I. High resolution X-ray Spectroscopy on the Eve of ASTRO-H

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Hitomi (Astro-H): in memoriam

The quiescent intracluster medium in the core of the Perseus cluster
What are X-rays?

High Energy Photons
E = 0.1 -- 200 kev
Wavelength = 0.1 -- 100 Å
T = 10^6 -- 10^{10} K

We can see:
Very high temperature
Non-thermal particle acceleration
Atomic Processes

Source: Javier Garcia (CfA)
In 1962 Giacconi et al. discovered Scorpius X-1, the first extra-solar X-ray source.
Scorpius X-1 is a low-mass binary involving a compact primary
The spectrum of an X-ray binary is quite complicated.

Spectrum of the Cyg X-1 binary containing a black hole (Figure from Gierlinski et al 1999)
X rays are absorbed by the Earth atmosphere

Source: NASA
In 1999 X-ray astronomy comes of age

Chandra observatory

**Instruments/detectors**: High-resolution images with CCDs. Transmission grating spectrometers (0.1 - 10 keV).

**Mirror description**: 4 nested pairs with an area of 1145 cm**2 and 0.5 arc sec resolution.

XMM-Newton Observatory

**Instruments/detectors**: CCD cameras and reflection grating spectrometers (0.1 - 12 keV).

**Mirror description**: 3 modules with 58 mini-mirrors each giving a total area of 4300 cm**2 and 5 arc sec resolution.
The mirror of X-ray telescopes are very different to those in the optical

Source: Chandra Observatory
Chandra has two transmission gratings: HETG and LETG

Source: Chandra Observatory
Diffraction grating in XMM-Newton is of the reflection type

Source: ESA
X-ray extended solar corona taken with the Yohkoh satellite

Source: Yohkoh satellite
X-rays are produced in the geocorona by H-atom collisions with C, O and Ne ions of the solar wind.

Source: Chandra Observatory
Chandra image of Jupiter showing concentrations of auroral X-rays near the north and south magnetic poles

Source: NASA/CXC/SWRI/G.R.Gladstone et al.
X-radiation of Saturn is due to the reflection of solar X-rays by its atmosphere.

Solar X-ray light reflection on the Moon taken with the ROSAT probe

Source: Cambridge Astronomy
The noticeable spectral resolution increase of Chandra LETGS may be appreciated in the Capella spectrum.

OGS spectrum of Capella taken by the Einstein probe (Mewe et al 1982)

Chandra LETGS spectrum of Capella (Mewe et al 2001)
With the Chandra MEG and HEG it is possible to distinguish the quiescent and explosive phases of cataclysmic variables.

SS Cyg spectra in the quiescent and explosive phases. Images by Patterson & Raymond (1985) and Okada et al. (2008)
Low-mass binaries are used as backlight sources to study ISM X-ray absorption

Spectra of the low-mass binary GS 1826-238 by Pinto et al (2010)
X-ray image of the Crab Nebula showing the rings produced by the interaction with the pulsar (neutron star) that still excites it.

Source: AIP
Supernova remnant spectra show X-ray lines such as Lyα and Heα,β of third-row elements (Ne, Mg, Si, S, Ar and Ca) and Fe K,L

Source: Chandra Observatory
Chandra and XMM-Newton observations have greatly contributed to establish the AGN unified model.
The line profiles of Fe Kα may be used to determine the relativistic properties of the accretion disk.

*Fit of the model by Bromley et al. (1996) of the Fe Kα line profile in AGN MCG-6-30-15 (Tanaka et al. 1996 Nature 375, 659). The model disk has an internal radius of 7.2 r_g, external radius of 15.8 r_g and inclination radius of i = 30°. Source: NASA.*
*Chandra* and *XMM-Newton* observations have greatly contributed to establish the AGN unified model.

XMM-Newton (RGS) spectrum of AGN PG 1211+143 where a warm absorber is perceived with lines blue-shifted by 3000 km/s (Kaspi & Behar 2010)
A microquasar is an X-ray binary system with a compact (black hole or neutron star) primary.
Disk wind from the microquasar GRO J1655-40 appears to have a magnetic origin.

Intracluster medium shows temperatures of ~10-100 MK produced by intense gas flux in the process of galaxy formation.

Credits: X-ray (NASA/CXC/SAO/A.Vikhlinin et al.); optical (SDSS); simulation (MPE/V.Springel)
ICM X-ray spectrum shows emission lines from high-Z chemical elements

Observations of Chandra Deep Field South have allowed the detection of black holes in the early universe.
Although GRB have short durations (seconds or minutes) their X-ray afterglow can last for days, months or years.
X-ray continuum is mainly produced by three atomic processes

- Bremsstrahlung
- Inverse Compton
- Synchrotron radiation
X-ray Emission Mechanisms

Continuum

Source: Javier Garcia (CfA)
X-ray Emission Lines

for a multi-electron atom

Source: Javier Garcia (CfA)
X-ray Emission Mechanisms

Lines

- **Line positions** provide information about the gas composition (identification), as well as about its dynamics (redshifts, gas outflows).

