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# Probing X-ray Emitting Plasma with High Resolution Chandra and XMM-Newton Spectra

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**Abstract.** Highlights of interesting astrophysical discoveries are reviewed in the context of high resolution X-ray spectroscopy made possible with *Chandra* and *XMM-Newton* , and its relevance to atomic physics calculations and measurements is discussed. These spectra have shown that the overlap between astrophysics and atomic physics is stronger than ever, as discoveries of new X-ray lines and edge structure is matching the need for increasingly detailed theoretical calculations and experimental measurements of atomic data.

## 1. X-ray spectral probes of astrophysical systems at high resolution

High resolution X-ray spectroscopy provides a powerful new tool for advancing our understanding of the physical environments of energetic astrophysical systems. As demonstrated with *Chandra* and *XMM-Newton* spectral studies, the scientific impact is far reaching, encompassing studies of stars, supernova remnants (SNR), X-ray binaries (XRBs), active galactic nuclei (AGN), clusters, and the interstellar and intergalactic medium (respectively ISM and IGM). To give a flavor for some of the newly X-ray discovered spectral features and their relevance to spectral modeling and calculations, I will draw mostly on examples from observations of AGN and XRBs with which I have been involved. See Paerels & Kahn (2003) for a complete review of *Chandra* and *XMM-Newton* results.

### 1.1. Narrow emission and absorption lines

Narrow (i.e. barely resolved) emission and absorption lines are nearly ubiquitous in the astrophysical sources seen at high resolution. From the lines strengths alone, we can deduce much about the conditions of the plasma, which range from the "X-ray cold" where fluorescent emission and photoionzation prevail to the "X-ray hot" where collisional ionization dominates. From the view of atomic calculations and spectral modeling, the parameterization of the emitters and absorbers are at an advanced state as demonstrated by high resolution spectral studies of the photoionized plasma in Seyfert galaxies (e.g., Sako et al. 2000; Ogle et al. 2000; Branduardi-Raymont et al. 2001; Collinge et al. 2001; Lee et al. 2001, 2002a; Kaspi et al. 2000, 2001, 2002; Brinkman et al. 2002; Kinkhabwala et al. 2002; Blustin et al; Sako et al. 2003). Specific features which demonstrate the power of high resolution spectroscopy come from the detection of high order (low oscillator strength) resonance absorption lines (i.e. higher than Lyman $\gamma$) which are the mark of high optical depth clouds (e.g., Lee et al. 2001; Kaspi



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et al. 2002). Commonly used atomic codes include [5]`Cloudy`: Ferland et al. (1998), [6]`XSTAR`: Kallman & Bautista (2001) and [7]`photoion`: Kinkhabwala et al. (2003).

Strong evidence for non-equilibrium collisionally ionized plasma can be seen in SNRs observed with *Chandra*and *XMM-Newton*. One of the best examples is 1E 0102.2-7219 where spectral-line images reveal progressive ionizations in the remnant attributed to a reverse shock (Flanagan et al. 2004; and Fig. 5 of Flanagan et al. 2003).

### 1.2. P-Cygni Profiles, Line Variability, Doppler Shifts, and Spatial-Spectral Doppler mapping

Outflows have been seen in many different forms in *Chandra* and *XMM* spectra. Key spectroscopic signatures include (1) Doppler-shifted absorption and/or emission lines which provide information on the kinematics and geometry of the outflow, (2) P-Cygni profiles (red-shifted/rest-frame emission from material out of the line-of-sight, accompanied by blue-shifted absorption lines from the foreground, line-of-sight part of the wind) as seen in both X-ray binaries (e.g. Circinus X1: Brandt & Schultz 2000; Schultz & Brandt 2002) and AGN (e.g. NGC 3783: Kaspi et al. 2001; 2002), and (3) more subtle variability effects (e.g. the micro-quasar GRS 1915+105: Lee et al. 2002b). Of these, the most remarkable are those which show relativistic velocities (e.g. the BHC SS 433 where $v_{\rm jet} \sim 0.27c$, Marshall, Canizares & Schultz 2002), and more recently also seen in QSOs and Narrow line Seyfert galaxies. From the X-ray measurements of these lines and shifts, a great deal can be learned about the X-ray portion of the flow. For example, based on the line broadening, information about the flow opening angle can be deduced while density diagnostics using observed He-like lines can provide important limits on the mass flow rate. For some of the brighter SNRs, spatial-spectral Doppler mapping can be used to reveal the 3-D structure of the SNR (e.g. 1E 0102, Fig 6 of Flannagan et al. 2003) – see Dewey (2002) for technique; for Cassiopeia A, see Willingale et al. (2002).

