Accretion in Neon-Rich UCXBs: The Peculiar Case of 4U 1626-67

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Outline

- Introduction: A brief history of 4U 1626-67
- This work: *Chandra* spectroscopy of 4U 1626-67
  - Emission lines!
  - Plasma modeling!
- Conclusions and discussion: some musings on the nature of the donor star

Ultracompact X-ray binaries: the basics

UCXBs are X-ray binaries with **neutron star accretors** and **orbital periods less than an hour** (or thereabouts)

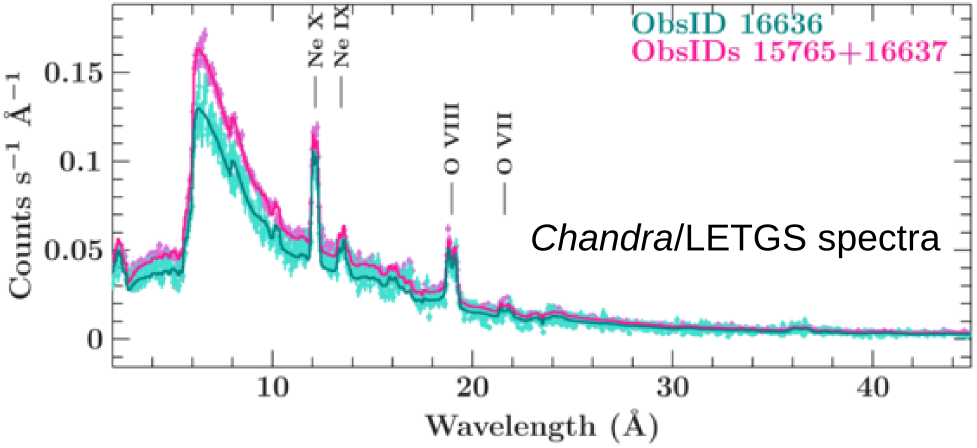
(compare: Am CVn systems, ultracompact CVs with white dwarf accretors)

All are **hydrogen-depleted**, many appear C/O rich, some are Ne-rich as well

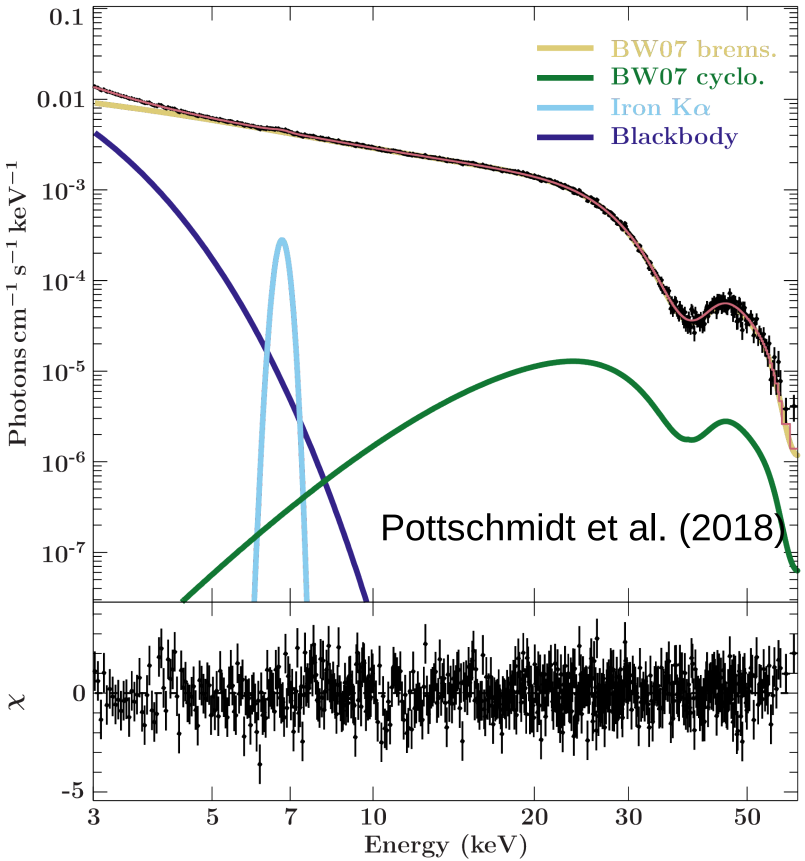
About a dozen known sources (maybe more since I last checked)

4U 1626-67: A unique UCXB

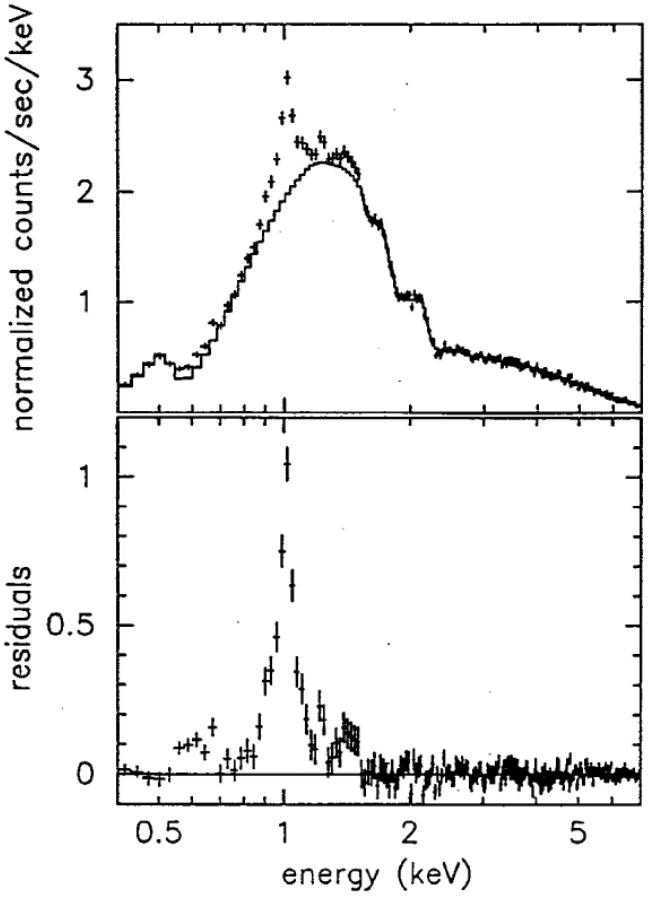
- **Only UCXB to host a strongly-magnetized X-ray pulsar**
- Orbital period: 42 minutes
- Hydrogen/helium-depleted companion