- **Line intensities** provide information about the column of the absorbing material (including ions), constrains on the ionization degree of the gas \( (\xi = L/nR^2) \), temperature and density.

- **Line shapes** provide information about the thermal and turbulent motions of the gas, and can also probe relativistic effects near strong gravitational fields.

The X-ray band \( (\sim 0.1 - 10 \text{ keV}) \) covers the emission and absorption produced by the inner-shell transitions of the astrophysically abundant ions \( (C \rightarrow Ni) \).

Source: Javier Garcia (CfA)
Interaction of X-rays with ions produce absorption and emission lines (fluorescence)

Illustrating these processes in the relatively simple case of Ne-like Fe XVII, the photoexcited K-vacancy states

\[
h \nu + 1s^22s^22p^6 \rightarrow 1s2s^22p^6np
\]  

have access to the following decay tree:

\[
\begin{align*}
1s2s^22p^6np & \xrightarrow{Kn} 1s^22s^22p^6 + h \nu_n \quad (2) \\
& \xrightarrow{K\alpha} 1s^22s^22p^5np + h \nu_\alpha \quad (3) \\
& \xrightarrow{KLn} \begin{cases} 
1s^22s^22p^5 + e^- \\
1s^22s2p^6 + e^- 
\end{cases} \quad (4) \\
& \xrightarrow{KLL} \begin{cases} 
1s^22s^22p^4np + e^- \\
1s^22s2p^5np + e^- \\
1s^22p^6np + e^- 
\end{cases} \quad (5)
\end{align*}
\]
Auger damping changes the behavior of the K edge

Figure from Palmeri et al (2002)
The damped behavior of the K edge is observed in ions with $N \geq 4$. 

Figure from García et al. (2005)
K edge morphology depends on the ionization parameter

Fig. 8.—Opacities for a photoionized gas in the oxygen K-edge region for ionization parameters in the range $-3 \leq \log \xi \leq 1$. 

Figure from García et al. (2005)
Theoretical fine tuning relies on accurate laboratory measurements.

Experiment and RMPS: Sant’Anna et al (2011)
BP-optical potential: García et al (2009)
Atomic processes involved in the modeling of astronomical X-ray systems

<table>
<thead>
<tr>
<th>Process</th>
<th>Initial</th>
<th>Final</th>
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</thead>
<tbody>
<tr>
<td><strong>Collisional processes</strong></td>
<td></td>
<td></td>
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<tr>
<td>Electron-impact excitation</td>
<td>$X^{z+} + e \rightarrow X^{z+\ast} + e'$</td>
<td></td>
</tr>
<tr>
<td>Electron-impact de-excitation</td>
<td>$X^{z+\ast} + e \rightarrow X^{z+} + e'$</td>
<td></td>
</tr>
<tr>
<td>Electron-impact ionization</td>
<td>$X^{z+} + e \rightarrow X^{(z+1)+} + e' + e''$</td>
<td></td>
</tr>
<tr>
<td>Three-body recombination</td>
<td>$X^{z+} + e + e' \rightarrow X^{(z-1)+} + e''$</td>
<td></td>
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<tr>
<td><strong>Radiative processes</strong></td>
<td></td>
<td></td>
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<tr>
<td>Photo-excitation</td>
<td>$X^{z+} + \gamma \rightarrow X^{z+\ast}$</td>
<td></td>
</tr>
<tr>
<td>Spontaneous emission</td>
<td>$X^{z+\ast} \rightarrow X^{z+} + \gamma$</td>
<td></td>
</tr>
<tr>
<td>Stimulated emission</td>
<td>$X^{z+\ast} + \gamma \rightarrow X^{z+} + 2\gamma$</td>
<td></td>
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<tr>
<td>Photo-ionization</td>
<td>$X^{z+} + \gamma \rightarrow X^{(z+1)+} + e$</td>
<td></td>
</tr>
<tr>
<td>Radiative recombination</td>
<td>$X^{z+} + e \rightarrow X^{(z-1)+} + \gamma$</td>
<td></td>
</tr>
<tr>
<td>Stimulated recombination</td>
<td>$X^{z+} + e + \gamma \rightarrow X^{(z-1)+} + \gamma_1 + \gamma_2$</td>
<td></td>
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<tr>
<td><strong>Dielectronic recombination</strong></td>
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<tr>
<td>Resonance capture</td>
<td>$X^{z+} + e \rightarrow X^{(z-1)+\ast\ast}$</td>
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<tr>
<td>Auger breakup</td>
<td>$X^{(z-1)+\ast\ast} \rightarrow X^{z+} + e$</td>
<td></td>
</tr>
<tr>
<td>Radiative stabilization</td>
<td>$X^{(z-1)+\ast\ast} \rightarrow X^{(z-1)+\ast} + \gamma$</td>
<td></td>
</tr>
</tbody>
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Table from Foster et al (2011)