### 1.3. Inner Shell lines

'Low' ionization (in the X-ray sense) lines such as O III-VI or Fe VI-XVII are typically only seen in other wave-bands (e.g. UV), but photoexcitation of the ion's inner shell electron followed by auto-ionization causes resonance lines to appear in the X-ray band. These lines have been detected in the X-ray spectra of AGN: (1) the broad structure between $\sim 15.5 - 17$ Å ($\sim 0.72 - 0.8$ keV) known as the 'unresolved transition array' (UTA) of inner-shell 2p-3d resonance absorption lines in weakly ionized M-shell Fe VI-XII (for calculations, see Behar, Sako & Kahn 2001) was first detected in the Seyfert galaxy IRAS 13349+2438 (Sako et al. 2001) and since seen in NGC 3783 (Kaspi et al. 2002), (2) similarly, the K-L resonance absorption (inner shell 1s-2p transition) of Li-like oxygen

[5]http://www.nublado.org/

[6]http://heasarc.gsfc.nasa.gov/docs/software/xstar/xstar.html

[7]http://xmm.astro.columbia.edu/research.html

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for calculations, see Pradhan 2000) was also first discovered in a Seyfert galaxy (MCG-6-30-15: Lee et al. 2001). Since then, lower ionization oxygen lines have also been seen in this source (Sako et al. 2003; Lee et al. in prep), and inner shell lines of Si VII-XII and S XII-XIV have been reported in NGC 3783 (Kaspi et al. 2002). Low ionization oxygen lines have also been detected in the X-ray binaries and attributed to the line-of-sight ISM or that intrinsic to the source (e.g., Paerels et al. 2001; Takei et al. 2002; Juett, Schultz & Chakrabarty 2004).

For highly extincted extragalactic sources where a UV spectrum cannot be seen, the inner shell lines can eventually provide a powerful alternative for studying the "lukewarm" part of the partially ionized gas in the AGN environment (i.e. the warm absorber). For ISM studies, these lines provide an important diagnostic for the abundance distributions in our local Universe.

### 1.4. Edge Structure (XAFS) and Shifts

Photoelectric edges are seen as prominent spectral features in X-ray spectra of sources with significant absorption, from which we can deduce the optical depth and hydrogen column of the absorbing medium. However, based on the edge discontinuity alone, we cannot distinguish between gas versus dust phase absorption. In some cases, dust has been inferred as the source of an Fe L photoelectric edge at $\sim 17.7$ Å ($\sim 0.7$ keV) (e.g., Lee et al. 2001, 2002a). However, the most direct probe of dust is if the X-ray Absorption Fine Structure (XAFS), which probes material in solid form can be extracted from high resolution data of bright highly absorbed XRBs. Tentative detections of these features have been reported in the *Chandra*spectrum of GRS 1915+105 (Lee et al. 2002b).

## 2. Concluding Thoughts

The wealth of high resolution *Chandra*and *XMM-Newton* spectra accumulated over the course of the last $\sim$ four years has provided us with a very rich laboratory for probing the details of astrophysical plasma. While the atomic physics calculations appear to be well suited to model the high resolution X-ray data in hand, much of the detailed modeling has been parametric. Our next step should be to take the wealth of atomic and satellite data and connect it to the detailed models of the astrophysical sources themselves.

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