 6¼ days) observation of MCG-6-30-15. Each point represents about 120 counts.

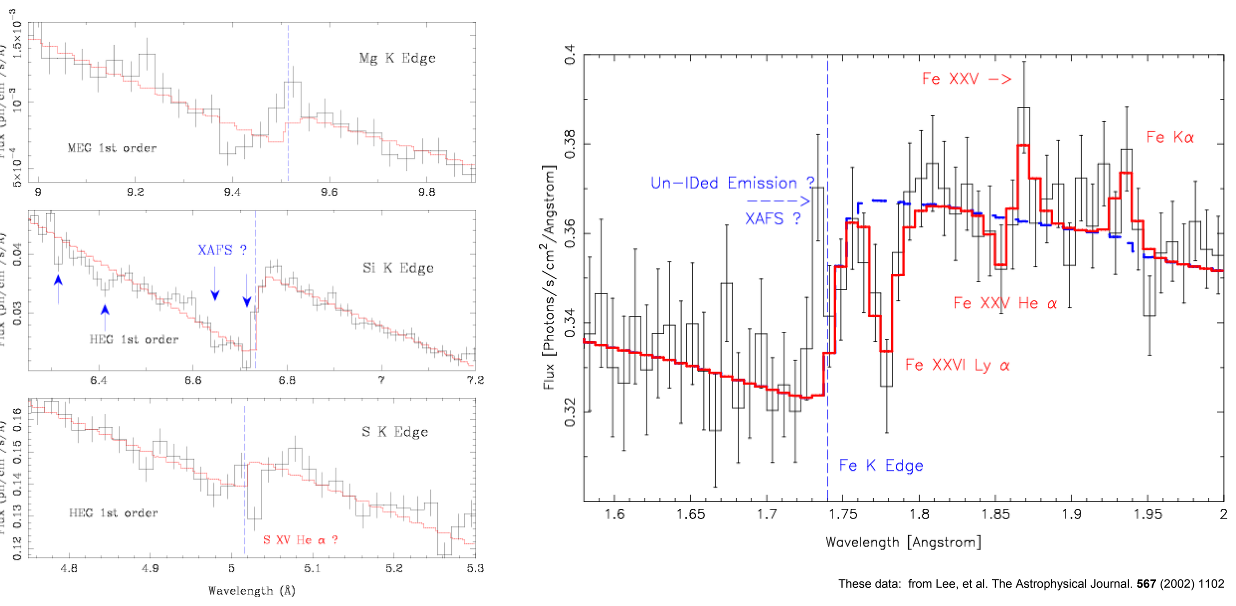
This makes a 10 ppm environmental sample seem positively chock-full of signal!



Fe data from Kortright&Kim Phys. Rev. B62 (2000) 12216
Lee, et al. The Astrophysical Journal. 554 (2001) L13

These data from Lee et al, The Astrophysical Journal, to be published

More data from Chandra



These data: from Lee et al. The Astrophysical Journal 567 (2002) 1102

Chandra spectrum of microquasar GRS 1915+105:
~15 solar masses, ~43,000 light years away

What is required for solid-state, X-ray astronomy?

Energy resolution

Future instruments will have energy resolution similar to a normal spectroscopy beamline.

Time, lots of time

These measurements are severely count rate limited. The best current instruments, looking at bright objects, receive 10s of counts per energy bin. We had 200 kiloseconds on the ill-fated Astro-E2 – enough to get noise below the *purple* in the plot to the right..

Comparison of current and future instruments

	Gratings 0.25 - 6 keV FWHM			Calorimeter 6-10 keV FWHM		
	$\Delta E/E=3.3\times10^{-3}$ Baseline Con-X	$\Delta E/E=10^{-3}$ Chandra	Ideal $\Delta E/E$	$\Delta E/E\sim1.1\times10^{-3}$ Suzaku	$\Delta E/E=6.7\times10^{-4}$ Baseline Con-X	Ideal $\Delta E/E$
Gas vs. dust	Difficult without context	YES (isolate WA though)		YES	YES	
Different dust	NO WAY !	MAYBE, with good statistics	3.3×10^{-4} – silicates from Fe/oxides but $Fe_3O_4 = Fe_2O_3$	OK with good statistics	silicates from iron / oxides	3.3×10^{-4} –
Discern oxides	NO WAY !	NO	2×10^{-4}	NO	very hard to not possible	2×10^{-4}

Proposed

Astro-E2

An improbable and highly imperfect "beam line".