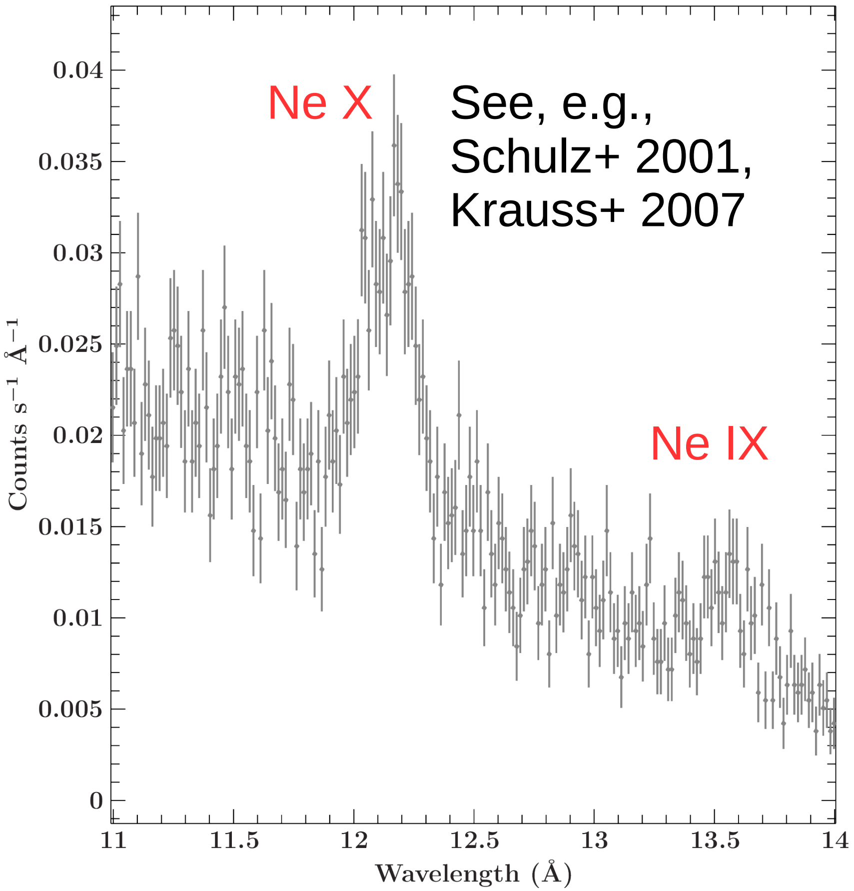


Very strong neon and oxygen lines



Cyclotron line in hard X-rays: 5e12 G magnetic field





Asca spectra (Angelini+ 1995): line complex around 1 keV

Chandra HETGS resolves into broad, double-peaked Ne IX-X, O VII-VIII

Ne/O line profiles

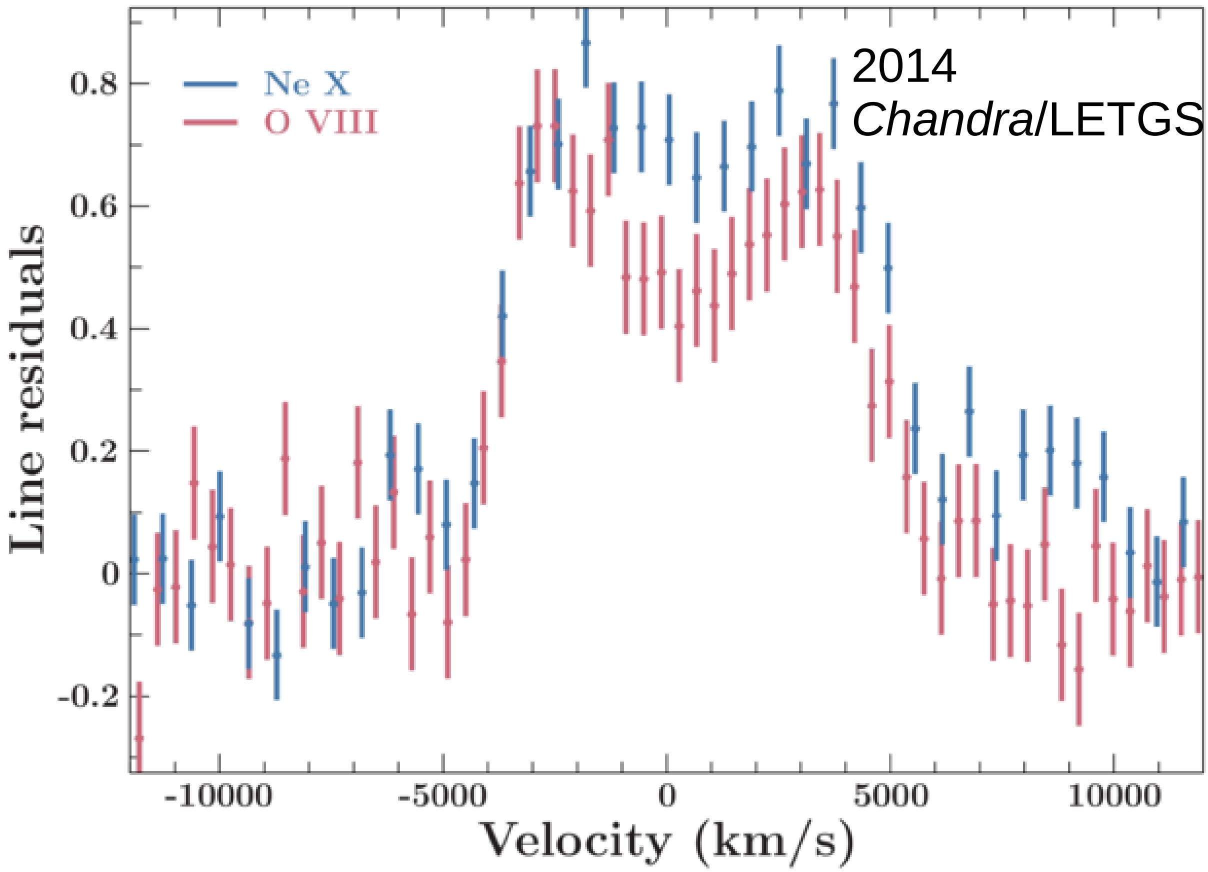
Ne X and O VIII have same velocity width, similar profiles.

From diskline fits to lines:

- **R_{in}~ 1700 GM/c^2 ~ 3.5x10^8 cm**
- ***i* ~ 38 degrees**

Compare:

- R_{co} ~ 3000 GM/c^2
- i < 33^o from, e.g., Chakrabarty 1998, Schulz+ 2001
- **R_{in} < R_{co} consistent with pulse period spin-up**



2014 *Chandra*/LETGS

Plasma diagnostics: He-like triplets

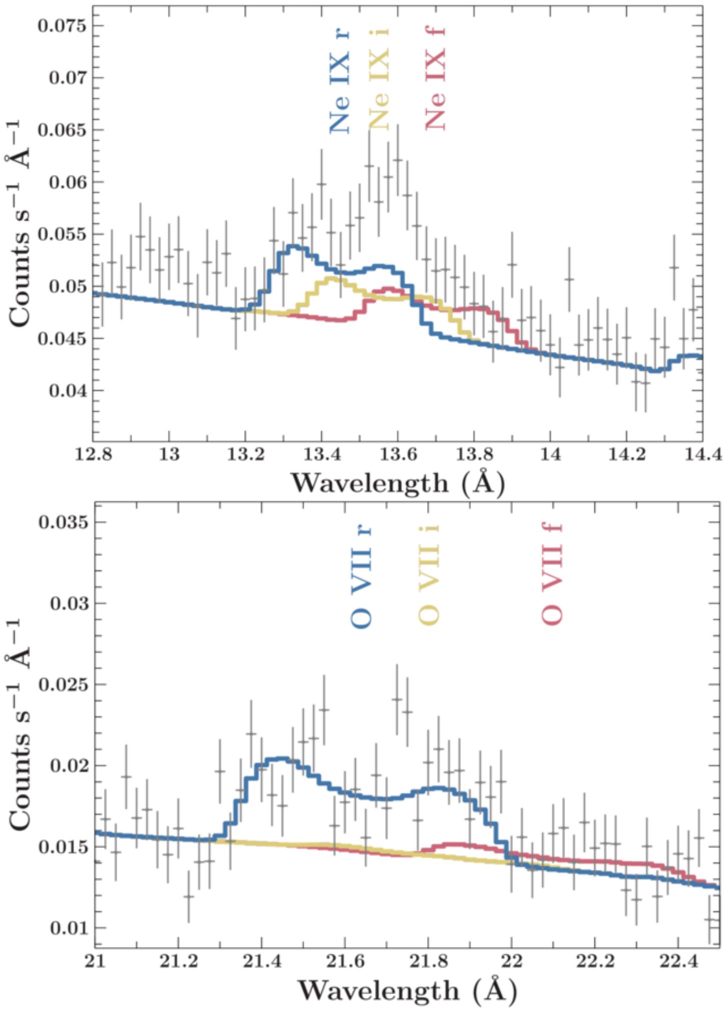
If we model the He-like lines as disk lines, the *resonance* line is dominant

Compare: Schulz+ (2001), who found *r* < *i* during spin-down epoch.

