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

Yangsen Yao

MIT Kavli Institute

Q. Daniel Wang

Umass Astronomy Dept.

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Introduction

√ Abundance:

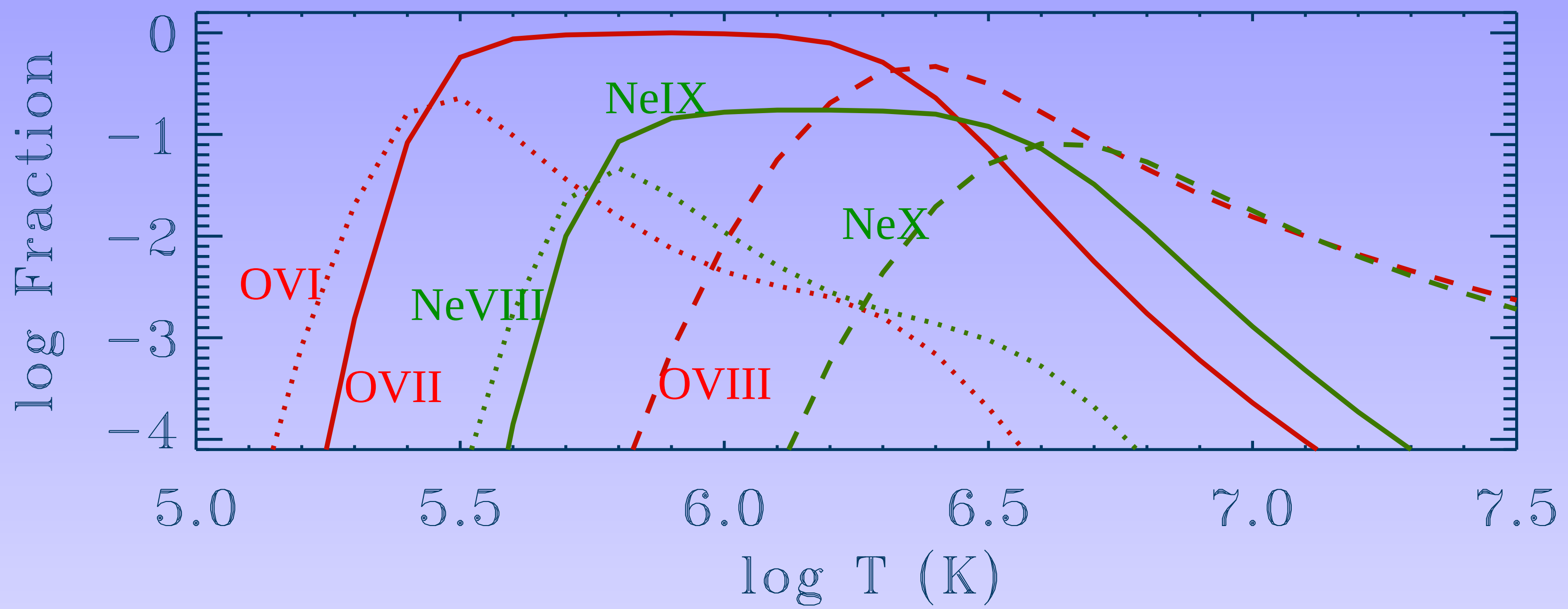
- ⋆ Recent downward revision of solar abundances of C, N, O, and Ne brings an inconsistency between solar model predictions and helioseismological measurements (e.g., Bahcall et al. 2005);
- ⋆ All metals are produced in stars; stellar abundance vs. ISM one —> metal enrichment history of ISM!

√ 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 *absline*

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



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

- An advanced absorption line model *absline* (Yao & Wang 2005):

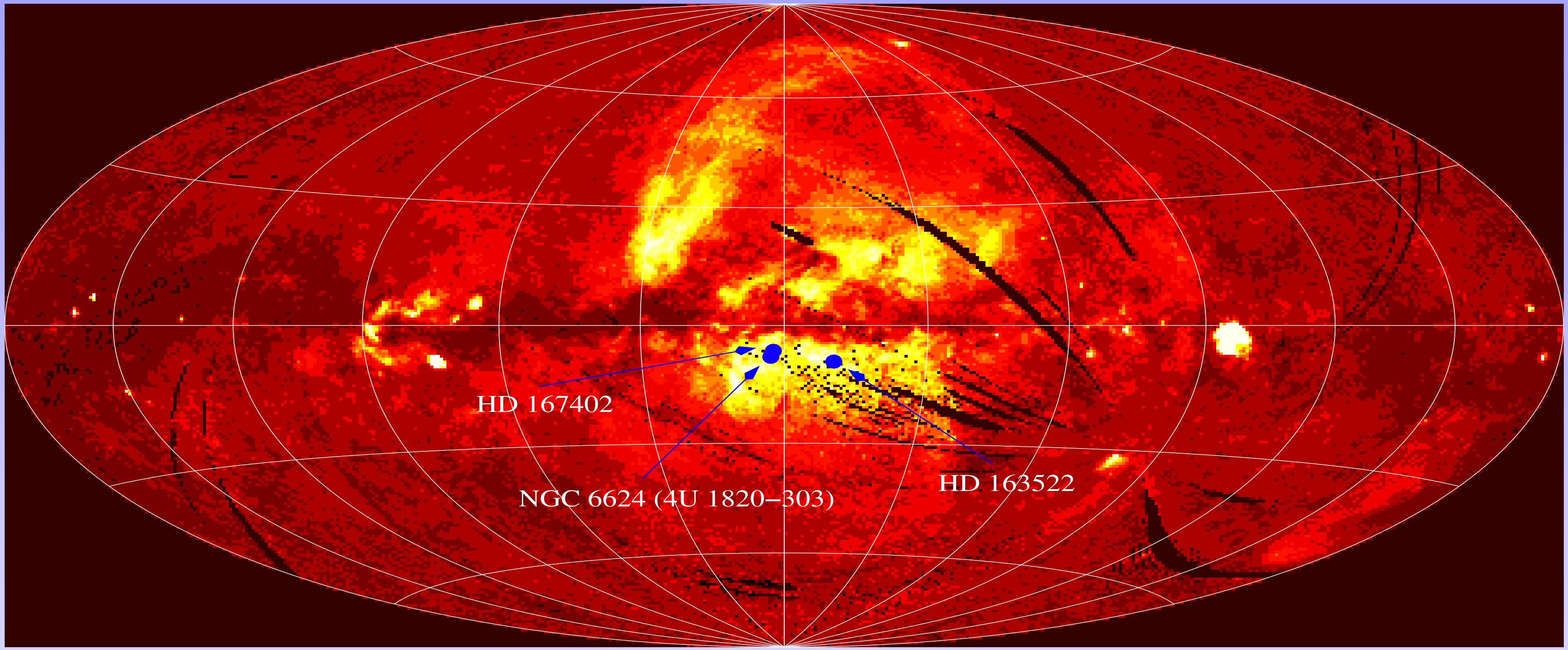
  $I(\epsilon) = I_c(\epsilon)e^{-\tau(\epsilon)}$ (Neither "Gaussian" nor "gabs"!!)

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

  Joint analysis capability!

