Structure of the gas in the Milky Way: X-ray absorption in the cold, warm and hot ISM

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with

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High-Resolution X-ray Spectroscopy
• The atom is excited by a photon.

• There is one **photoabsorption cross-section** for each ion.

• There are two decay processes:
  
  X-ray fluorescence

  Auger effect.

**ISM ABSORPTION AFFECTS ALL X-RAY SPECTRA!**
Ionization Equilibrium: $I_{oneq}$

\[ I_{obs}(E) = e^{-\tau} I_{source}(E) \]

\[ \tau = \sum_{k,j} \sigma_{k,j} \cdot N_h \cdot A_k \cdot n_{k,j} \]
Ionization Equilibrium: $I_{\text{ioneq}}$

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\[ \frac{dn_{k,j}}{dt} = (C_{k,j}) - (D_{k,j}) \]

- Photoionization (Verner et al. 1996).
- Auger probabilities (Kaastra & Mewe 1993).
- Collisional ionization (Voronov 1997)
- Radiative recombination (Verner & Ferland 1996)
- Dielectronic recombination (Arnaud & Rothenflug 1985)
**Ionization Equilibrium: \textit{loneq}**

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**MODEL PARAMETERS:**

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- Collisional ionization (Voronov 1997).
- Radiative recombination (Verner & Ferland 1996).
- Dielectronic recombination (Arnaud & Rothenflug 1985).
- Temperature (Te).
- Ionization parameter (\(\xi\)).
- Hydrogen column density (\(N_h\)).
- Redshift (z).
- Turbulent broadening (\(\nu_{\text{turb}}\)).
DATA SAMPLE

Galactic Sources → LMXB
Extragalactic Sources → Blazars

> 1000 counts in the 21-24 Å wavelength region
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We did not impose additional constrains! (e.g. O VII Ka detection)
Gatuzz+17 (in preparation)

18 Galactic sources - 41 Extragalactic sources

165 observations from Chandra
257 observations from XMM-Newton

Galactic Sources → LMXB
Extragalactic Sources → Blazars

> 1000 counts in the 21-24 Å wavelength region

We did not impose additional constraints! (e.g. O VII Ka detection)
A detailed analysis of the ISM

COLD COMPONENT (Te ~ 10000 K): O I, Ne I, Fe I, Metallic Fe
WARM COMPONENT (Te ~ 51000 K): O II, O III, Ne II, Ne III
HOT COMPONENT (Te ~ 1.9 MK): Ne IX, O VII, O VIII

¡COLLISIONAL IONIZATION EQUILIBRIUM!

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SATURATION OF THE LINES

Draine 2011

\[ \frac{W_\lambda}{\lambda} \]

\[ W \sim \sqrt{\ln N_i} \]  
Damped

\[ W \sim \sqrt{N_i} \]  
Saturated

Linear

\[ W \sim N_i \]  
Damped
SATURATION OF THE LINES

\[ W_\lambda / \lambda \]

- **Linear** \( W \sim N_i \)
- **Saturated** \( W \sim \sqrt{\ln N_i} \)
- **Damped** \( W \sim \sqrt{N_i} \)

Draine 2011

Bannister et al. 2003

\[ \text{WD2218+706 C IV} \]
\[ \log N = 13.62 \]
SATURATION OF THE LINES

Gupta et al. 2012

Draine 2011

Gupta et al. 2012

OVII Kα

45 < b (km/s) < 128
16.03 < log(NOVII/cm⁻³) < 16.68

OVII Kβ

NGC3783
SATURATION OF THE LINES

Galactic sources: \( v_{\text{turb}} = 75 \text{ km/s} \) (cold-warm) \( v_{\text{turb}} = 60 \text{ km/s} \) (hot)

Extragalactic sources: \( v_{\text{turb}} = 60 \text{ km/s} \) (cold-warm) \( v_{\text{turb}} = 110 \text{ km/s} \) (hot)
DISTRIBUTION OF THE GAS

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DISTRIBUTION OF THE GAS

\[ N_i = \int_{\text{observer}}^{\text{source}} n_i(r) \, dr \]
DISTRIBUTION OF THE GAS

