Emission- & Absorption-Measure Distributions

High Resolution X-Ray Spectroscopy: Towards XEUS and Con-X
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Outline

• Emission Spectra
  - EMD and why we want it
  - Fundamental Limitations
  - Results from coronal flares

• Absorption Spectra
  - Measured quantities
  - Absorption Measure Distribution (AMD)
  - Results for AGN outflows

• Conclusions
Emission Line Spectra

Flaring
Quiescent (Scaled)
Residual

Nordon et al. 2006
Line Flux: Reminder

- Fundamental plasma quantity: photons emitted per second per cm$^3$: $n_j A_{ji}$
- In the steady state coronal approximation: What comes up must come down: $n_j A_{ji} = n_e n_i Q_{ij}(T_e)$, $n_i = n_q$, plus cascades
- In astrophysical terms: 

\[ \text{since } (n_j/n_q) \sim n_e, \text{ the } F_{ji} \sim n_e n_H \sim n^2 \]
- For observed line flux $F_{ji}$ now divide by $4\pi d^2$ and integrate over volume
Emission Measure

• Now, for an isothermal, isochemical plasma, however, steady state coronal plasma CANNOT in reality be isothermal, so
The EM Distribution

• So, what we are seeking is:

• In general, the derivation of the EMD is subject to confusion due to the entanglement of thermal and chemical contributions ($F_{ji} \sim A_{zEMD}$)

• The X-ray band is unique in its richness: Fe-L comes to the rescue providing an abundance-free distribution (also, line ratios between ions)

• Once the EMD profile is known, normalizations for different elements yield the ABUNDANCES
Ionic Distributions

RGS+EPIC

LETGS

[Graphs showing normalized emissivity as a function of kT (keV) for different ions in RGS+EPIC and LETGS]
Finding the EMD: The Inversion Problem

- Degeneracy is inherent even for high-accuracy measurements
  - Solution is non-unique
  - No physics to hint at the EMD shape
  - No escape from width of line emissivity curves
  - EMD variations on small temperature scales produce indistinguishable spectra

- Solution: fit for average EMD in $T$-bins
  - Produces meaningful, well localized errors
  - Limited temperature resolution
  - Dependent on ionization balance (e.g., Gu 2003)
Different EMD Shapes
The Desire for EMD Confidence Dictates Low $T$-Resolution

How far can one go from $T_1$ to $T_2$ to compensate for $\delta EMD(T_1)$ with $\delta EMD(T_2)$ (to within $\Delta \chi^2 < 1$)?

Nordon et al. 2006
Some Results: Giant Flare on $\sigma$ Gem

Nordon et al. 2006
Abundances
Flare vs. Quiescence

![Graph showing abundances of elements (O, Ne, Mg, Si, Al, S, Ar, Ca) vs. element Z for Algo Flare vs. Quiescence.](image)
Atomic Data? Sanity Check

Total emissivities H-like and He-like

Emissivity [photons cm$^{-3}$ s$^{-1}$]

$kT$ [eV]

- O APED
- O our
- Ne APED
- Ne our
and Fe-L, e.g. Fe$^{+19}$
What about Absorption?
Absorption: The Same, but Slightly Different

- Measured quantity: Equivalent width and optical depth of (several) lines & edges (partial covering can complicate things considerably).
- Fundamental plasma quantity: Optical depth and ionic column density
  \[ \tau_{ij} = N_{\text{ion}} \sigma_{ij} \]
  \[ N_{\text{ion}} = \int_{r_{\text{min}}}^{r_{\text{max}}} n_q dr \]
- Again, all ions are essentially in their ground state and in astrophysical terms:
  \[ n_q = \left( \frac{n_q}{n_Z} \right) \left( \frac{n_Z}{n_H} \right) n_H = f_q(\xi) A_Z n_H \]
- Ionization parameter replaces \( T_e \)
- Thus: for isochemical, isothermal (iso-\( \xi \)) absorber: one obtains an Equivalent \( N_H = N_{\text{ion}} / f_q A_Z \)
In Fact, $N_H$ is Distributed

- An isothermal plasma near an intense ionization source (quasar) is even less likely than an isothermal coronal plasma.
- There must be an Absorption Measure Distribution (AMD):
  \[
  N_H = \int \frac{dN_H}{d\xi} (\xi) d\xi \equiv \int AMD(\xi) d\xi
  \]
- SRON group (Steenbrugge, Costantini) has explored power-law AMDs (for NGC 5548, Mrk 279), but see talk by Goncalves.
- Again, in the AMD derivation there can be confusion due to the entanglement of thermal and chemical contributions ($N_{\text{ion}} \sim A_Z\text{AMD}$).
- In absorption, the X-ray band is even more all-inclusive.
- Inner-shell absorption reveals ALL CHARGE STATES (barring bare).
- Particularly, 26 ions of Fe allow for an abundance-free AMD analysis relying on $T$ and $f_q(\xi)$ (XSTAR by T. Kallman).
Individual Ionic Column Densities

~ log(T) [K]

NGC 3783

Equivalent $N_{\text{H}}$ [cm$^{-2}$]

Holczer et al. 2006

Holczer et al. (2003)

Krongold et al. (2003)
Reconstructing The AMD

Krongold et al.
Netzer et al.

Holczer et al. 2006

\( \log(\xi) \) [erg cm \( s^{-1} \)]
Abundances
(more reliable than emission)
Conclusions

- Astrophysical X-ray plasmas are generally NOT isothermal
- There always is a distribution: EMD or AMD
- The EMD and AMD play a role in comparative studies
- Essential for reliable abundance determination
- The EMDs/AMDs happen to be rather broad, thus few-T models do not usually represent the EMD/AMD correctly
- In the absence of a physical model for the EMD or AMD, the best representation is a step function, which allows for local well-constrained error estimates
- L-shells provide powerful diagnostics, but T- or $\xi$- resolution is limited by fundamental physics; the ionic distributions
- To that end, the ionization balance (atomic data) is key
THANK YOU
FOR YOUR ATTENTION
Stability Analysis