Source: 4U 1820–303 (NGC 6624)

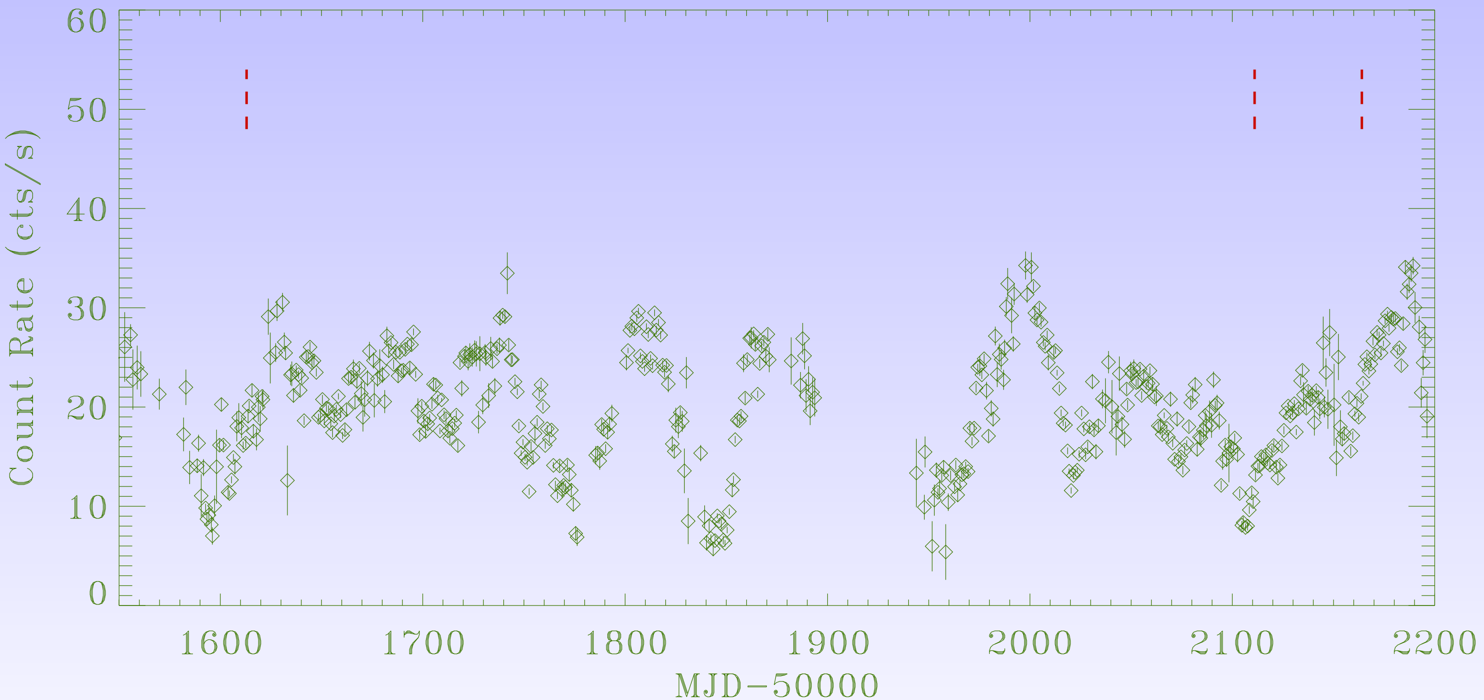
Galactic center region: Why 4U 1820–303?



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 = 7.6kpc
   $\Longrightarrow \sim$ 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).

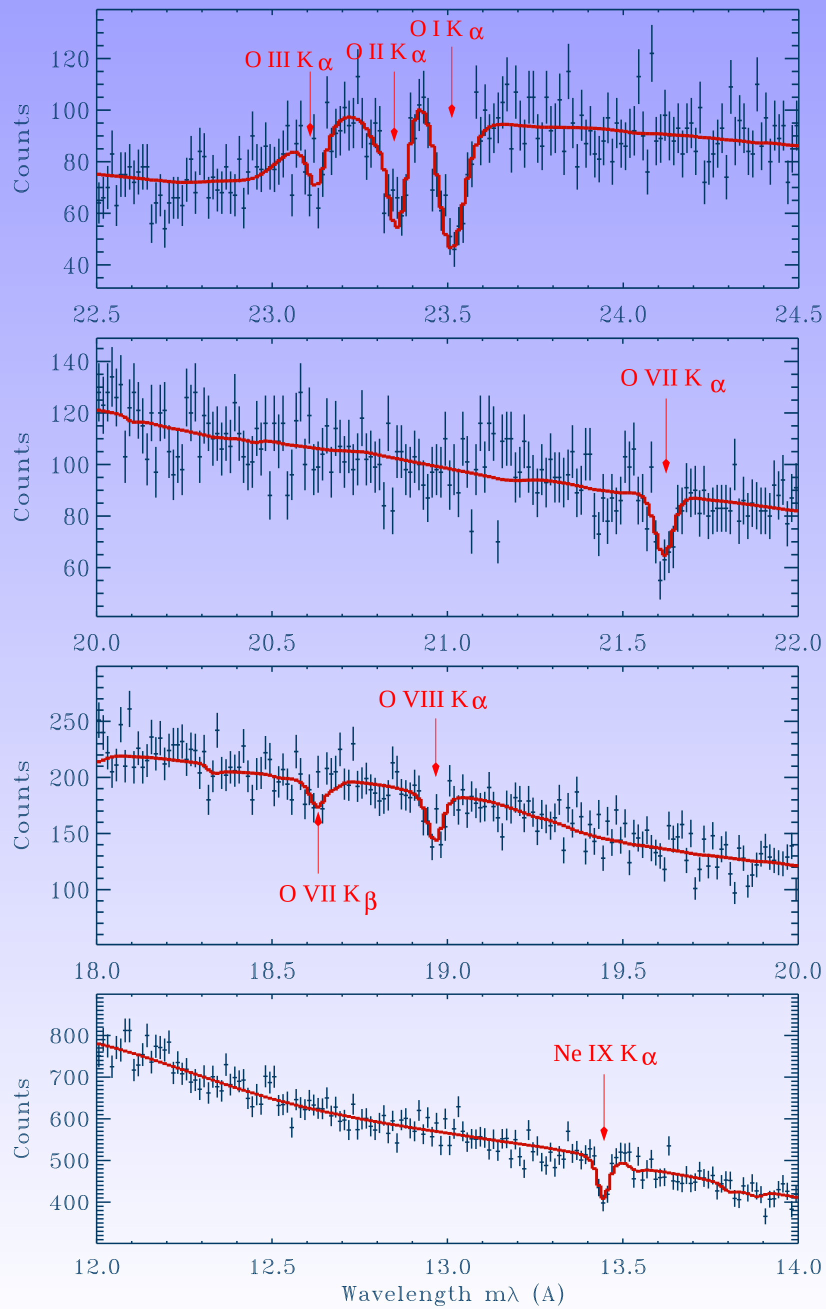
Chandra observations & diagnostic results (1)