Can't constrain *i* or *f* lines very well generally: Ne R-ratio is 1.0 ± 0.7, oxygen is unconstrained

However, UV continuum probably makes this dubious in any case

G-ratio + He-like/H-like ratio combined are consistent with high (~10 MK) plasma temperatures



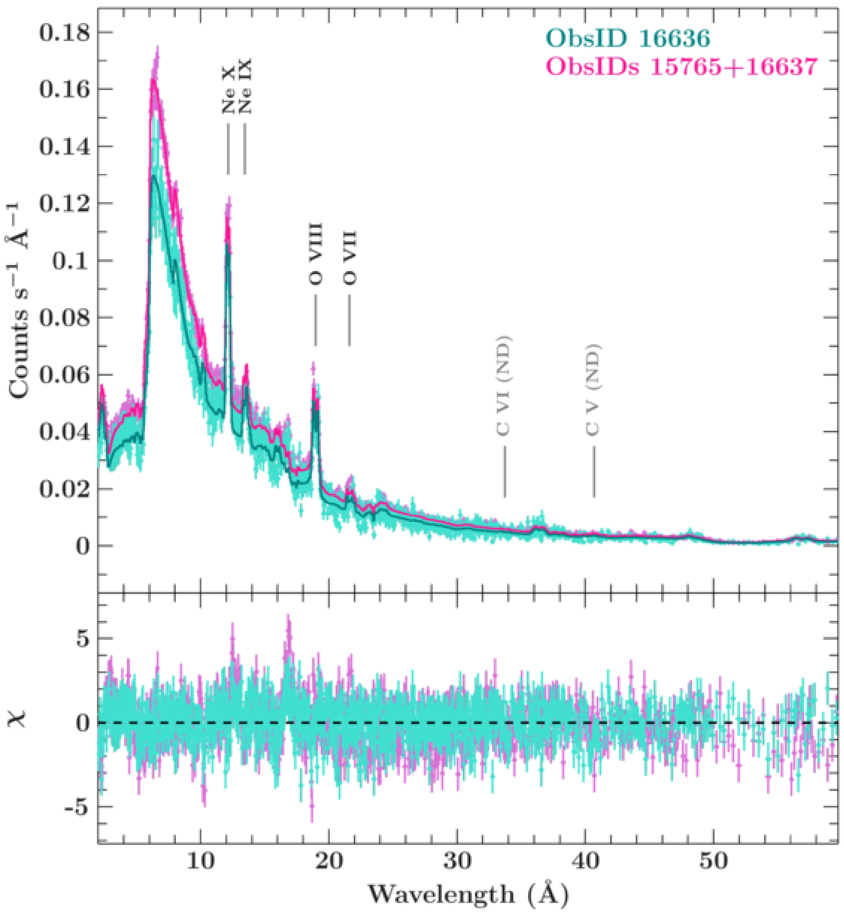
Spectral fitting

Disk-blurred collisional plasma (rdblur convolved with APEC plasma model), only C/O/Ne/Mg/Fe

Best fit: **two-temperature plasma**: **~13 MK and ~2.5 MK**

But: need **~3.5x higher Ne abundance** to produce enough Ne emission

Similarly, can place limits on Mg, Fe: **less than 0.2x solar Mg abundance, ~0.07 Fe** (although Fe might be suspect – no LETGS coverage of, e.g., Fe XXV)



Summary of *Chandra* spectroscopy results

- Clear double-peaked Ne IX-X, O VII-VIII features
- Line profiles support **inclination of ~38^{o}** and an **inner disk radius of ~1700 R_G**
- Spectrum well-fit by **two-temperature collisional plasma** plus PL+BB continuum
- Plasma is **highly neon-enriched**, deficient in Mg, Fe.

Interesting note: both temperature components find same inner+outer disk radius. Azimuthal temperature distribution? Non-equilibrium plasma?

On the nature of the donor star

Possible donor stars

Lots of previous work (e.g., Levine+ 1988, Chakrabarty 1998, Nelemans+ 2010, Heinke+ 2013). Possibilities are **helium star** or **white dwarf**, both very low-mass.

Now, from this work:

- High(er) inclination than previous estimates
- Highly enhanced Ne abundance
- Very low Mg upper limit

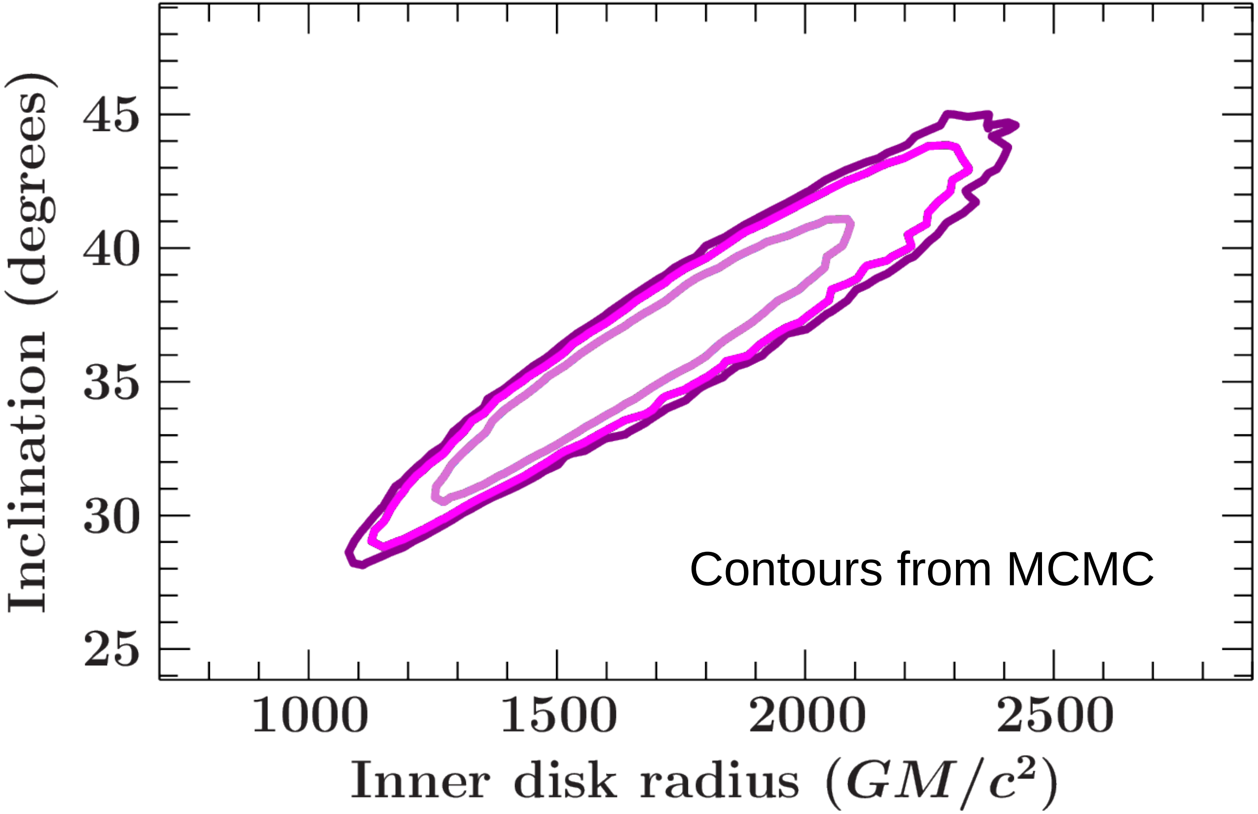
Binary parameters

No eclipses, so source can't be highly inclined.

Must fill Roche lobe, otherwise we don't get enough accretion.

Levine+ (1988): **asini < 8 lt-ms**

Inclination: our results are **incompatible with inclinations < 28°.**



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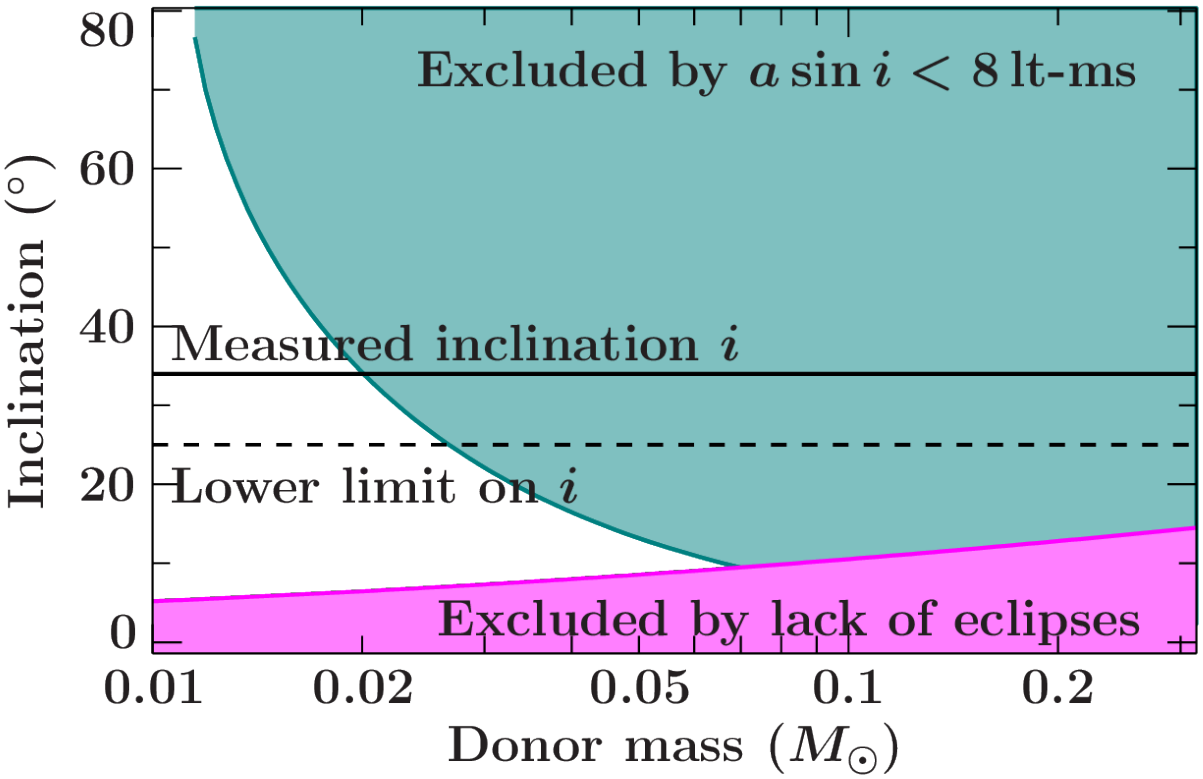
Donor mass must be < 0.02 solar masses



Chemical composition!