The light source

The "light source" is a brightly emitting astrophysical system (black hole, neutron star, etc) that is energetic enough to illuminate and ionize the surrounding material. The figure shows an artist's impression of such a system. The x-rays are generated by ionized particles spiralling towards the object – a sort of *inverse* synchrotron. XAS studies of astrophysical systems are complicated by the frequent presence of absorption and emission lines from hydrogenic and helium-like ions (see the Chandra data below) in the data which are often attributed to photo-ionized material (accretion disk, stellar wind, etc.) near the black hole.

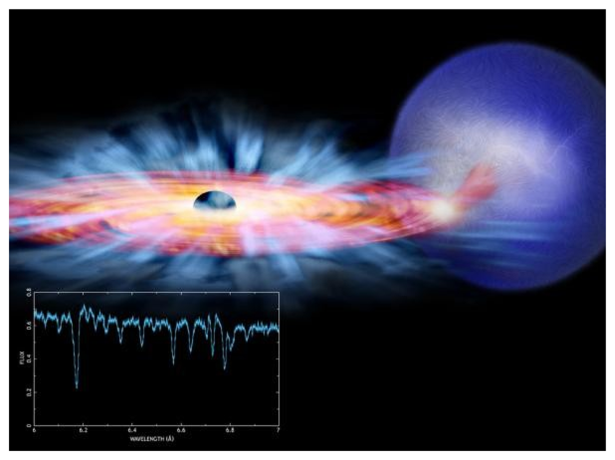


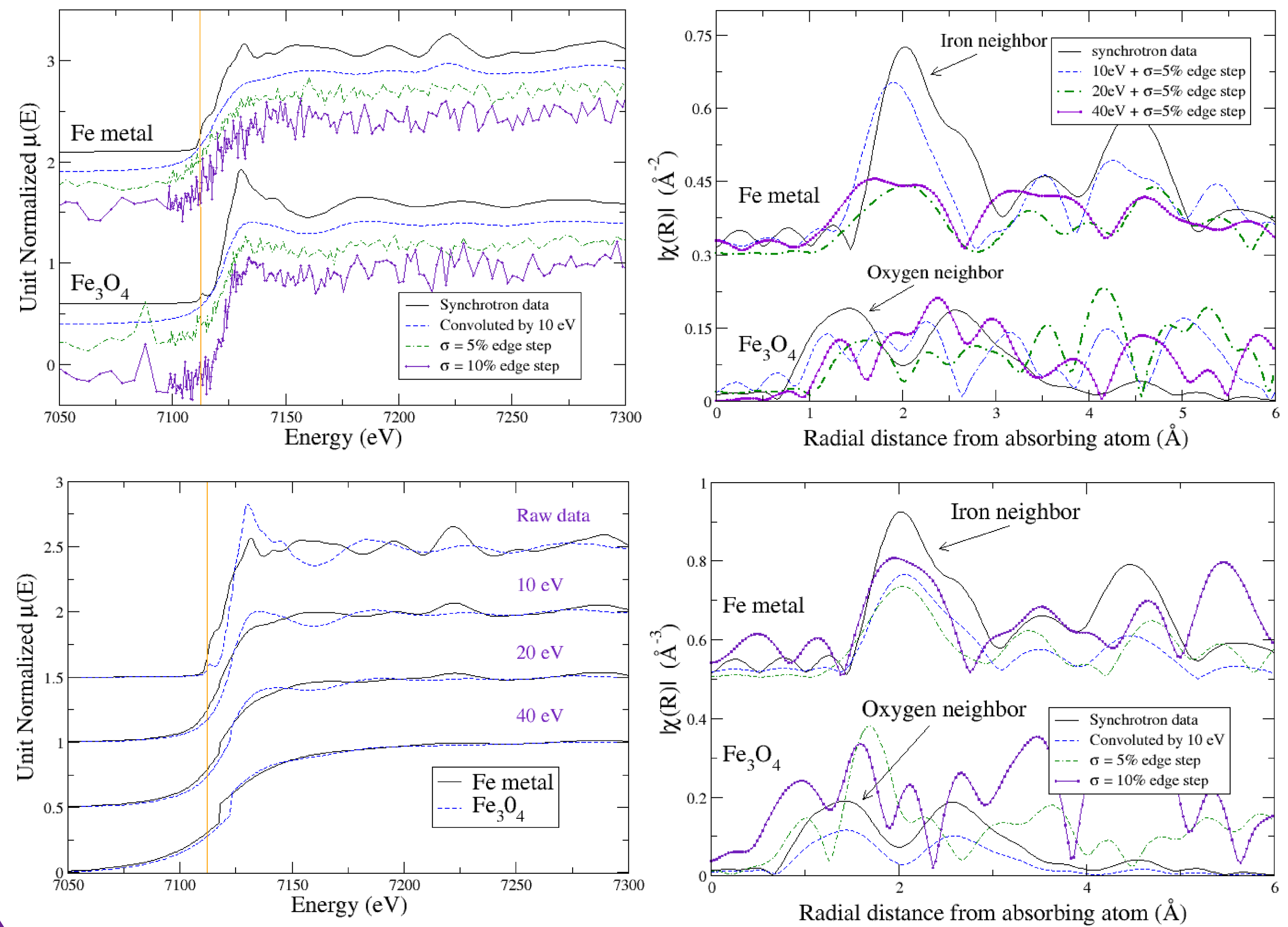
Illustration credit: NASA/CXC/M. Weiss; X-ray spectrum credit: Miller et al. Nature 441 (2006) 953