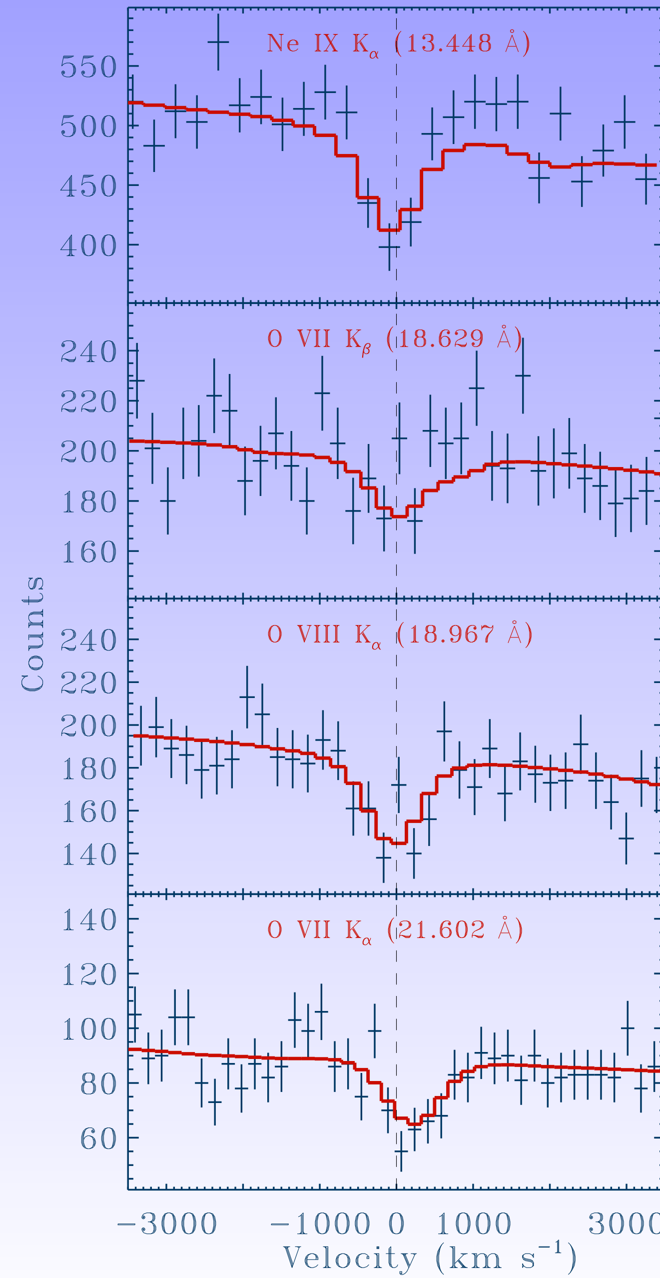
ObsID	Obs. Date	Detector and Grating	Exp. (ks)
98	2000 Mar. 10	HRC-LETG	15.12
1021	2001 Jul. 21	ACIS-HETG	9.70
1022	2001 Sep. 12	ACIS-HETG	10.89



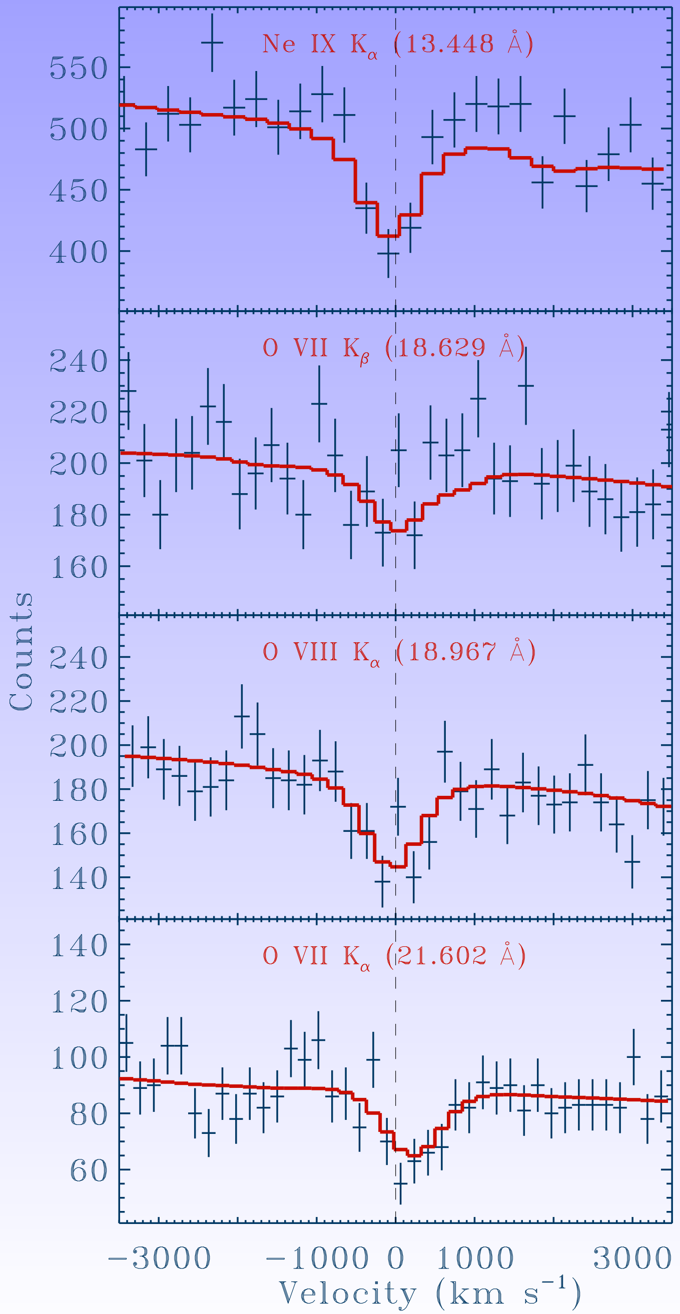
Our final spectrum: co-add all the three observations!

Chandra observations & diagnostic results (2)





Chandra observations & diagnostic results (3)



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

$b_v = 255(165, 369)$ km s^{-1},

log[T (K)] = 6.34(6.29, 6.41),

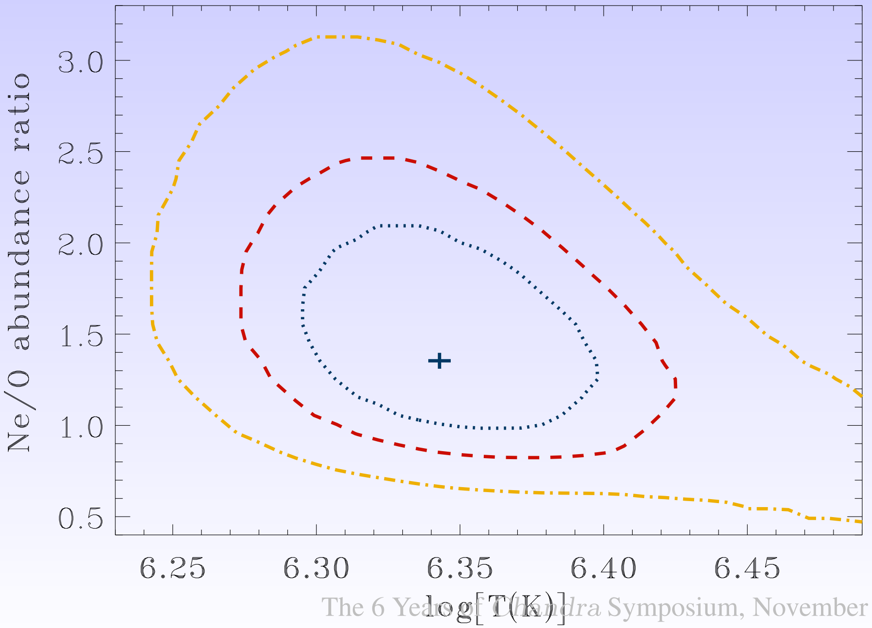
log[$N_{\rm OVII}$ (cm^{-2})] = 16.3(16.1,16.5),

log[$N_{\rm OVIII}$ (cm^{-2})] = 16.4(16.2, 16.6),

log[$N_{\rm NeIX}$ (cm^{-2})] = 16.0(15.9, 16.1),

Ne/O abundance ratio: 1.4(0.9, 2.1) solar

(Anders & Grevesse 1989)

