X-raying the multi-phase ISM along the sightline to the Galactic Center

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Abundance:

- Recent downward revision of solar abundances of C, N, O, and Ne brings an inconsistency between solar model predictions and helioseismological measurements (e.g., Bahcall et al. 2005);
- All metals are produced in stars; stellar abundance vs. ISM one \(\rightarrow\) metal enrichment history of ISM!

Hot gas volume filling factor:

- The importance: interaction between the Galactic disk and corona, the significances of the magnetic field, cosmic rays, and turbulence motion in cooling/heating the ISM, and the pressure balances among multiple ISM phases.
- McKee & Ostriker (1977): “three phase ISM model”, \(\eta_h \gtrsim 80\%\).
- Slavin & Cox (1993): considering the magnetic field and thermal conduction, \(\eta_h \sim 18\%\)!
- Arbitrated by OBSERVATIONS!!!
Absorption line diagnostic & a model \textit{absline}

- Ionization fraction vs. $T$ (Arnaud & Rothenflug 1985):

  ![Graph showing ionization fraction vs. temperature for various ion species]

  - The majority part of hot gas can only be traced by X-ray!

- An advanced absorption line model \textit{absline} (Yao & Wang 2005):

  $I(\epsilon) = I_c(\epsilon) e^{-\tau(\epsilon)}$ (Neither “Gaussian” nor “gabs”!!)

  $\tau(\epsilon) \sim \tau(\epsilon, E_l, f_{ij}, \Gamma, N_H, f_a, T, b_v(T, \xi))$ (All physical parameters!)

  Joint analysis capability!
Source: 4U 1820–303 (NGC 6624)

Galactic center region: Why 4U 1820–303?

1. LMXB: no stellar wind confusion;
2. Very bright and super compact (< 0.1\(R_\odot\)): no systematic confusion;
3. Residing in NGC 6624 (l, b) = (2°.79, -7°.91) and D = 7.6 kpc

\(\Rightarrow \sim 1\) kpc below the disk plane!
4. Pulsar (PSR 1820-30A/B) DM: 87 cm\(^{-3}\) pc \(\sim 2.7 \times 10^{20}\) cm\(^{-2}\).
5. UV observations on nearby stars: HD 167402 and HD 163522 (O VI and Al III line; \(v_b=62\) km s\(^{-1}\)) (Savage et al. 1990).
### Chandra observations & diagnostic results (1)

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Obs. Date</th>
<th>Detector and Grating</th>
<th>Exp. (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>98</td>
<td>2000 Mar. 10</td>
<td>HRC-LTEG</td>
<td>15.12</td>
</tr>
<tr>
<td>1021</td>
<td>2001 Jul. 21</td>
<td>ACIS-HETG</td>
<td>9.70</td>
</tr>
<tr>
<td>1022</td>
<td>2001 Sep. 12</td>
<td>ACIS-HETG</td>
<td>10.89</td>
</tr>
</tbody>
</table>

Our final spectrum: **co-add all the three observations!**
Chandra observations & diagnostic results (2)

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Assuming an isothermal temperature distribution, and a CIE absorption plasma:

\[ b_v = 255(165, 369) \text{ km s}^{-1}, \]

\[ \log[T (\text{K})] = 6.34(6.29, 6.41), \]

\[ \log[N_{\text{O VII}} (\text{cm}^{-2})] = 16.3(16.1,16.5), \]

\[ \log[N_{\text{O VIII}} (\text{cm}^{-2})] = 16.4(16.2, 16.6), \]

\[ \log[N_{\text{Ne IX}} (\text{cm}^{-2})] = 16.0(15.9, 16.1), \]

Ne/O abundance ratio: 1.4(0.9, 2.1) solar (Anders & Grevesse 1989)
Chandra observations & diagnostic results (4)

—— How is Ne/O ratio influenced if isothermal and CIE assumptions are relaxed? ——

dN\(_H\)(T) \propto e^{-\frac{(\log T - \log T_0)^2}{2(\sigma \log T)^2}} d[\log(T)]

dN\(_H\)(T) \propto T^\gamma dT

Ne/O abundance ratio is \(\sim\) 1.4 solar value!

Comparison: (N/O) in cool phase is 1.6(0.9, 2.3) times solar toward Cyg X–2 (Takei et al. 2002).

