Mixing of hot and cold gas in shocked plasma

LETG observation of BD+30°3639 (Campbell's star)

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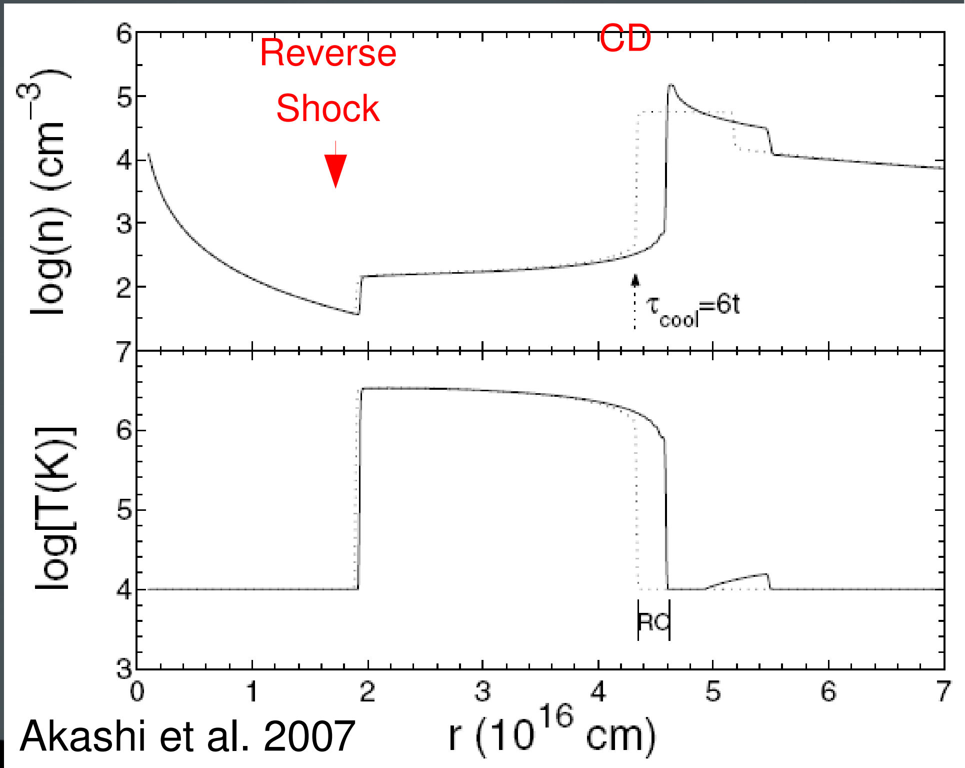
Planetary Nebula BD+30°3639

- Intermediate mass (1-8 $M_\odot$), post-AGB star.
- Composed of:
  - Slowly expanding (~30 km/s) AGB-gas envelope
  - Fast post-AGB wind ~700 km/s (Leuenhagen et al. 1996)
  - Central to-be white dwarf
- Assumed distance: 1.2 kpc (Li et al. 2002)

X-rays from PN

- Fast wind from the central star is shocked when hitting the slow expanding envelope.
- X-ray emitting bubble is formed between the reverse shock and the contact discontinuity (CD).