“Abundance” is a tricky term - we don’t have any hydrogen!

So we **measure everything relative to oxygen** (because it’s convenient), e.g.,

$$\frac{n_{\mathrm{Ne}}}{n_{\mathrm{O}}} = \frac{\mathrm{Abund(Ne)}}{\mathrm{Abund(O)}} \left(\frac{n_{\mathrm{Ne}}}{n_{\mathrm{H}}}\right)_{\mathrm{ISM}} \left(\frac{n_{\mathrm{O}}}{n_{\mathrm{H}}}\right)_{\mathrm{ISM}}^{-1}$$

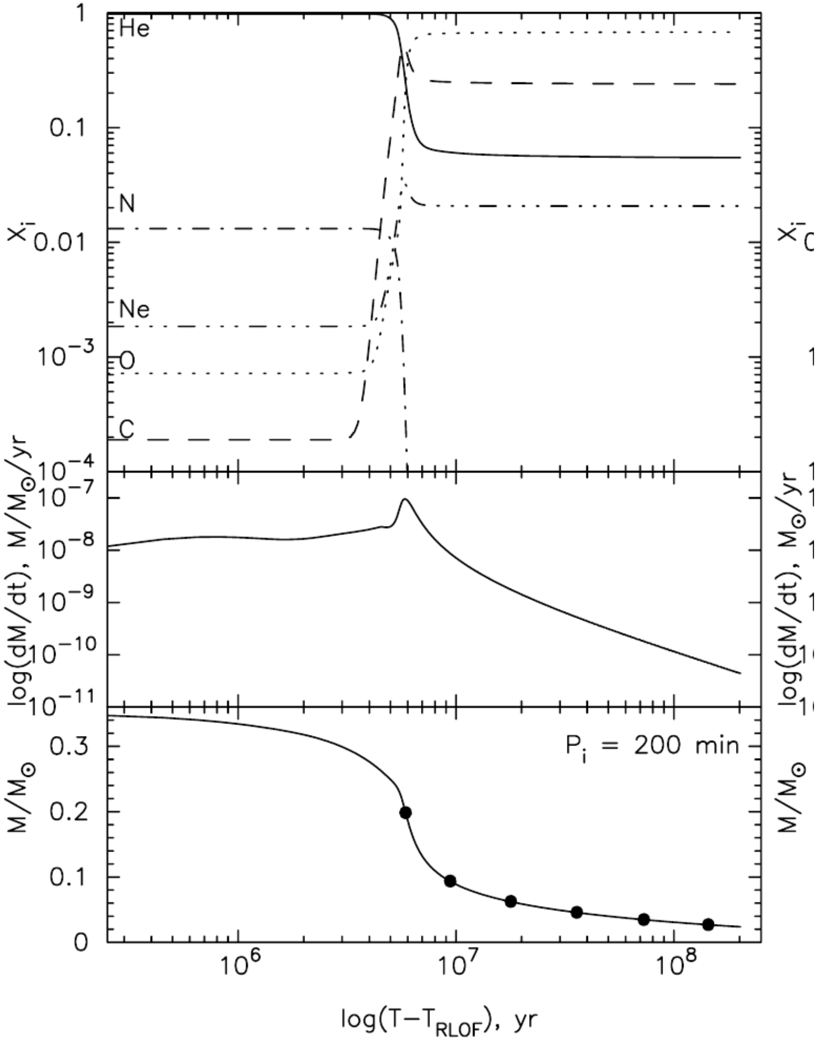
Results:

- Ne is *60%* of oxygen number density (*cf*. ~17% in ISM)
- Mg limited to <1% (~5% in ISM)
- Fe is around 0.4% (~5% in ISM) (but LETGS not great for Fe XXV-XXVI)

On helium stars...

- Nelemans et al. (2010): possible to get right donor mass, right orbital period, and lose all helium
- Heinke+ (2013): prefer He star due to 1626’s long-term flux – He star can deliver higher accretion rate

- However: **Ne is enhanced, but only to ~percent levels.** We see ~30% neon!
- Also: accretion rate still an order of magnitude too low (but WD have this same problem)



On white dwarfs...

If it’s a WD, what composition? O/Ne is tempting...

Isern et al. (1991), on C/O white dwarfs:

“ ^{22}Ne can settle down at the center as an outcome of solidification. ”

Segretain et al. (1994, right): Ne abundance at core can increase by factor of ~10!

Similar effect for Mg in O/Ne WD?

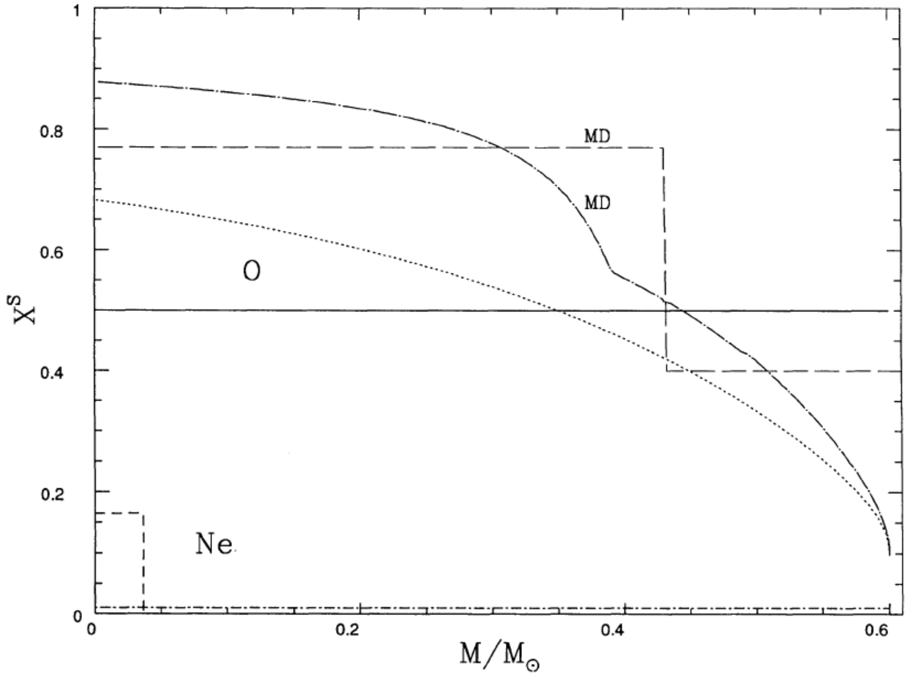


Fig. 4 from Segretain et al. (1994)

On white dwarfs...

Our numbers:

- Neon: **60% relative to oxygen** by number
- Magnesium: **<1% relative to oxygen**

Companion mass is ~0.02 $M_{\odot}$ - stripped down to its core.

If C/O, should see enhanced Ne.

If O/Ne, should (?) see enhanced Mg.