The measures on the Sun:

✓ (Ne/O) = 2.85 \pm 0.07 solar; solar model problem solved!!! (Drake & Testa 2005)

About 3\(\sigma\) larger than our Ne/O ratio in hot phase!

✓ (Ne/O) \sim 1 solar (Schmelz et al. 2005; Young 2005)

Consistent with our measurement in hot phase!

Solar model problem comes back?!
Define $N^w_O = N_{\text{OII}} + N_{\text{OIII}}$, ($N_{\text{OII}}$ and $N_{\text{OIII}}$ are measured in this work)

$N^h_O = \beta N_{\text{OVII}} + N_{\text{OIII}}$, \(\beta \geq 1\) for OVI and OIX.

\[(O/H)^h = \alpha (O/H)^w, \alpha \geq 1,\]

\[\theta = \frac{T^w N_{\text{OII}} + N_{\text{OIII}}}{T^h N_{\text{OVII}} + N_{\text{OIII}}}, \quad T^w \sim 8 \times 10^3 \text{ K},\]

Pressure balance: $T^h n^h = \zeta T^w n^w$, \(\zeta \geq 1\) for other pressure source (magnetic field?)

\[\eta^h + \eta^w + \eta^c = 1 \text{ and } \eta^h = \chi \eta^w.\]

\[\Rightarrow \chi = \frac{\beta}{\zeta \alpha \theta}.\]

\[
\begin{align*}
\ast & \quad \text{For } \alpha = \beta = \zeta = 1, \quad \chi = 36(14, 67). \\
& \quad \text{For } \eta^w = \eta^c, \quad \eta^h = 0.95(0.92, 0.99)!
\end{align*}
\]

\[
\ast \quad \text{Requiring } \eta^h \lesssim 0.8, \quad \zeta \gtrsim 4.5(1.8, 8.2)!
\]

Consistent with the situation in Local ISM (Bowyer et al. 1995)!!!
Assuming the emission and absorption are produced in the same gas:

\( EM = n_e n_H D \eta^h = 0.84 n^2_H D \eta^h \), factor 0.84 accounting for He contribution;

\( N_H = n_H D \eta^h \), \( D \) is the distance.

\[ \eta^h = 0.84 N^2_H / (EM \times D) \]

- **ROSAT 3/4 keV SXB** (Snowden et al. 1997):
  - Transfer the intensity to emission measure: \( EM \sim 0.12 / A \) cm\(^{-6}\) pc
  - The real measurement: \( N_H = 1.26(0.79, 1.58) / A \times 10^{20} \) cm\(^{-2}\),
  - \( \eta^h = 1.53(0.96, 1.93) / A \) \( A \) is the metallicity!

Taking into account the extragalactic contribution will cause an increase of \( \eta^h \)!

- **H\( \alpha \) map** (Finkbeiner 2003) (warm phase filling factor):
  - H\( \alpha \) measure: \( 5R \sim EM = 10 \kappa \) cm\(^{-6}\) pc (\( \kappa \gg 1 \) accounting for the extinction correction).
  - The pulsar \( DM, N_e \sim 2.68 \times 10^{20} \), tracing all the free electrons.
  - \( \eta^w = 0.059 \xi^2 / \kappa \), \( \xi (\leq 1) \) accounting for the warm electron fraction.

The filling factor of hot gas is indeed large!
The OVII, OVIII, and NeIX Kα absorption lines have been clearly detected in the Chandra grating spectrum of 4U 1820–303.

A joint-analysis of the above lines with non-detected OVII Kβ absorption line provides $b_v$, $T$, and $N_{ion}$. The derived Ne/O abundance ratio of 1.4(0.9, 2.1) times solar, is insensitive to the exact temperature distribution assumed.

The obtained Ne/O ratios is significantly smaller than the value indicated in the recent emission line measurement of solar-like stars, but consistent with the direct measure from the Sun itself.