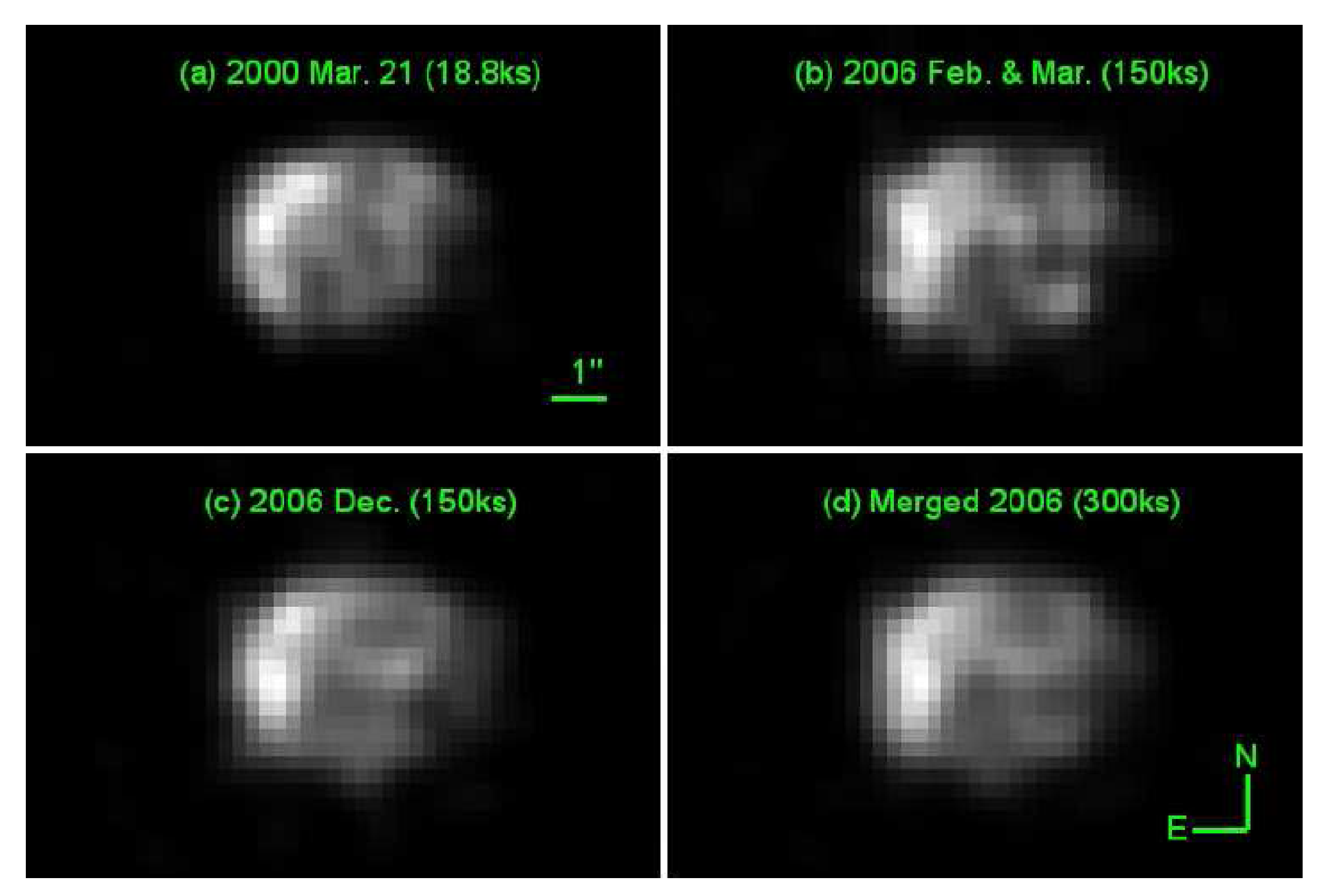
BD+30°3639 Abundances and T

- Imaging spectroscopy (ASCA, Suzaku, Chandra-ACIS) find:
  - C, N, Ne to be significantly over abundant
  - Fe significantly depleted

  (Kastner et al. 2000, Maness et al. 2003, Murashima et al. 2006)
- However, optical/IR measurements of the envelope find Ne to be depleted.
- Predicted temperatures for the shocked gas (spherical model) are ~4 times higher than measured.