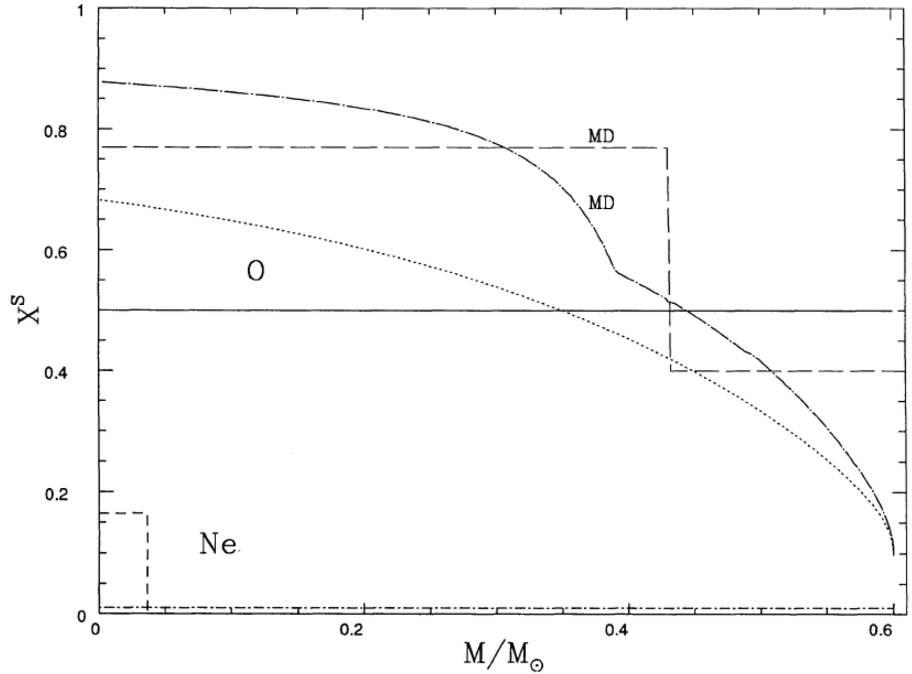
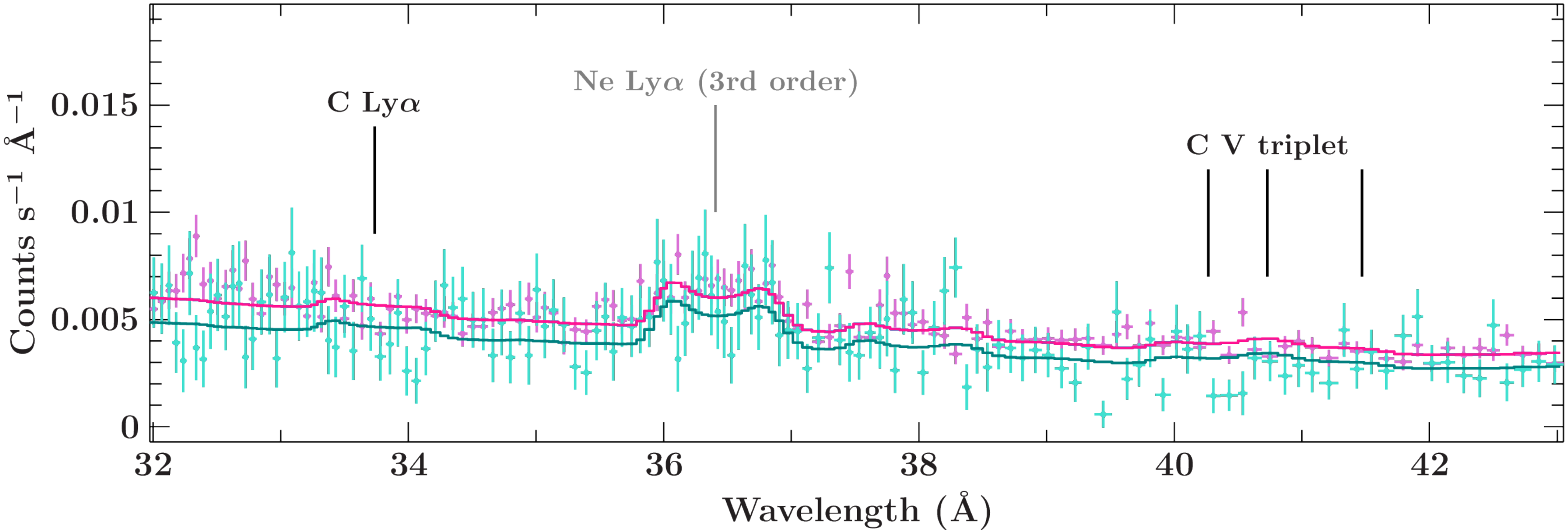


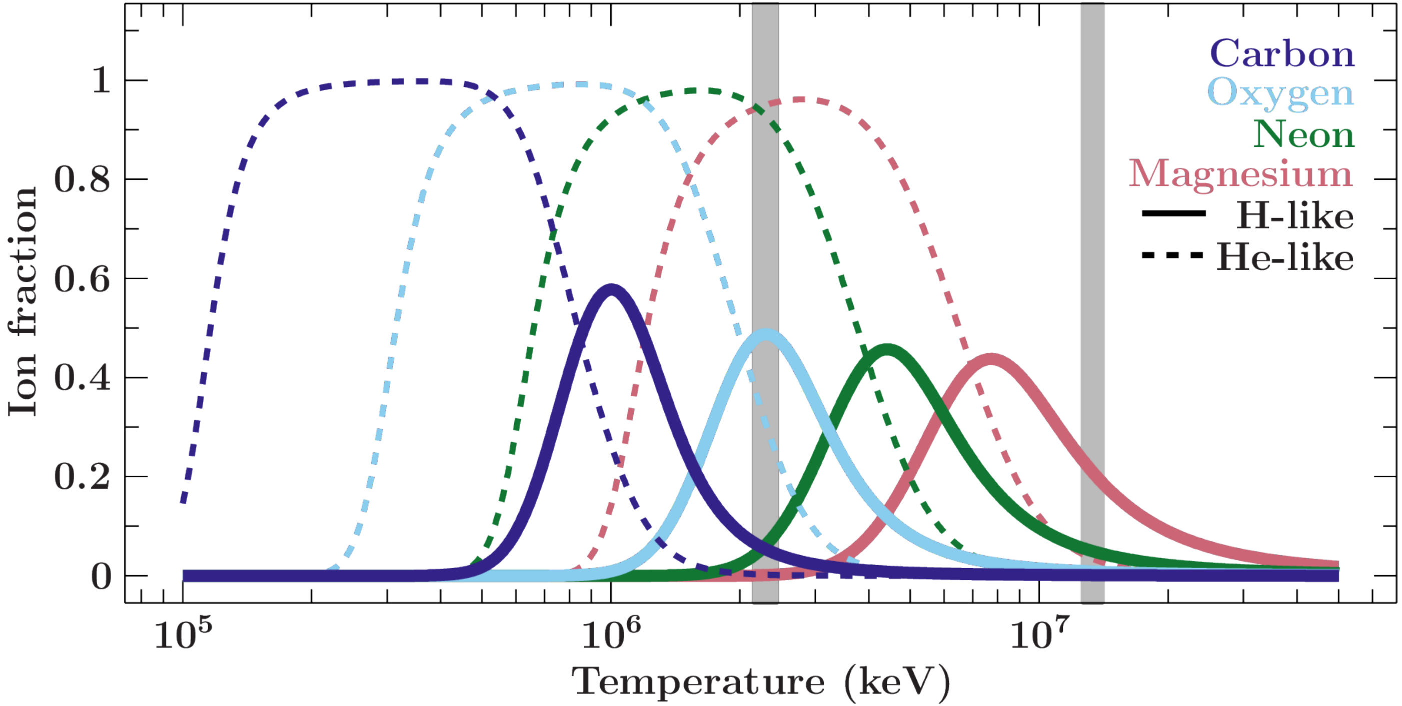
Fig. 4 from Segretain et al. (1994)

Ok, if it’s a C/O white dwarf, where’s the carbon?



Ok, if it's a C/O white dwarf, where's the carbon?