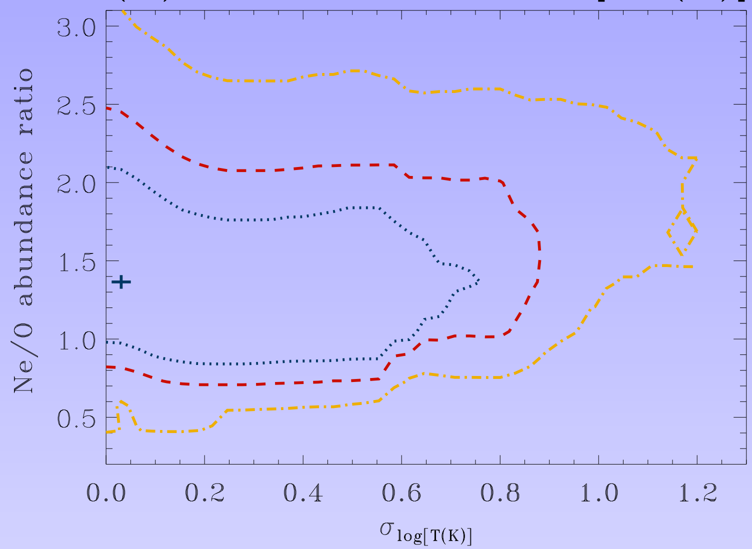


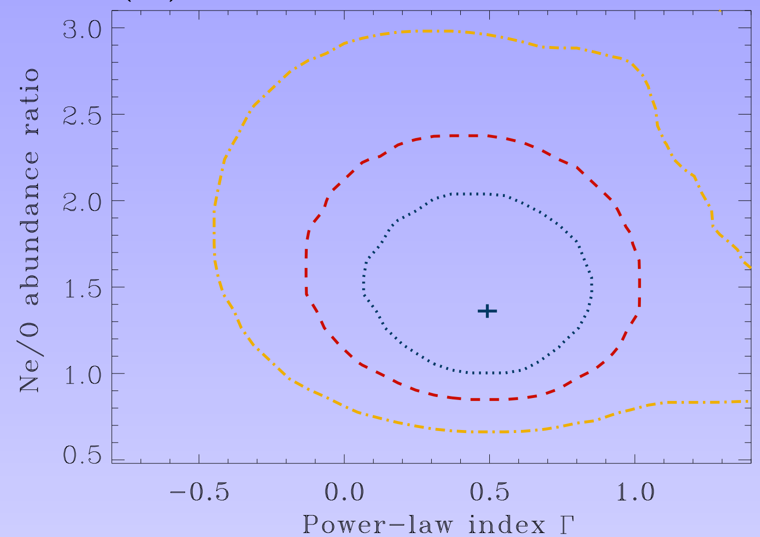
Chandra observations & diagnostic results (4)

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

$$dN_H(T) \propto e^{\frac{-(logT - logT_0)^2}{2(\sigma_{logT})^2}} d[log(T)]$$

$$dN_H(T) \propto T^{\Gamma} dT$$





Ne/O abundance ratio is ~ 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 3σ 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!
  Solar model problem comes back?!

Hot gas filling factor (1)

✓ Define $N_O^w = N_{\rm OII+OIII}$, ($N_{\rm OII}$ and $N_{\rm OIII}$ are measured in this work)
$N_O^h = \beta N_{\rm OVII+OVIII}$, $\beta \geq 1$ for OVI and OIX.
$(O/H)^h = \alpha (O/H)^w$, $\alpha \geq 1$,
$\theta = \frac{T^w N_{\rm OII+OIII}}{T^h N_{\rm OVII+OVIII}}$, $T^w \sim 8 \times 10^3$ K,
Pressure balance: $T^h n^h = \zeta T^w n^w$, $\zeta \geq 1$ for other pressure source (magnetic field?)
$\eta^h + \eta^w + \eta^c = 1$ and $\eta^h = \chi \eta^w$.
$\Rightarrow \boxed{\chi = \frac{\beta}{\zeta \alpha \theta}}$.

- ⋆ For $\alpha = \beta = \zeta \simeq 1$, $\chi = 36(14, 67)$.
  For $\eta^w = \eta^c$, $\eta^h = 0.95(0.92, 0.99)!$
- ⋆ Requiring $\eta^h \lesssim 0.8$, $\zeta \gtrsim 4.5(1.8, 8.2)!$
  Consistent with the situation in Local ISM (Bowyer et al. 1995)!!!

Hot gas filling factor (2)

✓ Assuming the emission and absorption are produced in the same gas!
$EM = n_e n_H D\eta^h = 0.84 n_H^2 D\eta^h$, factor 0.84 accounting for He contribution;
$N_H = n_H D\eta^h$, D is the distance.

$\eta^h = 0.84 N_H^2/(EM \times D)$

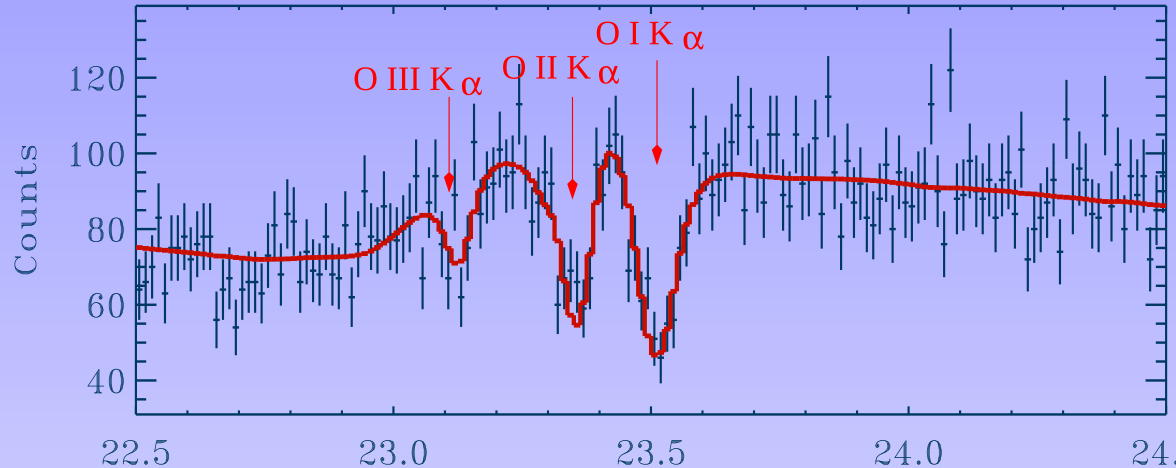
- ⋆ *ROSAT* 3/4 keV SXB (Snowden et al. 1997):
  Transfer the intensity to emission measure: EM $\sim$ 0.12/A cm^{-6} pc
  The real measurement: $N_{\rm H} = 1.26(0.79, 1.58)/{\rm A} \times 10^{20} {\rm cm}^{-2}$,
  $\eta^h = 1.53(0.96, 1.93)/A$ A is the metallicity!
  Taking into account the extragalactic contribution will cause an increase of η^h!
- ⋆ Hα map (Finkbeiner 2003) (warm phase filling factor):
  Hα measure: $5R \sim$ EM = 10κ cm^{-6} pc ($\kappa \gtrsim 1$ 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.

