XMM/RGS: Cumulative spectrum of 30 X-ray bursts

Photospheric X-ray absorption spectrum from surface of neutron star (?)

If correct identification: gravitational redshift! $z = 0.35$


First two pages: a few extra comments on the Curve of Growth (Jelle’s lecture)
Also: slow spin (fortuitous)!
First Astro-H Science Summer School
Minakami Onsen, August 19-21, 2010

5. High Resolution Spectroscopy

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Part 1:
  High Resolution Spectroscopy
  Historical Precedent: grating spectroscopy with Chandra and XMM
  Types of Equilibrium: simple diagnostics
  Basics of He-triplet Spectroscopy
  T-diagnostics: collisional and radiation-dominated plasmas

  Brief Break

Part 2:
  n-diagnostics
  Non-equilibrium situations
  Radiative transfer issues

NB: I will be discussing emission spectroscopy; Jelle will address absorption
What is ‘high’ in ‘high resolution’?

Chandra and XMM gratings

Fano-limited CCD

5 eV μCal

radial velocity (100 km/s)

radial velocity (100 km/s; 100 photons)

resolution power E/ΔE

5 eV μCal

photon energy (keV)

thermal Doppler (10° K)

dielectronic satellite lines

Raman

density (Fe L)

density (He-like ions)

Compton width

ρE(κα), removal valence electron

RRC (KT = 10 eV)

excitation mechanism

charge state

EXAFS

ΔE(κα), removal valence electron

Fano-limited CCD
Historical Context

A few crystal spectrometer experiments; most notably Einstein FPCS (Canizares, MIT); First ‘resolved’ spectroscopy in X-ray astronomy (resolve elements, charge states)

Fe XVII (Ne-like) 2p-3s \(2p-3d\) 2p-4d

H-like O Ly\(\beta,\gamma,\delta\)

H-like Ne Ly\(\alpha\)

But FPCS was inefficient. 

*Einstein* and EXOSAT had transmission grating spectrometers; likewise: novel, but inefficient

ASCA was the first ‘general purpose’ spectrometer; CCDs resolve element, ionization stage, and some further spectral detail

Kawashima and Kitamoto, 
Truly general purpose, fully resolved astrophysical spectroscopy (but point sources only!): Grating spectrometers in Chandra, XMM:

NB: 5 eV microcalorimeter spectrum will appear almost the same!
Types of Equilibrium

Very roughly: *collisional*, and *radiation-driven* plasmas

‘hot gas’
(unspecified energy source)

Cool, recombining plasmas

Very simple, robust spectroscopic signature of recombining plasma:

**Radiative Recombination Continua (RRC)**

Collisional equilibrium

Photoionization equilibrium
Fig. 1. Phase-averaged energy spectrum of Cyg X-3 obtained by SIS 0. The emission lines from He-like and H-like ions and electron binding energies for K-shell and L-shell of H-like and He-like ions are indicated.
Cygnus X-3 with Chandra HETGS

Fully resolved RRC’s; Width $\Delta E \sim kT_e \sim \text{few eV}$
Another simple diagnostic to discriminate between collisional excitation and recombination or charge exchange: the ‘series decrement’

Collisional excitation makes \( n=1-2 \) (for example), but can only make much less \( n=1-3, 4, 5... \) so flux ratio’s \( (3-1)/(2-1), (4-1)/(2-1), ... \) (the ‘decrement’) small

Both recombination and charge exchange populate higher-\( n \) levels more effectively, leading to relatively stronger higher-order series members (‘flat decrement’).

![Graph of Lyman transitions](image)

Basics of He-like ‘Triplet’ Spectroscopy

write total wavefunction as product $\psi(\text{spatial})\psi(\text{spin}) = \psi(l_1/l_2)\psi(s_1,s_2)$

Two electrons: can have $|\uparrow\uparrow>, |\downarrow\downarrow>, |\uparrow\downarrow>, |\downarrow\uparrow>$. But these are not all eigenstates of $J$. Eigenstates of $J$ are:

$|\uparrow\uparrow>, |\downarrow\downarrow>, |\uparrow\downarrow> + |\downarrow\uparrow>$ (symmetric in the spins, total spin 1) ‘triplet’

$|\uparrow\downarrow> - |\downarrow\uparrow>$ (antisymmetric in the spins, total spin 0) ‘singlet’

He-like ion

Fig. 1. The He-like ion, showing those terms and processes involved in the present analysis. The wavelengths indicated apply to the case of oxygen vii.

