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

Chandra/LETGS spectra

Pottschmidt et al. (2018)
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:
- \( R_{\text{in}} \sim 1700 \text{ GM/c}^2 \sim 3.5 \times 10^8 \text{ cm} \)
- \( i \sim 38 \text{ degrees} \)

Compare:
- \( R_{\text{co}} \sim 3000 \text{ GM/c}^2 \)
- \( i < 33^\circ \) from, e.g., Chakrabarty 1998, Schulz+ 2001
- \( R_{\text{in}} < R_{\text{co}} \) consistent with pulse period spin-up
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 \(~3.5\times\) higher Ne abundance to produce enough Ne emission

Similarly, can place limits on Mg, Fe: less than \(0.2\times\) 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°* 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): \( \text{asini} < 8 \text{ lt-ms} \)

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

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

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

Levine+ (1988): $a \sin i < 8 \text{ lt-ms}$

Inclination: our results are incompatible with inclinations $< 28^\circ$.

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.,

\[
\frac{n_{\text{Ne}}}{n_O} = \frac{\text{Abund}(\text{Ne})}{\text{Abund}(\text{O})} \left(\frac{n_{\text{Ne}}}{n_H}\right)_{\text{ISM}} \left(\frac{n_O}{n_H}\right)^{-1}_{\text{ISM}}
\]

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:

“$^{22}\text{Ne}$ 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?
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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°, 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)
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** ($R^2/D_{10} \rightarrow 100$)

*Chandra-HETGS spectra*