For the first time, we provide an observational constraint to the hot gas filling factor $\eta^h$; $\eta^h \sim 1$, and/or the thermal pressure of the hot gas is several times higher than that of warm one (a situation similar to that in local ISM).
IUE observation on HD 163522: Al III ($v_b=62$ km s$^{-1}$) (Savage, Sembach, & Massa 1990).
For $v_b = 62 \text{ km s}^{-1}$:

- $\log[N_{\text{OI}}(\text{cm}^{-2})] = 17.6(17.3, 17.9)$
- $\log[N_{\text{OII}}(\text{cm}^{-2})] = 17.4(16.9, 17.6)$
- $\log[N_{\text{OIII}}(\text{cm}^{-2})] = 17.0(16.5, 17.5)$

A 50% variation of $v_b$ only causes $\lesssim 20\%$ changes of $N$. 
HRC-LEG only!
Parameters: $\lambda_E = 14.28(14.23, 14.35) \, \text{Å}$, $\tau_E = 8.6(7.0, 10.2) \times 10^{-2}$. Adopting the cross section $3.67 \times 10^{-19} \, \text{cm}^{-2}$ (Balucinska-Church & McCammon 1992), we obtain $N_{\text{Ne}} = 2.3(1.9, 2.7) \times 10^{17} \, \text{cm}^{-2}$. 
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<table>
<thead>
<tr>
<th>Included line(s)</th>
<th>$b_v$ (cm$^{-2}$)</th>
<th>$\log N_{\text{O}^+6}$</th>
<th>$\log T$(K)</th>
<th>Ne/O</th>
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<tr>
<td>O$^+6$Kα</td>
<td>$&lt; 446$</td>
<td>17.2(16.3,18.7)</td>
<td>…</td>
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### Chandra observations & diagnostic results (6)

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<tr>
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<th>(b_v) (cm(^{-2}))</th>
<th>log (N_{O+6})</th>
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The diagram shows the relationship between \(b_v\) (cm\(^{-2}\)) and \(b_v\) (km s\(^{-1}\)).
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<td>325(197,490)</td>
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<td>6.34(6.29,6.41)</td>
<td>⋯</td>
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<tr>
<td>$O^{+6}K\alpha$, $K\beta$, $O^{+7}K\alpha$, $Ne^{+8}K\alpha$</td>
<td>255(165,369)</td>
<td>16.3(16.1,16.5)</td>
<td>6.34(6.29,6.41)</td>
<td>1.4(0.9,2.1)</td>
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\[ \text{log } N_{O+7} = 16.4(16.2, 16.6), \quad \text{log } N_{Ne+8} = 16.0(15.9, 16.1). \]
### Applications (3) – a summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ISM Phase</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>neutral</td>
<td>warm ionized</td>
<td>hot</td>
</tr>
<tr>
<td>column density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>17.6(17.3, 17.9)</td>
<td>17.6(17.2, 17.8)</td>
<td>16.7(16.5, 16.8)</td>
</tr>
<tr>
<td></td>
<td>17.9(17.7, 18.1)</td>
<td>17.6(17.3, 17.8)</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>21.2 (^e)</td>
<td>20.4</td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>17.4(17.3, 17.5)</td>
<td>16.0(15.9, 16.1)</td>
<td></td>
</tr>
<tr>
<td>Abundances</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O/H</td>
<td>0.3(0.2, 0.6)</td>
<td>2.0(0.8, 3.6)</td>
<td>(\gtrsim 0.94)</td>
</tr>
<tr>
<td></td>
<td>0.5(0.3, 0.9)</td>
<td>2.2(1.1, 3.5)</td>
<td></td>
</tr>
<tr>
<td>Ne/H</td>
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<td></td>
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The measures of Takei et al. (2002) toward Cygnus X–2 (87.°30, -11.°29):

- (O/H) = 0.47 ± 0.16 solar in cool phase, and will be 1.5 times higher if consider the compound form, toward Cygnus X–2.
  Our value is $N_{\text{OI}+\text{OII}+\text{OIII}}/[N(\text{HI})+(1 - \xi)\eta N_e] = 0.52(0.33, 0.85)$ solar.
- (Ne/H) = 0.75 ± 0.20 from Takei et al. (edge study).
  (Ne/H) = 1.2 ± 0.2 (this work). Metal enhancement toward GC region!?
- (Ne/O) = 1.6(0.9, 2.3) in cool atomic phase (Takei et al.)
  (Ne/O) = 2.1(1.3, 3.5) in cool phase, and 1.4(0.9, 2.1) in hot phase (this work).

The measures on the Sun:

- (Ne/O) = 2.8507 solar; solar model problem solved!!! (Drake & Testa 2005)
  Apparently consistent with our value in cool phase.
  Note: uncertainty of compound oxygen contribution!
  About 3 larger than our Ne/O ratio in hot phase!
- (Ne/O) = 1 solar (Schmelz et al. 2005; Young 2005)
  Consistent with our measurement in hot phase!
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