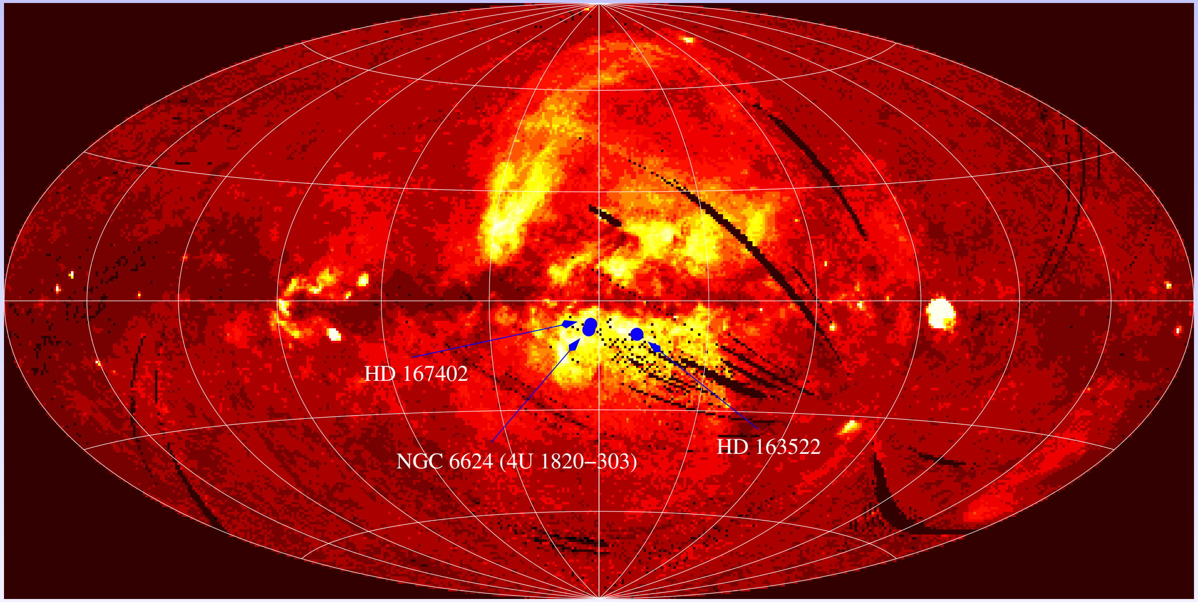
The filling factor of hot gas is indeed large!

Summary

- ✓ 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 η^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).

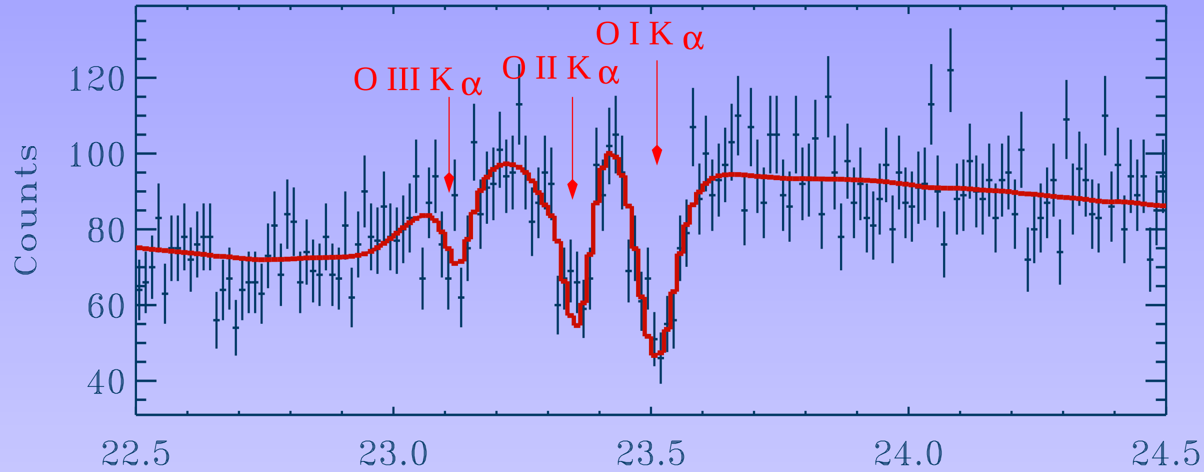
Chandra observations & diagnostic results (4)





IUE observation on HD 163522: Al III (v_b=62 km s^{-1}) (Savage, Sembach, & Massa 1990).

Chandra observations & diagnostic results (4)



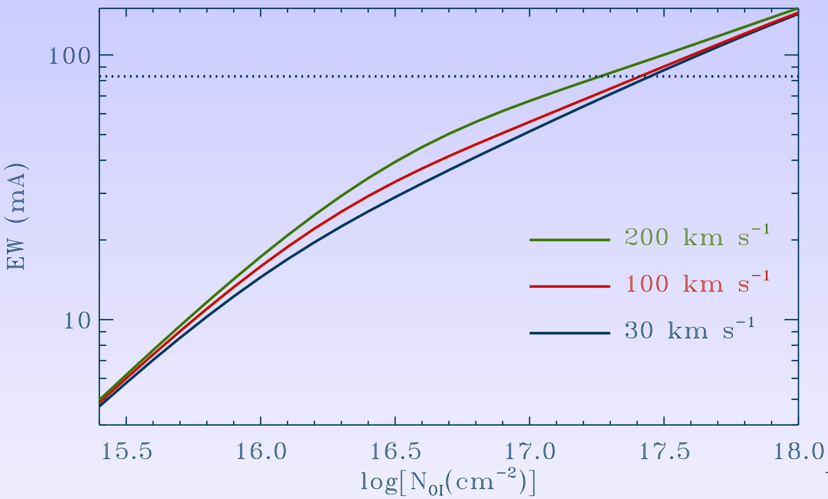
For v_b = 62 km s^{-1}:

log[N_{OI}(cm^{-2})] = 17.6(17.3, 17.9)