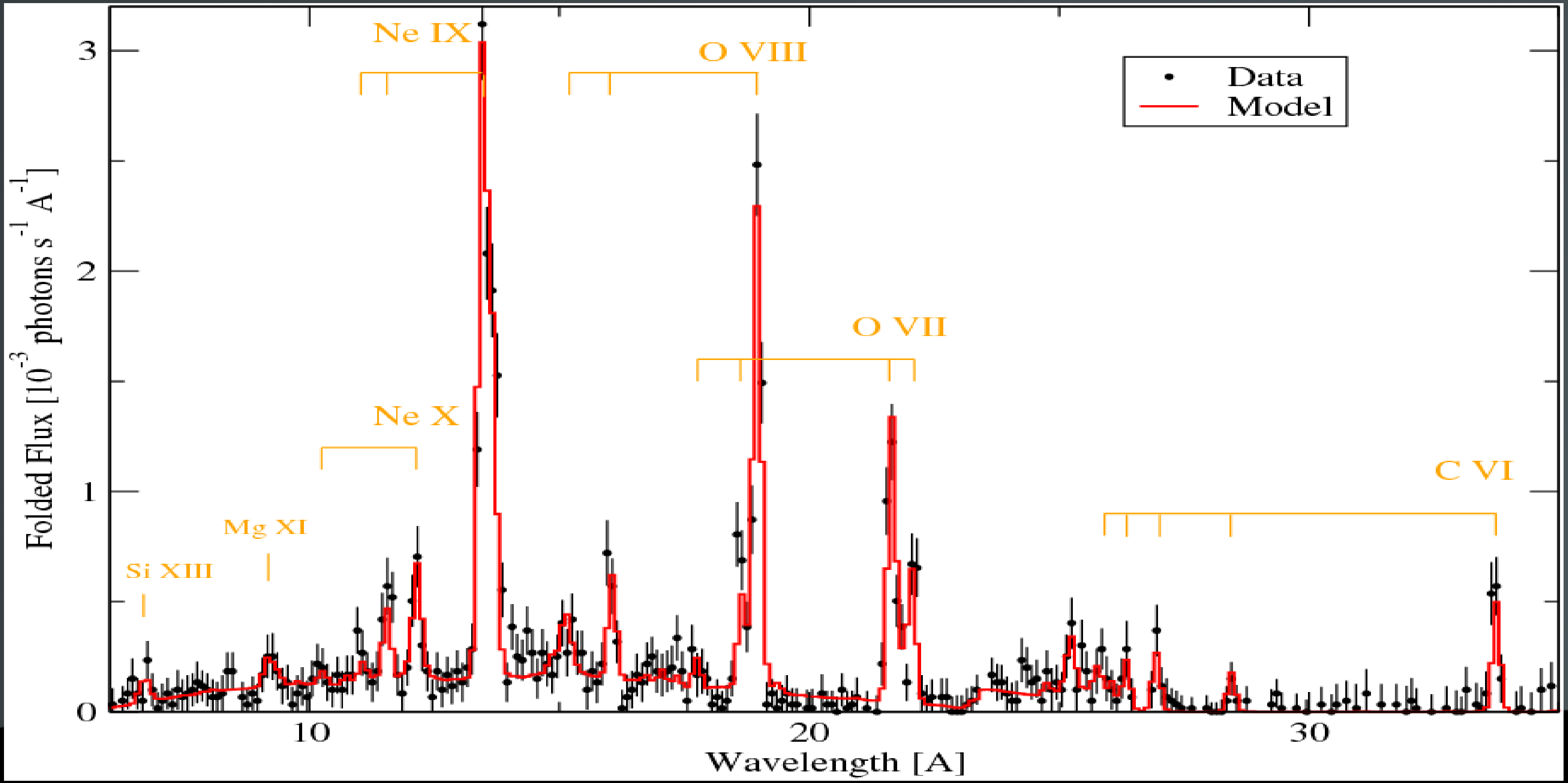
Chandra observations

- 5 ACIS+LETG observations during 2006 totaling ~300 ks
- The X-ray bubble is slightly resolved and shows variations from image obtained in 2000 (Yu et al. in writing)



LETG spectrum

- 2 temperatures APEC model with absorption ($N_H = 0.24\ 10^{22}\ cm^2$)
- Energy dependent Gaussian smoothening to account for spatial broadening