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COLD-WARM COMPONENTS (Robin et al. 2003)

\[ n(r) = n_0 e^{-\left(\frac{R}{R_c}\right)} e^{-\left(\frac{|z|}{z_c}\right)} \]

\[ R^2 = r^2 \cos^2 b - 2rR_{\text{sun}} \cos b \cos l + R_{\text{sun}}^2 \]

\[ z = r^2 \sin^2(b) \]
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HOT COMPONENT (Nicastro et al. 2016)

\[ n(r) = n_{flat}(r) + n_{sph}(r) \]

\[ n_{flat}(r) = \frac{n_{0,flat}}{\left[ 1 + \left( \frac{R}{R_{c,flat}} \right)^2 + \left( \frac{z}{z_{c,flat}} \right)^2 \right]^{3 \beta_{flat}/2}} \]

\[ n_{sph}(r) = \frac{n_{0,sph}}{\left[ 1 + \left( \frac{r}{r_{c,sph}} \right)^2 \right]^{3 \beta_{sph}/2}} \]

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DENSITY PROFILES

\[ n_0 = (10.28 \pm 5.14) \text{ cm}^{-3} \]
\[ R_c = (4.46 \pm 2.23) \text{ kpc} \]
\[ z_c = (0.34 \pm 0.10) \text{ kpc} \]
\[ \chi/d.o.f = 67.2/56 \]

\[ n_0 = (1.25 \pm 1.14) \text{ cm}^{-3} \]
\[ R_c = (2.91 \pm 1.02) \text{ kpc} \]
\[ z_c = (0.10 \pm 0.01) \text{ kpc} \]
\[ \chi/d.o.f = 72.8/56 \]
DENSITY PROFILES

\[ n_{0,\text{flat}} = (0.48 \pm 0.17) \times 10^{-2} \text{ cm}^{-3} \]
\[ R_{c,\text{flat}} = (50) \text{ kpc} \]
\[ z_{c,\text{flat}} = (0.41 \pm 0.12) \text{ kpc} \]
\[ \beta_{\text{flat}} = (0.96 \pm 0.47) \]

\[ n_{0,\text{sph}} = (2.06 \pm 0.37) \times 10^{-2} \text{ cm}^{-3} \]
\[ r_{c,\text{sph}} = (2) \text{ kpc} \]
\[ \beta_{\text{sph}} = (0.78 \pm 0.29) \]
\[ \chi / \text{d.o.f} = 78.6 / 54 \]
DENSITY PROFILES

--- Total density profile  -- --  Flattened component  ⋯ Spherical component

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DENSITY PROFILES

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WE DO NOT HAVE ENOUGH INFORMATION IN ORDER TO CONSTRAIN THE GALACTIC CENTER PROPERTIES!

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Betrayed by Its Shadow

Astronomers think they may have found where the bulk of the normal matter in the universe lurks: not in galaxies but in a form of intergalactic gas (mostly hydrogen) called the warm-hot intergalactic medium, or WHIM. The name connotes that the gas is less than blazingly hot and, consequently, glows too feebly to see directly. Looking in the interstices of a giant filament of galaxies called the Sculptor Wall, astronomers saw, in essence, the WHIM’s shadow: the gas absorbed x-rays from a background object at a distinctive wavelength.
O VII Ka AT z=0.03 FROM WHIM

1ES 1553+113 (Nicastro et al. 2013)

Mkn 501 (Ren et al. 2014)
ATOMIC DATA WARNING!

O VII Ka at z≈0.03 from WHIM
(Buote et al. 2009, Fang et al. 2010, Ren et al. 2014)
**ATOMIC DATA WARNING!**

O VII $\text{K}\alpha$ at $z \approx 0.03$ from WHIM
(Buote et al. 2009, Fang et al. 2010, Ren et al. 2014)

OR

O II $\text{K}\beta$ at $z = 0$ from ISM
(Nicastro et al. 2016)
Conclusions

- We have developed a new X-ray absorption model, called \textit{IONeq}, which consider ionization equilibrium conditions.

- We have analyzed 18 galactic and 41 extragalactic sources in order to study the X-ray absorption features due to the local ISM.

- The geometrical dependence of the hot absorbers observed in LMXBs spectra provides a hint about the ISM origin of such component.

- We used the column density values obtained from the X-ray spectra to compute density profiles for all three ISM gas components.

- the absence of column density values near the galactic center leads to degeneracy between some of the density profile parameters and therefore some assumptions are required.
THANK YOU!