We don't see carbon lines (carbon is *maybe* seen in UV…). But at 2.5 and 13 MK, **we don't expect to see very much** (we *would* expect Mg, though!):



Remaining questions

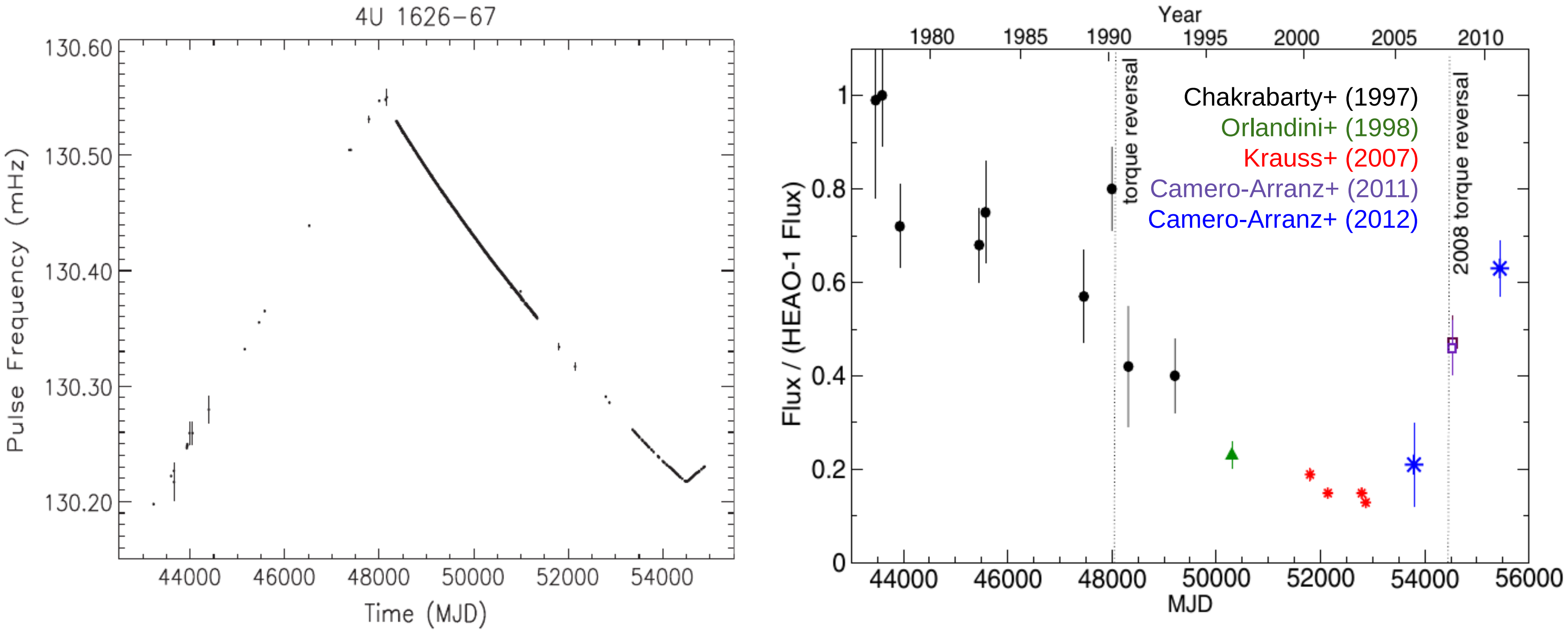
- Possibly still **too much neon** even for crystallized C/O WD.
  - Anomalously high Ne abundance to start?
  - Binary evolution screwing with things?
- Timescales! Crystallization is a ~10 Gyr process - can a NS retain a strong magnetic field for long enough?
- Alternately: young O/Ne – not enough time for Mg to sink.

Yungelson et al. (2002) suggested **accretion-induced collapse** formed the NS. This would explain why we see a young pulsar (high B-field, slow pulse period)

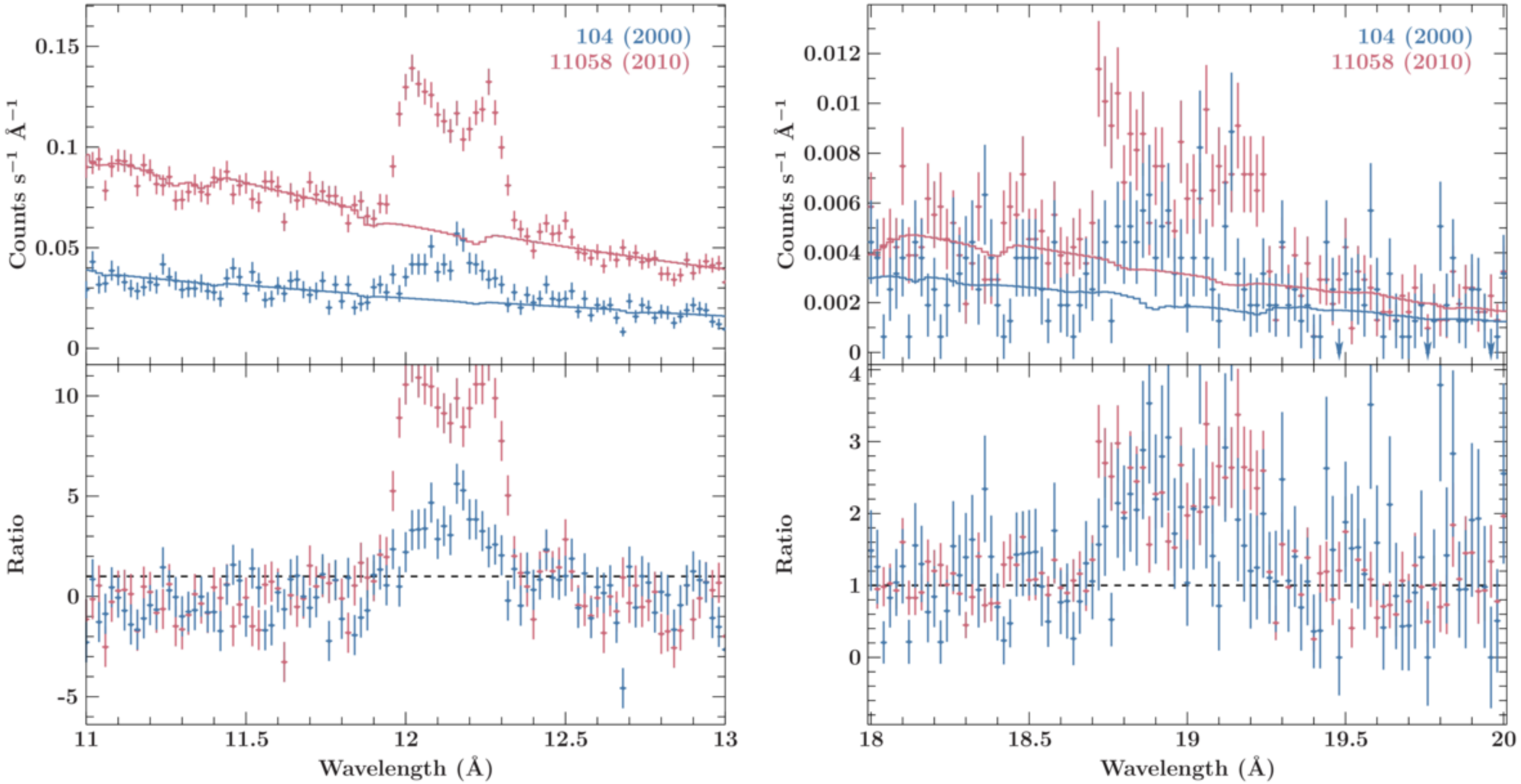
Conclusions

- Double-peaked lines and line ratios support a *collisionally-ionized, two-temperature, disk-blurred plasma* as the origin of the lines
- Inner radius from lines implies that emission comes from *innermost edge of disk*
- Inclination constrained to $>28^{o}$, incompatible with higher-mass donors
- Highly abundant neon: O/Ne, or crystallized C/O WD
- White dwarf donor *moderately* preferred over helium star – but questions remain!