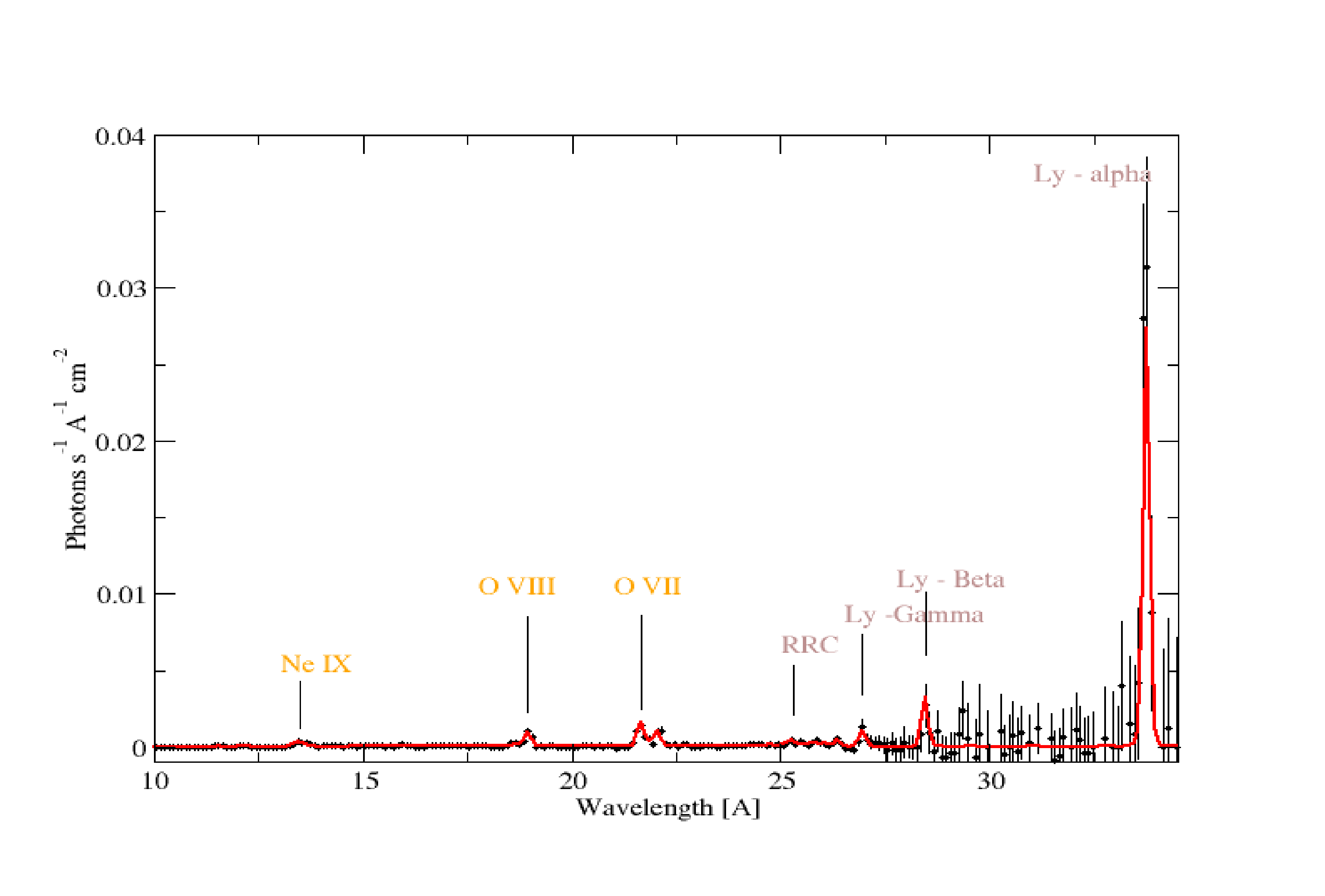
Absorbed thermal model

- kT_1 = 160 eV, kT_2 = 260 eV, N_H=0.24 10^{22} cm^2
- No significant EM at higher T
- Abundances relative to H poorly constrained. C/H ≥ 40 solar
- At least half of the continuum is due to scattering from C
- Ne/O enhanced, N/O, Mg/O, Fe/O depleted
  - Can be explained by s-process within the pulse driven convective zone (Herwig 2005)

Coming paper by Yu et al.