The beamline and the sample

The "beamline" is the long expanse between the distant object and the Chandra observatory. The "sample" is the material in proximity to the object and the interstellar dust littering the space between there and here – very inconvenient!

Other wavelengths provide some information about the content of the interstellar medium: IR sees polyaromatic hydrocarbons; presence of dust inferred depletion of UV signal and reddening, polarization of the optical; radio sees signature of gases. X-rays are sensitive to both gas and solid phase matter.

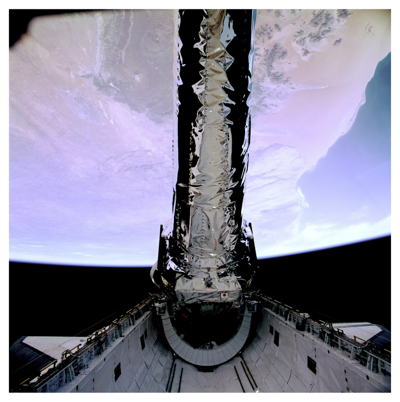
How noisy and broadened can data be, yet still distinguish a metal from an oxide?

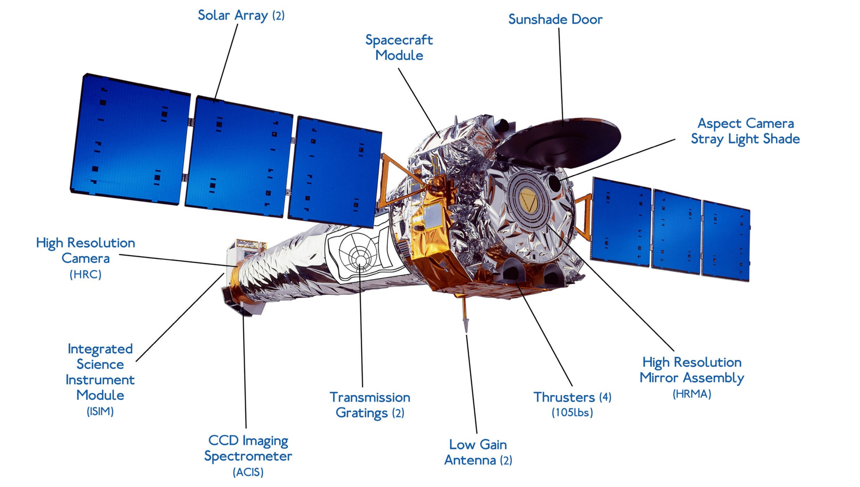


The detector

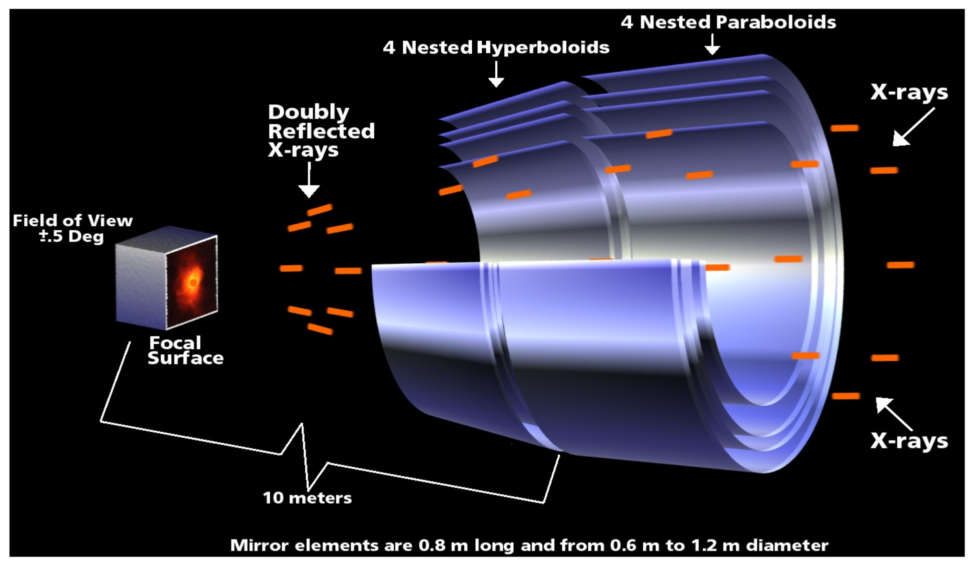
X-ray observatory in flight

NASA's Chandra X-ray Observatory, which (launched July 1999), ESA's XMM-Newton Observatory (Dec. 1999), and JAXA's AstroE/Suzaku (July 2005; initial launch 2001, failed) represent the most powerful and sophisticated ensemble of x-ray observatories in operation. The satellites compliment one another, with Chandra having the best imaging and spectral resolution to date and XMM having the largest collecting area and throughput.





Chandra was launched and deployed by the Space Shuttle Columbia. It combines highly polished (a few Å rms roughness) nested mirrors with 4 scientific instruments (1) ACIS-S: array of 6 CCD cameras and (2) HETGS: high energy transmission grating spectrometer, our instrument of choice for XAS studies as it has the highest spectral resolution of any instrument currently flying. Also (3) HRC Camera: microchannel plates and (4) LETGS: low energy ...



For details: instrument and mission specs are at
http://chandra.harvard.edu/about/

Astro-E2 and the XRS

This images © Japan Aerospace Exploration Agency JAXA