Ground: space-symmetric, must be spin-antisymmetric, so $s = 0$ (2s+1 = 1; singlet)

### H-like Species

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<th>$\lambda_{\alpha_1}$ (Å)</th>
<th>$E_{\alpha_1}$ (keV)</th>
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<th>$E_{\alpha_2}$ (keV)</th>
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### He-like Species

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Appearance of the triplets: example: OVII in Capella with Chandra HETGS

First thing to note: resonance line is bright in collisional equilibrium plasmas

Spectroscopic power of He-like triplet spectroscopy due to the fact that upper levels for w, x, y, and z populated mostly by different mechanicsms, with different temperature dependence.

Example: coronal (collisional) equilibrium: CX to 1s2p 1S0 dominates over recombination to 1s2p 3P, 1s2s 3S1

NB: z not collisionally excited for ~ same reason it’s radiatively forbidden!

We will see many more applications of He-like triplets as we go along
Electron Temperature Diagnostics

Collisional plasmas:
- Fe L ionization balance
- He-like (I+F)/R ratio
- dielectronic satellites
- direct ion thermal velocity spectroscopy

Fe L ionization balance: simple-ionization states range from $2 \times 10^6$-3$ \times 10^7$ K
Fe L lines are bright!

Appearance of the Fe L collisional spectrum; Capella/XMM-Newton RGS
(something similar is true for photoionization equilibrium—but balance is usually ‘messier’—more ionization stages simultaneously present)

Upper levels of the resonance, and forbidden+intercombination lines mostly populated by collisional excitation, and recombination, respectively. CX and RR+DR have different $T_e$-dependence:

ratio $G = (x+y+z)/w$ is $T_e$-sensitive: High $T_e$ favors CX

*Careful:* blending with other transitions may bias simple measurement of $G$. Need to model emission spectrum, in practice.

Different curves are for different ratio’s of H-to He-like ion densities; allows for deviations from pure CIE. Lowest curve is pure CIE; higher curves apply to photoionization cases.

Electron temperature from Dielectronic Satellite Transitions

Presence of ‘spectator electron’ shifts levels a little bit (Coulomb shielding of nuclear field): the emission line will be slightly to lower energy as compared to equivalent line in ion +z: dielectronic ‘satellite’ to line in ion +z

don stage +z (e.g. He-like)
dielectronic recombination
Ion stage +(z-1) (e.g. Li-like)
Resonance line $w$ will be collisionally excited, the dielectronic satellite excited by DR; both processes different $T_e$ sensitivity: $T_e$ diagnostic
Also: both line emissivities scale with $n_e n_{\text{He-like}}$: no dependence on ion balance!

Example: He/Li-like Fe, thermal plasma at 1.65 and 2.30 keV

Bitter et al., *PRL*, 43, 129 (1979)
Photoionized and Recombining Plasmas: electron temperature from shape of the RRC


Shape of RRC directly maps out shape of the free electron Maxwell distribution!
Direct Ion thermal Doppler Broadening Spectroscopy

Thermal Doppler width of Lyα (rms):

\[
\sigma = \left( \frac{kT}{m c^2} \right)^{1/2} E_0 \approx \left( \frac{kT}{2 m_p Z c^2} \right)^{1/2} \times \frac{3}{4} \mathcal{R} Z^2
\]

\[
= 2.9 \ T_8^{1/2} (Z/26)^{3/2} \text{ eV}
\]

\[3^2 + 7^2 = 7.6^2\] so this is **feasible with Astro-H in the Fe K band** at \(kT_e \sim 10\text{ keV};\) but not at lower \(Z\) (e.g. Si K width is sub-eV at \(T_8 \sim 0.1\))

Need to know the shape of the response to reasonable accuracy (this example suggests \(\sim< 5\%\) of the width of the response)
Electron Density Diagnostics

F/I ratio in He-like triplets

At high density, or in presence of intense UV field (1630 Å for He-like O; shorter for higher-Z elements): population of upper level of z shifts to upper level of x,y:

ratio z/(x+y) is density diagnostic
ratio \( R = \frac{z}{x+y} \)