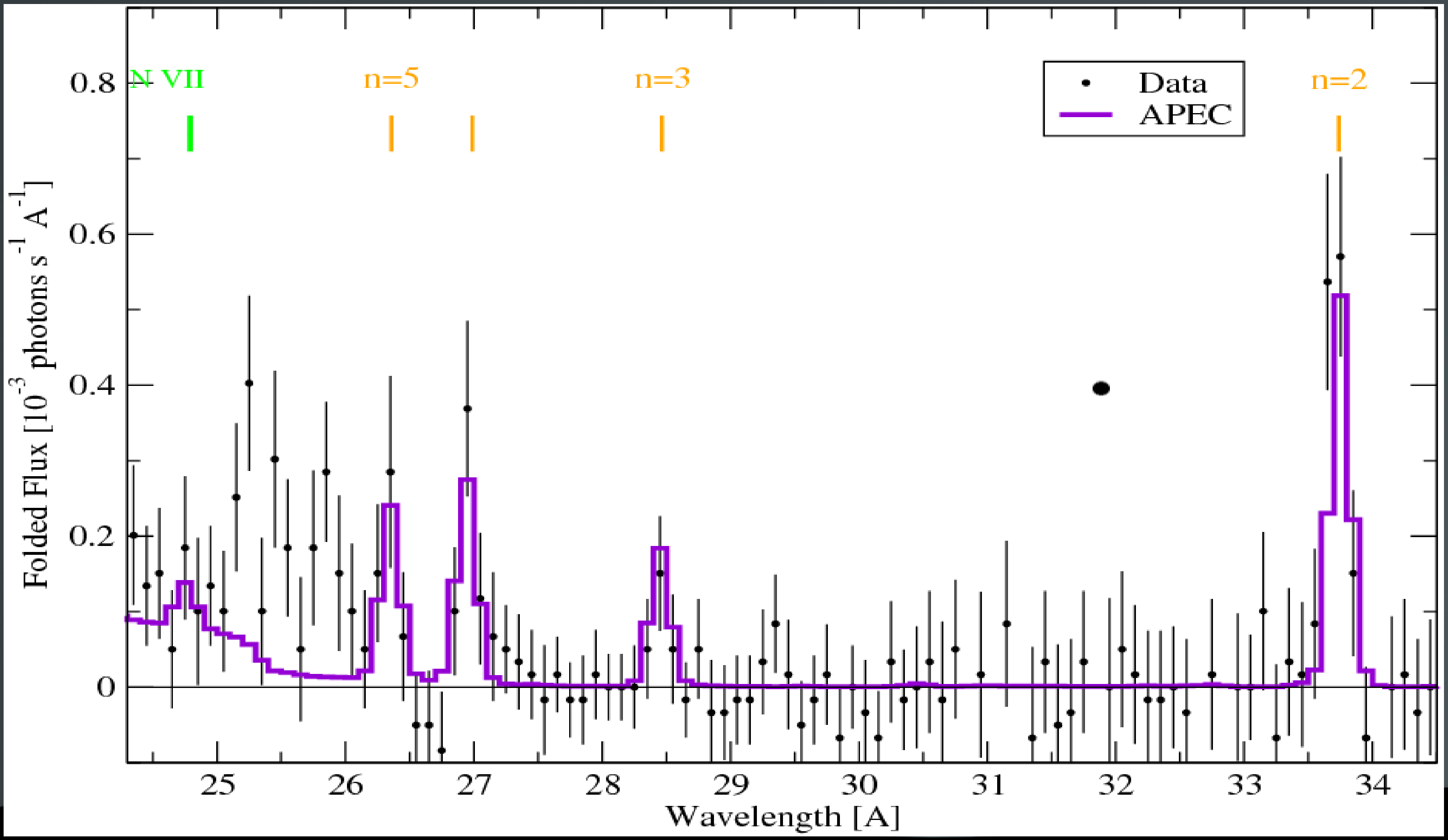
Source Spectrum

- Fluxed and corrected for absorption



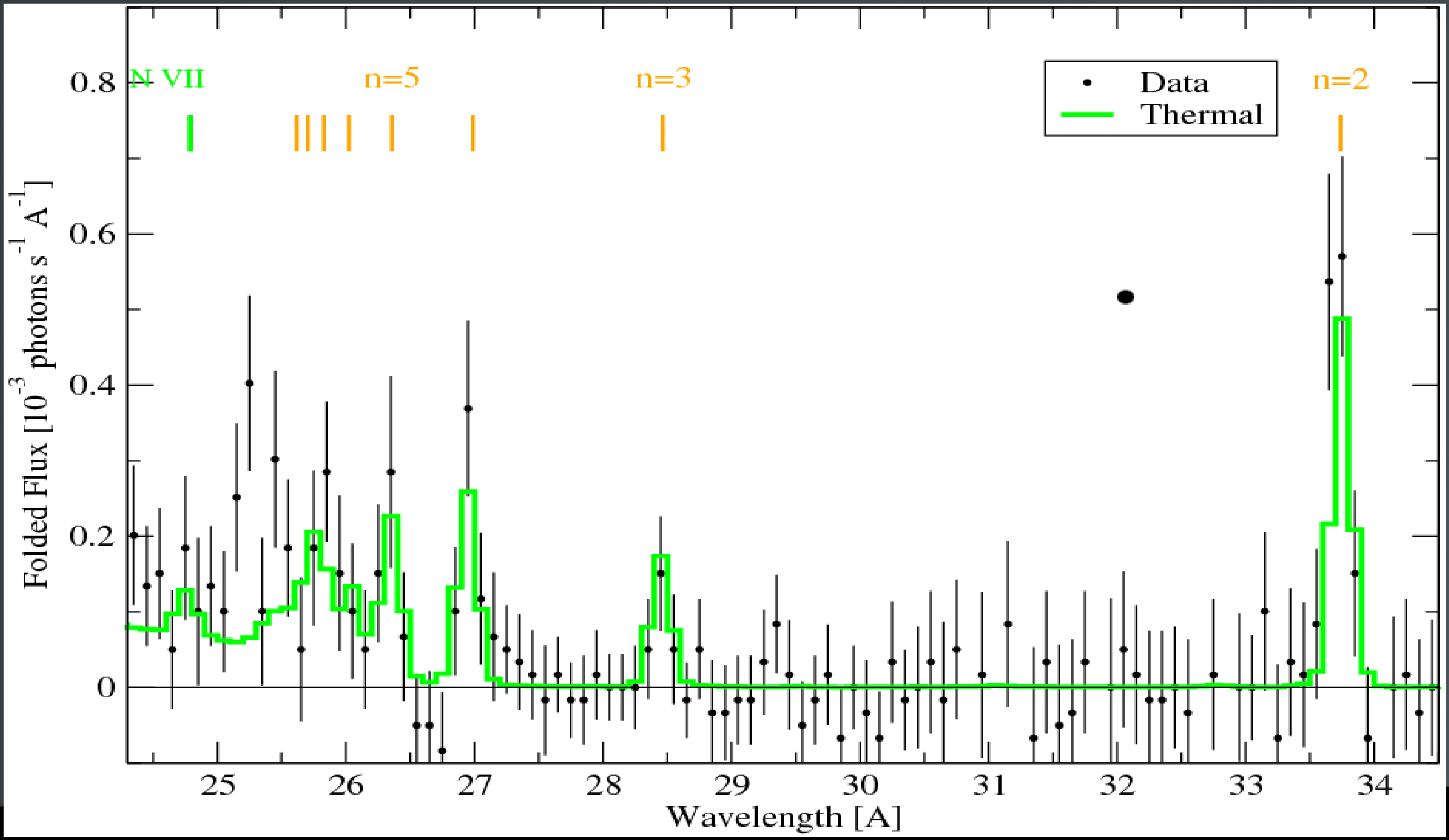
The Carbon lines

- 2-T APEC model, N_H=0.24 10^{22}



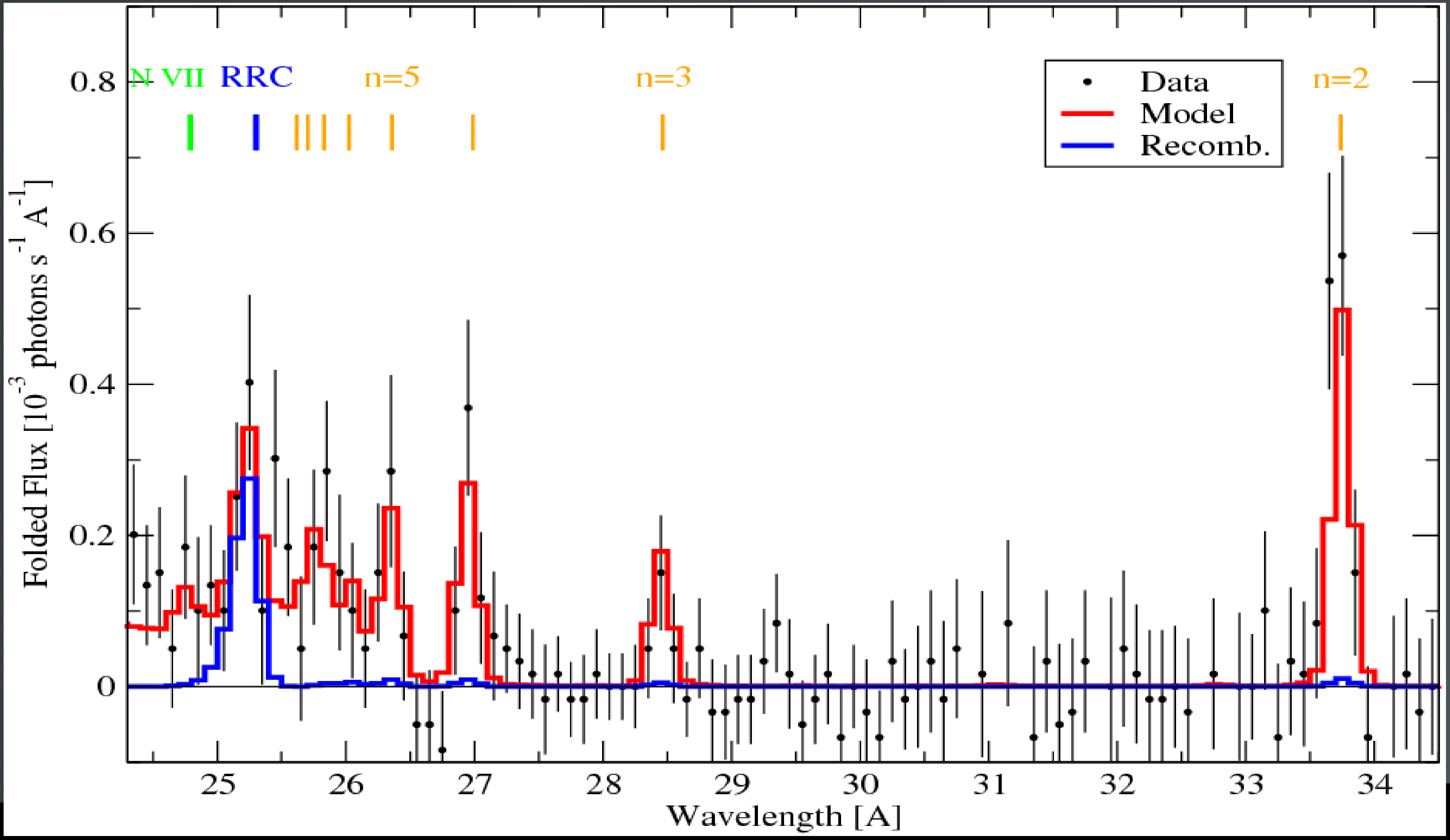
The Carbon lines

- 2-T APEC + N_H model with extended Ly series



The Carbon lines

- 2-T APEC + extended Ly series + RRC



RRC model

- Ruled out L-shell Si, S, Ar, Ca, Sc
- $kT_e = 2$ eV (<10 eV 90%), $I_{rec} = 1.5 \pm 0.5\ 10^{40}\ s^{-1}$
- Requires mixing of hot+cold gas out of ionization balance
- The CD region offers such interface
- Magnetic fields of order μG are likely to exist and suppress heat conduction on scale of a few electron R_L – required for maintaining steep T gradient