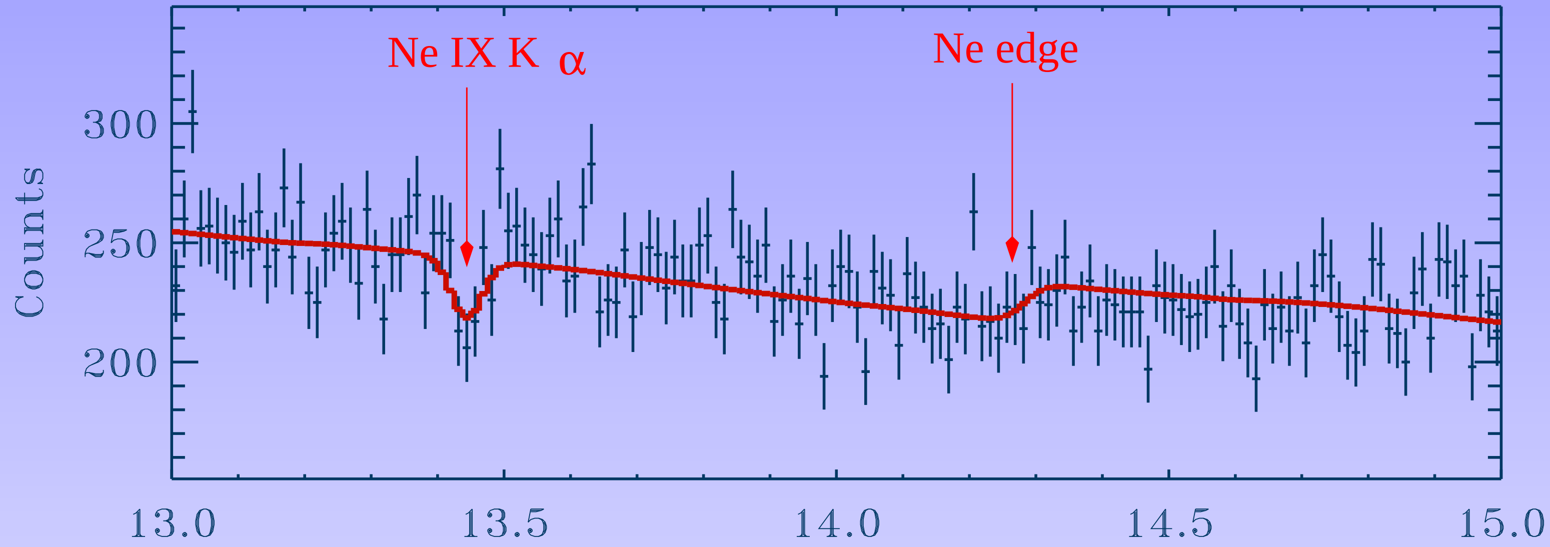
log[N_{OII}(cm^{-2})] = 17.4(16.9, 17.6)

log[N_{OIII}(cm^{-2})] = 17.0(16.5, 17.5)

A 50% variation of v_b only causes $\lesssim$ 20% changes of N.



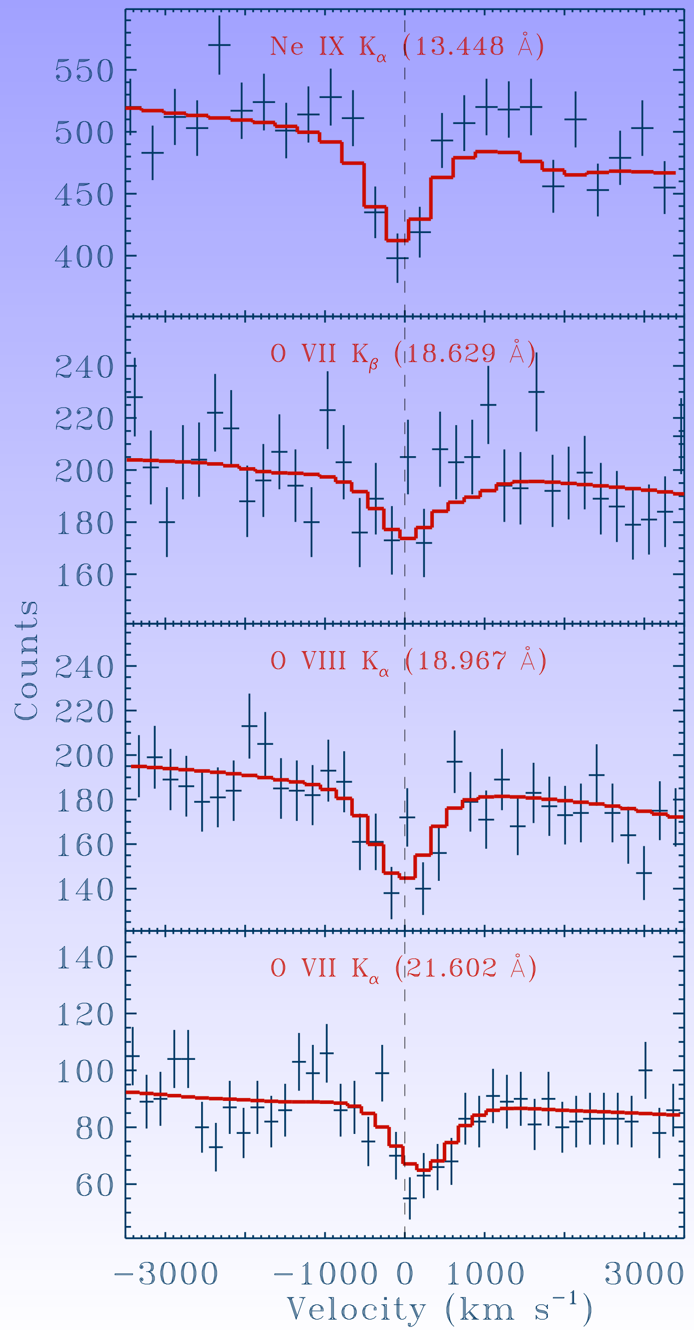
Chandra observations & diagnostic results (5)



HRC-LEG only!

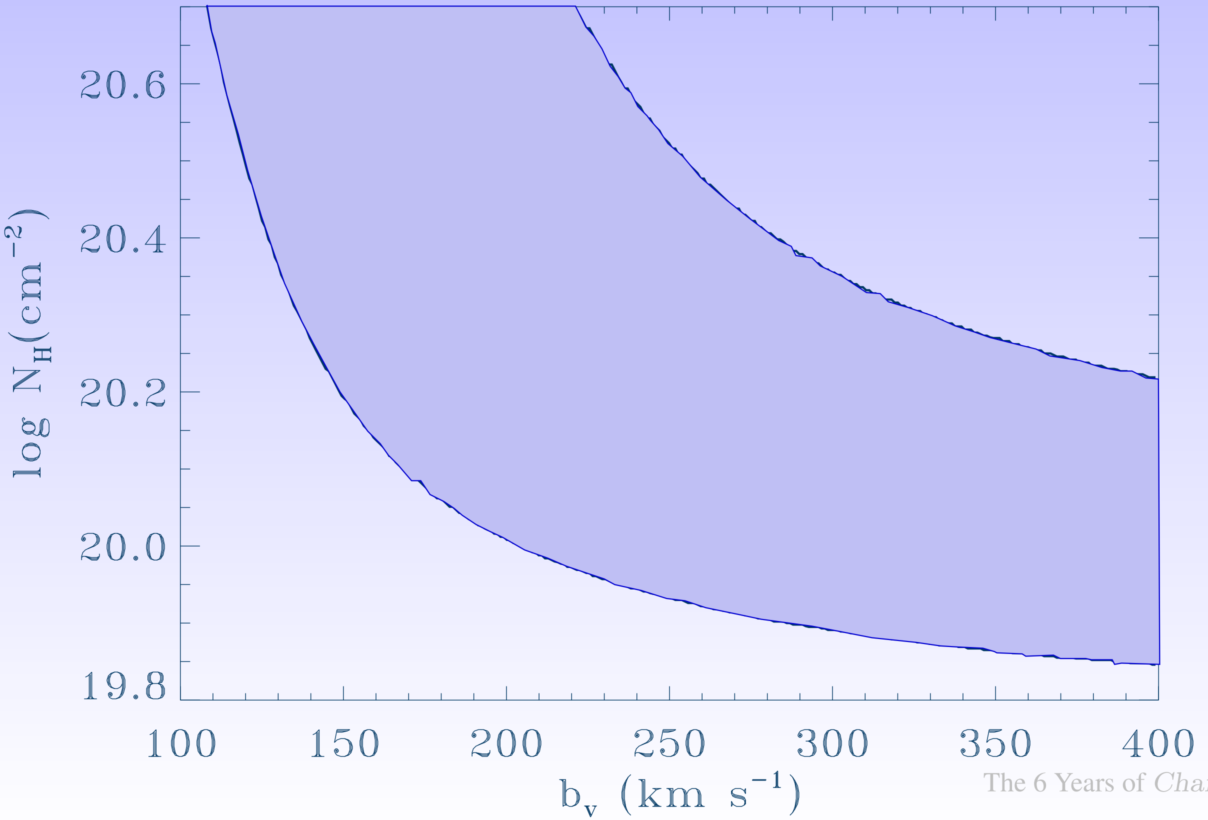
Parameters: λ_E = 14.28(14.23, 14.35) Å, $\tau_E = 8.6(7.0, 10.2) \times 10^{-2}$. Adopting the cross section 3.67×10^{-19} cm^{-2} (Balucinsha-Church & McCammon 1992), we obtain $N_{\rm Ne} = 2.3(1.9, 2.7) \times 10^{17}$ cm^{-2} .