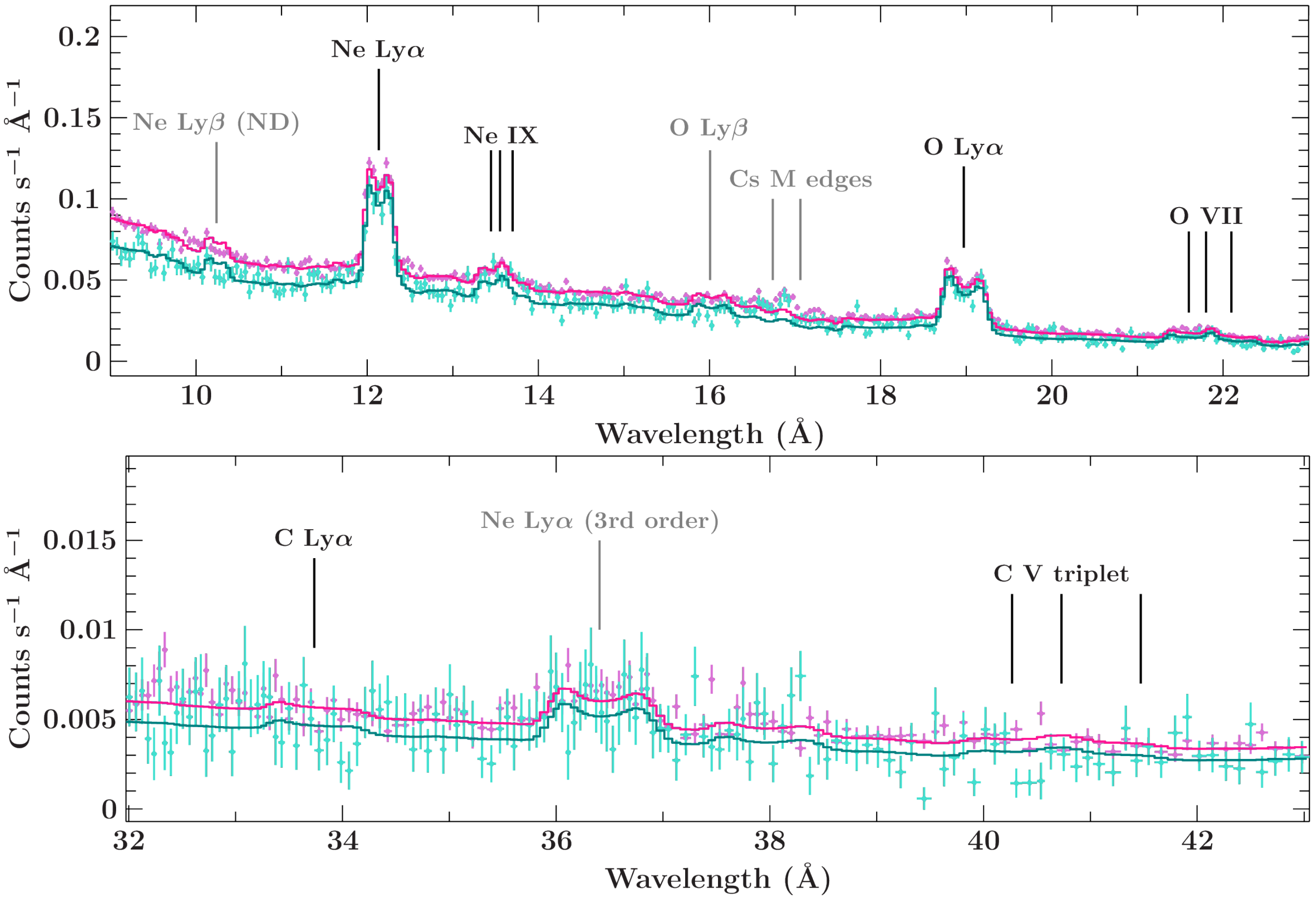
Spare parts



4U 1626-67: Pulse period and flux history (Camero-Arranz et al. 2010, 2012)

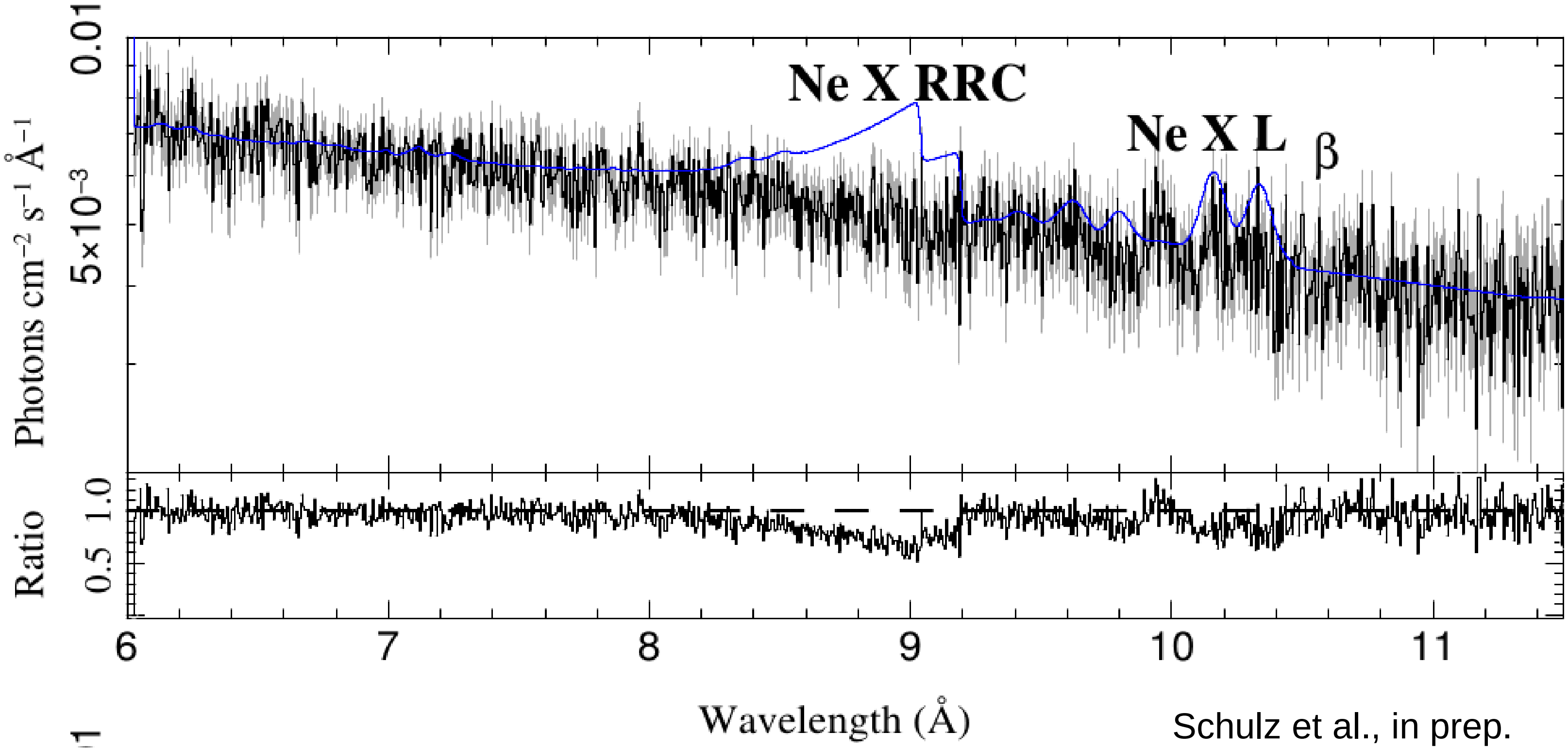


Ne X (left) and O VIII (right) pre-reversal (2000, blue) and post-reversal (2010, red)