- C VII R_L ($\sim \sqrt{mT/q}$) is 26 times larger than electron's – crossing the CD into the cold side.

RRC model - cont.

- Time scales:

τ_{slow}~300 s < τ_L~650 s < τ_{rec}~10^6 s

- Crossing C VII ions will tend to thermalize on the cool side and eventually recombine with cool e.
- A "naive" steady-state model: $I_{rec}=0.5V_p S_{CD} n_{C\,VII}$

$$n_{C\,VII}^{hot}=0.53\left(\frac{I_{rec}}{1.5\times10^{40}s^{-1}}\right)\left(\frac{R_{CD}}{4\times10^{16}cm}\right)^{-2}\left(\frac{kT}{100\,eV}\right)^{-1/2}cm^{-3}$$

- Taking C/H = 40 solar -> n = 400 cm^{-3} in the ball park

Not the whole picture

- The “naive” model leads to $E>10^4$ G
- Must account for other plasma effects:
  - Magnetization currents
  - Drifts
  - e penetrating the CD
  - Instabilities

Other Objects

- γ^2 Velorum (Schild et al. 2004)
- θ Muscae (Sugawara, yesterday)

(Colliding wind binaries)

Conclusions

- BD+30 3639 shows extremely high C abundance
- Significant contribution of high C order Ly series due to the high abundance – not included in APEC.
- Detection of RRC from C VII indicating mixing between 100 and 2 eV gas.
- Previous measurements over estimate N abundance due to not considering the above.
- Suggested location for the mixing is at the CD due to magnetic fields and the larger Larmor radius of ions relative to electrons.