Chandra observations & diagnostic results (6)



Chandra observations & diagnostic results (6)

Included line(s)	b_v (cm^{-2})	log N_{O+6}	log T(K)	Ne/O
$O^{+6}K\alpha$	< 446	17.2(16.3,18.7)	$\cdots$	$\cdots$



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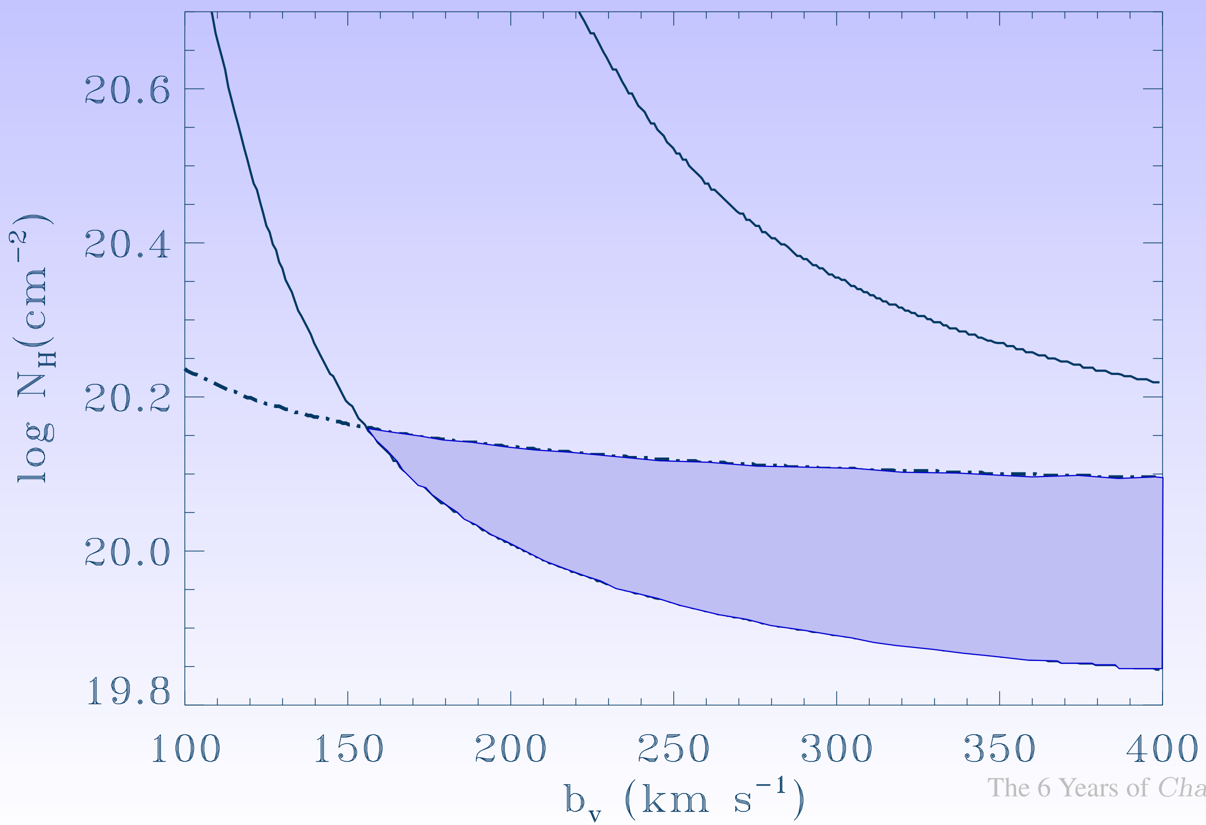
$O^{+6}K\alpha$	< 446	17.2(16.3,18.7)	$\cdots$	$\cdots$
$O^{+6}K\alpha$, $K\beta$	298(169,505)	16.3(16.1,16.5)	$\cdots$	$\cdots$