A microcalorimeter-based X-ray spectrometer was designed for energy resolution superior to the Chandra instrument in the hard x-ray regime. It was on the JAXA Astro-E launch of 10 February, 2000, which failed to reach orbit. Astro-E2 launched successfully on 10 July, 2005 carrying a new XRS. Three weeks after launch, the XRS developed an LHe leak leading to its early termination. Sadly, we had time on the XRS to make some astro-XAS measurements. And you think getting ID-line time is difficult...!

Conclusion

Solid state astrophysics – the characterization of materials found in astrophysical environments – by the application of the methods of synchrotron spectroscopy to x-ray observations is feasible given current technology and adequate measurement time. The major limitation is instrument availability – over-subscription rates on Chandra can be as high as 10:1. Chandra is the highest resolution x-ray spectrometer with the highest throughput at low energies currently in flight. The Astro-E2/Suzaku calorimeter (R.I.P.) would have filled a major gap, with high resolution and throughput in the hard x-ray regime.

References

- Our first stab at solid-state astrophysics: J.C. Lee and B. Ravel, The Astrophysical Journal, **622** 970 – 976 (2005)
- XAS-relevant references from the astrophysics literature: J.C. Lee, et al., The Astrophysical Journal, **554** L13 – L17 (2001); J.C. Lee, et al. The Astrophysical Journal, **567** 1102 – 1111 (2002); Y. Ueda, et al. The Astrophysical Journal, **620** 274 – 286 (2005)
- ATHENA and ARTEMIS: B. Ravel, and M. Newville, J. Synchrotron Radiat. **12**, 537—541 (2005)
- Chandra website: http://chandra.harvard.edu/
- Astro-E2 website: http://www.astro.isas.ac.jp/astroe/
- Con-X website: http://constellation.gsfc.nasa.gov/
- Bruce's contact info: bravel@anl.gov, http://cars9.uchicago.edu/~ravel
- Julia's contact info: http://cfa-www.harvard.edu/hco/astro/people/homepages/jclee.html

Argonne National Laboratory is managed by The University of Chicago for the U.S. Department of Energy.