Impact of sub-keV Soft Excess on Warm Absorbers

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Warm Absorber

- **Absorption Edges in Soft X-ray Spectra**
  - CV 392 CVI 490 OVII 740 OVIII 870 FeXVII 1260 NeX 1360 (eV)
  - C (V & VI) O (V - VIII) Fe (XVII - XXII)
  - Ne (IX & X) Mg (XI & XII) Si (XIII - XVI)

- **Properties**
  - Partially ionized gas in our line of sight to AGN
  - Distance from the source ~ 0.01 – 1 pc
  - Column Density ($N_H$) ~ $10^{22.1}$ cm$^{-2}$
  - Density ($n_H$) ~ $10^9$ cm$^{-3}$
  - Ionization Parameter $\xi$ ~ $10 - 100$ erg cm s$^{-1}$
  - Temperature ~ $10^5$ K - $10^7$ K

- **Current Issues**
  - Absorption features are blue shifted relative to optical emission lines, indicating outflow
  - Mass loss rate is a substantial fraction of the accretion rate, or exceeds it.
  - The X-ray warm absorber could coexist with a UV absorber, but it is still difficult to connect them.

- **Is the Warm Absorber in thermodynamic equilibrium?**
- **If so, does the gas have multiphase nature?**
CLOUDY

“Photoionisation Simulation for the discriminating astrophysicist since 1978”

http://www.nublado.org/

Inputs

Radiation Field

Geometry

Neutral Composition

Density

Thickness

Process

Basic Assumption

Atomic processes reached time–steady state

\[ n(X^{+i})\Gamma(X^{+i}) = n(X^{+i+1})n_e\alpha_{G}(X^{+i+1}, T) \]

Thermal balance achieved

\[ \Lambda_{\text{Coll}} + \Lambda_{\text{IC}} = (\Gamma_{\text{Ph}} + \Gamma_{\text{C}}) / n \]

Working principle

\[ \frac{\partial n_i}{\partial t} = \sum_{j \neq i} n_j R_{ji} + \text{Source} - n_i \left( \sum_{j \neq i} R_{ij} + \text{Sink} \right) = 0 \]
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Inputs
- Radiation Field
- Geometry
- Neutral Composition
- Density
- Thickness

Output → Thermal state & Ionic composition of cloud
Stability Curve

Each point in the curve have thermal and ionic composition information

\[ \xi = L/nR^2 \]

\[ \xi/T \sim (p_{\text{rad}})_{\text{ion}}/p \]

\[ \text{Curve - phase diagram} \]
Krolik et al. (1981) : Obtained the stability curve for cold gas and hot gas in AGN.


Hess et al. (1997) : Causes of instability in Warm gas as a function of ionizing continuum and abundance for low-mass X-ray binaries and Seyfert galaxies


Netzer 1994, 1996

Krolik & Kriss, 2001

Chelouche & Netzer, 2005
Influence of Atomic Physics
Susmita Chakravorty et. al,
2008 MNRAS, 384L, 24

\( f_v \sim \nu^{-\alpha} \)
\( n_H \sim 10^9 \text{ cm}^{-3} \)
Metals : Old \( Z_\odot \)

\( \Delta \log(\xi/T) \sim 10^5 K \)
\( \Delta M \log(\xi/T) \sim 10^6 K \)

Version \( \xi_5 \) \( N_{\text{phases}} \) \( \Delta \log(\xi/T) \) \( \Delta M \log(\xi/T) \)

\( C84 \) 45 2 0.05 0.47 0.05

\( C07 \) 74 2 0.22 0.46 0.07

\( C07, 2007 \)
&
\( C84 1993 \text{ to } 1996 \)
(Reynolds - Fabian, '95)
The ionizing continuum

- No stable states if $\alpha < 0.2$
- Multiphase WA if $\alpha \sim 0.8$
- For $\alpha > 1.1$, no unstable states

$f_\nu \sim [\nu^{-\alpha} + \eta \nu^{-\alpha_s}] e^{-\nu/\nu_{\text{max}}}$
Abundance

- No stable states if $\alpha < 0.2$
- Multiphase WA if $\alpha \sim 0.8$
- For $\alpha > 1.1$, no unstable states
- $Z_0$: Classical S-curve
- $Z > Z_{\text{sol}}$ enhances multiphase extended stable state at $10^6$ K
- $Z < Z_{\text{sol}}$ reduces multiphase

Komossa & Mathur (2001)
Systematic analysis of S-curves

Abundance

- No stable states if $\alpha < 0.2$
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- For $\alpha > 1.1$, no unstable states
- $Z_0$ : Classical S-curve
- $Z > Z_{\text{sol}}$ enhances multiphase
- $Z < Z_{\text{sol}}$ reduces multiphase
- X-ray Group : Most effective group $(C, O, Fe, Ne)$
- Oxygen : Most effective element at $10^5$ K. Needed for WA.
- Iron : Most effective element needed at $10^6$ K. Iron was formed when $T_{\text{UNIV}} = 1$ Gyr. WA before that different.
- $\alpha$-elements only gas : WA unlikely
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High density gas exposed to steep $\alpha_{\text{OX}}$ continuum shows effect

Hydrogen free free absorption becomes a dominant heating agent

Can this become a tool for direct determination of density?
Soft Excess & Warm Absorber

- Soft X-ray spectra fit with powerlaw.
- Fits high energy ~ 1 - 10 keV.
- Leaves excess at lower energies ~ 0.5 keV.
- Is likely to influence X-ray Group of elements & hence influence WA.

\[ f(v) \sim \left[ \{v^{-\alpha} + \eta' \frac{2\pi h}{c^2} \frac{v^3}{\exp(hv/\sqrt{KT_{se}}) - 1}\} + \eta'' f_{dbb}(v,T_{in}) \right] e^{\frac{v}{v_{\max}}}. \]

Blackbody as 'Soft excess'

- Can be fit with blackbody - $T_{se} \sim 0.15$ keV.
- Normalisation wrt. powerlaw - variable parameter.

Fabian and co-authors
Late 90’s and earlier this decade
✓ Disk Blackbody has no effect

✓ Soft excess : $10^5$ K phase. Remarkable stability. Solid support for gas in thermal equilibrium

✓ $10^6$ K phase : Unaffected

✓ $T_{se}$ : No qualitative difference
A combination of Soft Excess and Super Solar metallicity accounts for:

- Increased stability at $10^5$ K
- Multiphase scenario with $10^5$ K & $10^6$ K in pressure equilibrium
• $Z > Z_{\text{sol}}$ enhances multiphase extended stable state at $10^6$ K.

• X-ray Group (C, O, Fe, Ne) : Most effective group

• Oxygen : Most effective element at $10^5$ K. Needed for WA.

• Iron : Most effective element needed at $10^6$ K. Iron formed $T_{\text{UNIV}} = 1$ Gyr. WA before and after that will be different.

• Continuum having significant “Soft Excess” enhances WA at $10^5$ K.

• A combination of Soft Excess and Super Solar metallicity gives the best description of WA as gas in thermal equilibrium : Enhanced stability at $10^5$ K and multiphase scenario with $10^5$ K & $10^6$ K in pressure equilibrium