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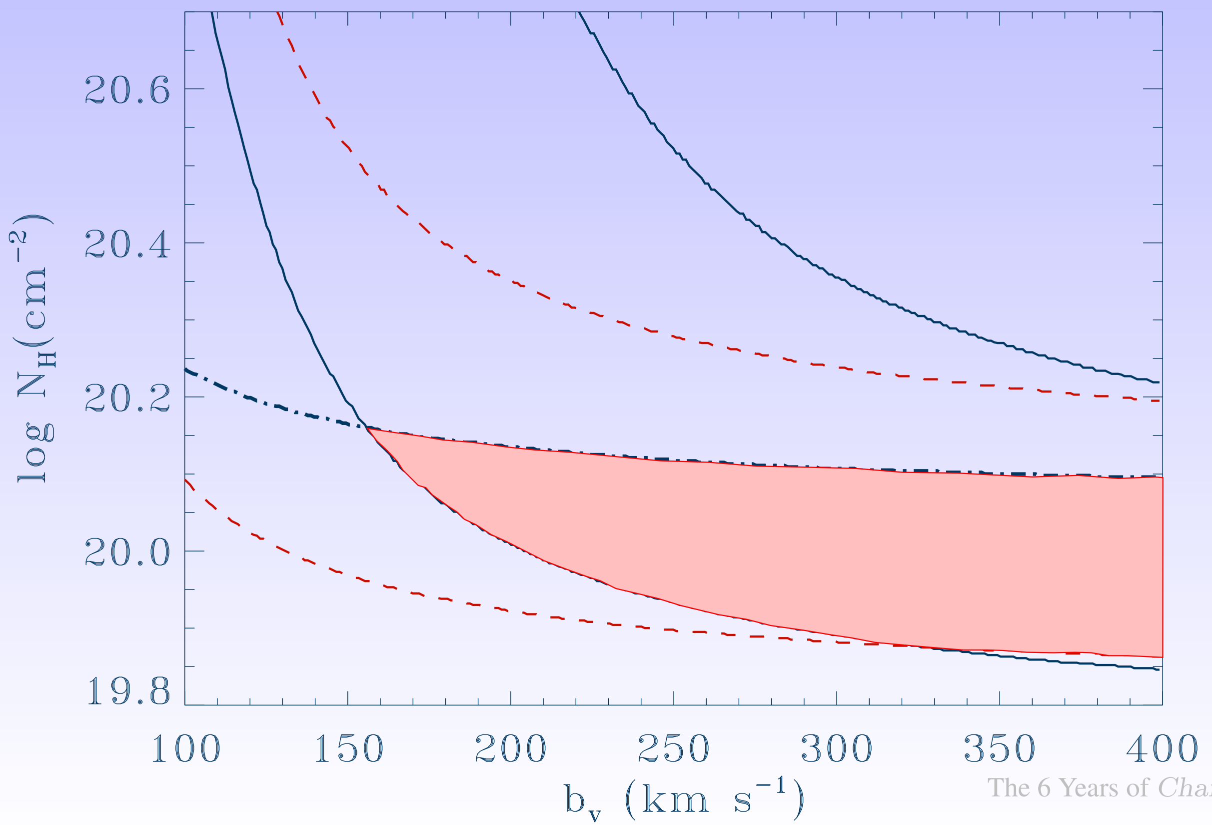
$O^{+6}K\alpha$, $K\beta$	298(169,505)	16.3(16.1,16.5)	···	···
$O^{+6}K\alpha$, $K\beta$, $O^{+7}K\alpha$	325(197,490)	16.3(16.1,16.5)	6.34(6.29,6.41)	···



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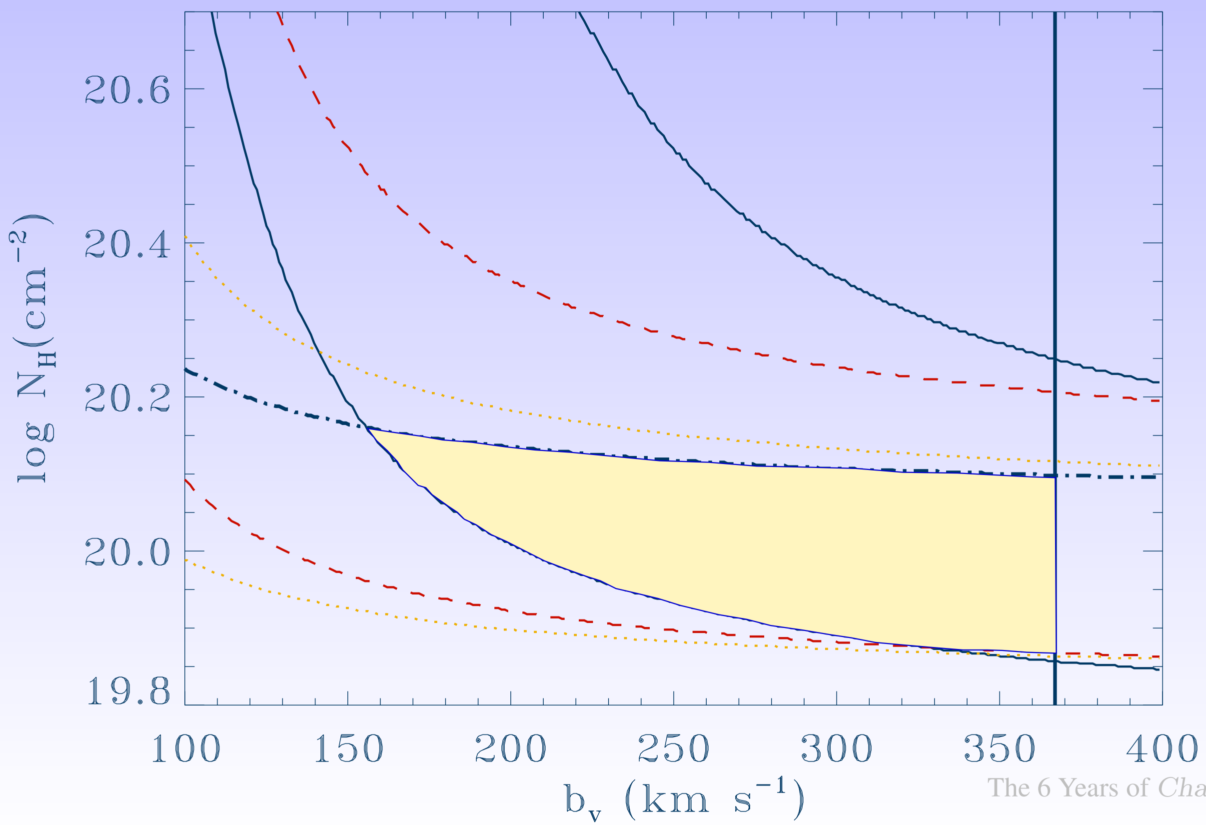
O^{+6}Kα, Kβ	298(169,505)	16.3(16.1,16.5)	$\cdots$	$\cdots$
O^{+6}Kα, Kβ, O^{+7}Kα	325(197,490)	16.3(16.1,16.5)	6.34(6.29,6.41)	$\cdots$
O^{+6}Kα, Kβ, O^{+7}Kα, Ne^{+8}Kα	255(165,369)	16.3(16.1,16.5)	6.34(6.29,6.41)	1.4(0.9,2.1)

log N_{O+7} = 16.4(16.2, 16.6), log N_{Ne+8} = 16.0(15.9, 16.1).



Applications (3) – a summary

<table>
<tr><th></th><th colspan="3">ISM Phase</th></tr>
<tr><th>Parameter</th><th>neutral</th><th>warm ionized</th><th>hot</th></tr>
<tr><td colspan="4">column density</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 colspan="2">17.9(17.7, 18.1)</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">17.6(17.3, 17.8)</td></tr>
<tr><td>H</td><td>21.2^{e}</td><td colspan="2">20.4</td></tr>
<tr><td>Ne</td><td colspan="2">17.4(17.3, 17.5)</td><td>16.0(15.9, 16.1)</td></tr>
<tr><td colspan="4">Abundances</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 colspan="2">0.5(0.3, 0.9)</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">2.2(1.1, 3.5)</td></tr>
<tr><td>Ne/H</td><td>1.2(1.0, 1.4)</td><td></td><td></td></tr>
<tr><td>Ne/O</td><td colspan="2">2.1(1.3, 3.5)</td><td>1.4(0.9, 2.1)</td></tr>
</table>

Applications (3) – comparisons

- ✓ 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 $N_{\rm OI+OII+OIII}/[N({\rm HI})+(1-\xi)\eta N_e]$ = 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).

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- The measures on the Sun:
  - ⋆ (Ne/O) $= 2.85 \pm 0.07$ solar; solar model problem solved!!! (Drake & Testa 2005)
    Apparently consistent with our value in cool phase.
    Note: uncertainty of compound oxygen contribution!
    About 3σ 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?!