Fig. 8. In case of pure photoionized plasmas (i.e. RR dominant at low temperature and DR dominant at high temperature), ratio \( R = \frac{z}{x+y} \) is reported as a function of \( n_e \) for C V, N VI, O VII, Ne IX, Mg XI, and Si XIII at different electronic temperatures (\( T_e \) in Kelvin). For low temperatures (the two first reported here: solid curves and dot-dashed curves), the value of \( R \) is independent of the value of \( X_{\text{ion}} \). As the temperature increases, \( X_{\text{ion}} \) is high enough to maintain recombination dominant compared to collisional excitation from the ground level: \( \sim 10^2 \) and \( 10^3 \) (for increasing temperature: respectively for long-dashed curves and short-dashed curves).
Non-equilibrium Situations

We discussed non-equilibrium plasmas yesterday; what are the spectroscopic diagnostics of deviations from equilibrium? (*)

NB: discuss only deviations from ionization equilibrium; deviations from kinetic equilibrium ($T_i$-$T_e$; nonthermal electrons; cosmic rays, ...) out of scope (e.g. collisionless shocks, feebleness of Coulomb interactions, ...).

**Ionizing plasmas:** ionization balance too low for prevailing electron temperature
(or photoionization parameter $\xi$)

Rough criterion:
low densities means: low collision frequency:
ionization balance lags. Typically reach ionization equilibrium for $n_e t > 10^{12}$ cm$^{-3}$ sec (depends on ion)

Examples: young supernova remnants; stellar flares; IGM, ...

(*) simplest diagnostic: if continuum gives $T_e$, compare to ionization balance....; trivial.
In the IGM, $n_e$ is so low that equilibrium timescales may be longer than the age of the Universe!
Innershell excitations in (relatively) low charge ions
Example: excitation of n=1-2 in Be-, Li-, and He-like Fe (EBIT experiment)

β: $1s^2 \ 2s^2 \rightarrow 1s \ 2p \ 2s^2$ (Be-like)
q: $1s^2 \ 2s \rightarrow 1s \ 2p \ 2s$ (Li-like)

All of this will be resolved by Astro-H

*Also: He-like triplet shows only w, no x,y,z! no recombinations (yet)*
Recombining plasmas: ionization balance too high for prevailing electron temperature (or photoionization parameter $\xi$)

Looks like a photoionized plasma:

He-like triplets will show bright $x,y,z$, compared to $w$;
May see RRC’s, if the plasma is cool enough.

XMM-RGS NGC 1068 again

bright $z$; faint $w$
Recombining plasma in SNR IC 443 with Suzaku (?!)

Radiative Transfer Issues

Plasmas of interest may be optically thin in strong resonance lines.

Two effects may be observable:

1. Scattering of resonance line photons
2. Scattering of continuum photons by strong resonance transitions

Lines with the highest (oscillator strength) \( \times \) (astrophysical abundance):

He-like \( \omega \) in O and Fe; Fe XVII 2p-3d 15.014 Å (826 eV)

Maybe in clusters; elliptical galaxies; Type II AGN with outflow

(1) Resonance scattering in spherically symmetric diffuse source:
photons scattered out of line of sight compensated by photons scattered
into line of sight further out (gas density low: no collisional destruction
of photons, so total photon luminosity must be conserved):

*image in resonance line photons will appear wider than image in
toptically thin radiation; but need angular resolution to see this! Not just
spectral resolution!*
(2) Scattering of continuum photons on strong resonance transitions in anisotropic situations (e.g. AGN outflow exposed to central continuum)

Will appear to enhance resonance lines; effect depends on velocity gradients!

Most extreme example: scattering of the X-ray background continuum by intergalactic OVII w – if you can resolve most of the point sources that make the background!

Finally: **Compton and Raman scattering of line photons** (in practice: Fe lines-scattering medium likely to be photoelectrically opaque at lower energies)
This will happen - we have seen it in X-ray binaries!

Analysis will reveal optical depth, electron temperature, angular distribution of scattering electrons/H-atoms, as seen from line source.

May give novel constraints on ‘cold reflection’ in AGN- important for relativistically distorted Fe emission lines (black hole spin, ...)
Compton ‘shoulder’ on Fe Kα (GX301-2, Chandra HETGS)

Width = 2 $\lambda_C$ (electron)!! (NB: plot against wavelength if you suspect Compton scattering!!)

Compton’s original experiment, in an astrophysical source...

(Courtesy Masao Sako, then Stanford; analysis: Watanabe et al., ApJL, 597, L37 (2003))
Quiz: A Gallery of He-like Triplets

What conditions produce these triplet spectra?
References to previous page:

7. IGM, theory: Churazov et al., 2010arXiv1007.3263C