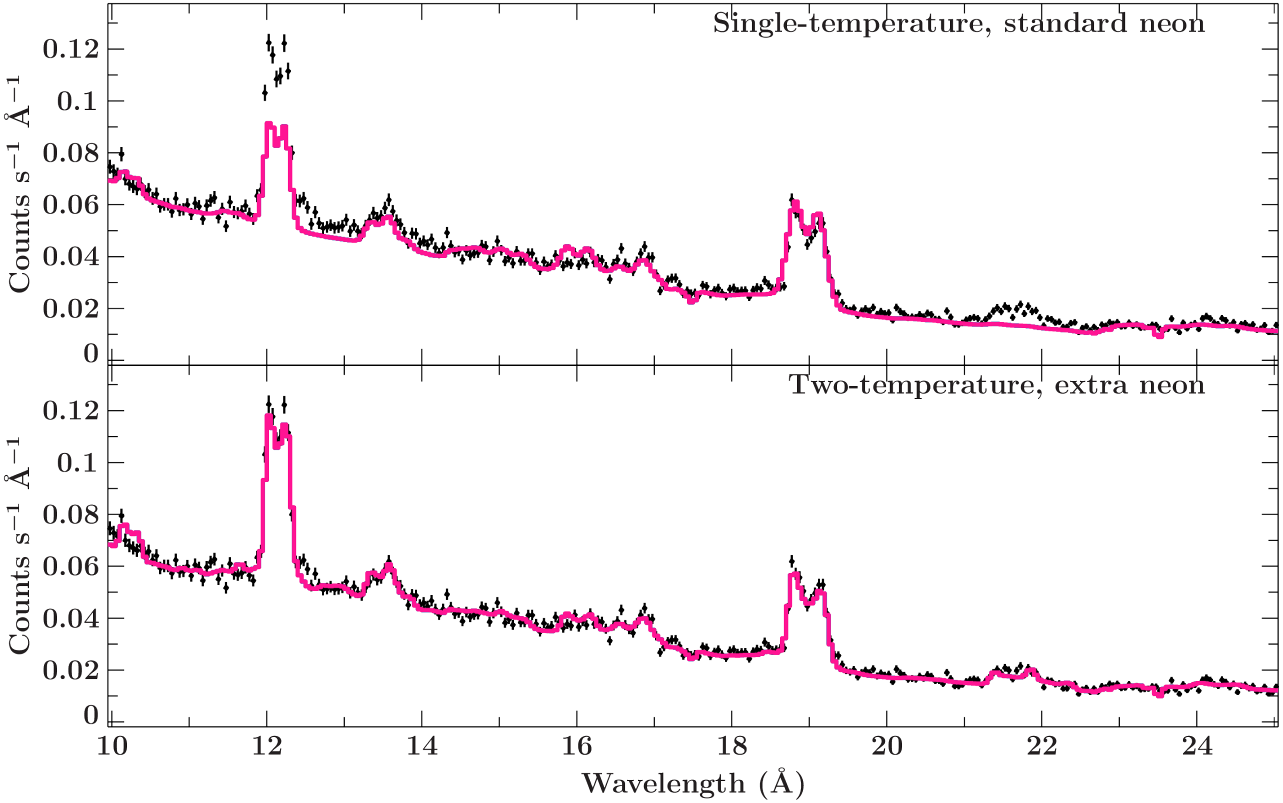
Ne Lyα
Ne Lyβ (ND)
Ne IX
O Lyβ
Cs M edges
O Lyα
O VII
Counts s⁻¹ Å⁻¹
Wavelength (Å)
C Lyα
Ne Lyα (3rd order)
C V triplet
Counts s⁻¹ Å⁻¹
Wavelength (Å)

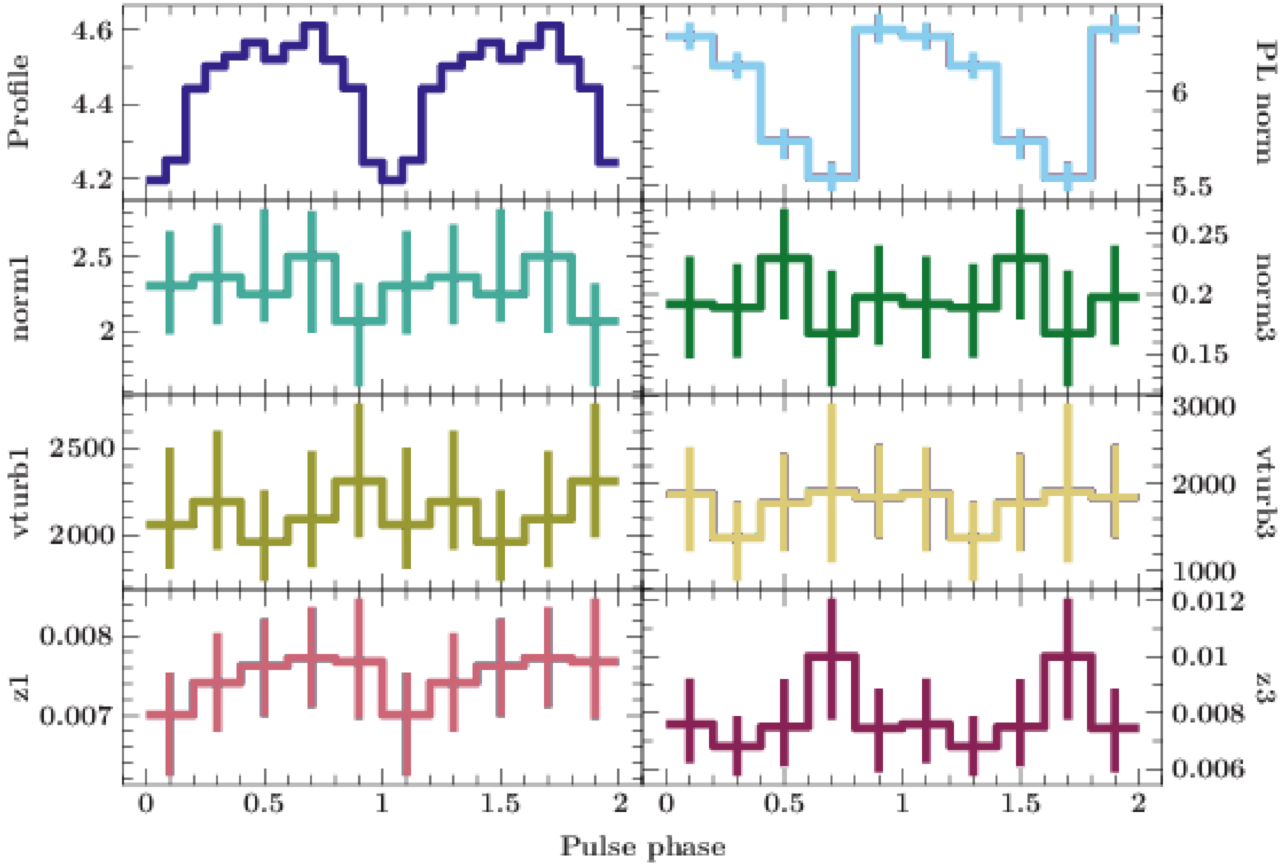
Photoionized plasma



Schulz et al., in prep.

Comparison: abundances and temperatures

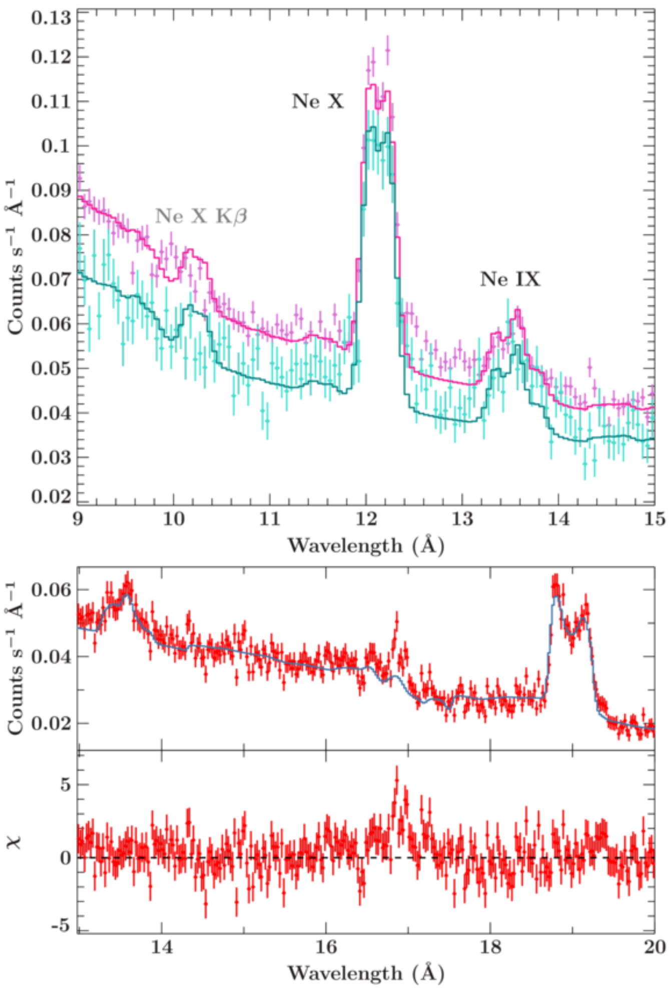




4U 1626-67: Phase-resolved APEC fits

Caveats...

- **APED model overproduces Ne X Kβ!** Data shows no Kβ at all.
    - Need some way to produce extra Kα or suppress Kβ...
- **Both APED and diskline fits fail to replicate red shoulder of Ne X line**
- **Unidentified feature around 16.8 Å** (Cs edges in the LETGS?)
- AtomDB/APED issues…
    - **APED assumes H/He plasma** in defining VEM
    - VEM, abundances thus difficult to interpret



Torque reversals

Torque reversal in 2008 came with an **increase in flux** and a change in spectral parameters:

PL got *softer* - photon index changed from ~0.8 to ~1.0

BB got *hotter* (from ~0.25 keV to 0.5 keV) **and *smaller*** (R^2/D_{10} 200 → 100)