Atmospheric effects with NICER
How do the assumptions on the neutron star atmosphere affect the neutron star parameter constraints with NICER?

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Introduction: Pulse profiles

- X-ray pulses and spectra can be modeled to infer neutron star (NS) mass (M) and radius (R)
- $M \& R \rightarrow$ Equation of state of high-dense matter in NS core

Riley+2019, Miller+2019
Introduction: Pulse profiles

- Pulse shapes depend on relativity (light bending, Doppler boosting, etc.) and thus on M&R.
- Pulses can differ between energies.
Introduction: Pulse profiles

- Flux: \( \text{d}F_E = I_E \text{d}\Omega = (1 - u)^{1/2} \delta^4 l'(\sigma', E') \cos \sigma \frac{\text{d} \cos \alpha}{\text{d} \cos \psi} \frac{\text{d}S'}{D^2} \)

- Intensity of photons in the spot frame depends on both energy \( E' \) and emission angle \( \sigma' \) (and thus phase).

- Dependence on \( \sigma' \) called atmospheric beaming pattern.

Salmi+2018
Introduction: Pulse profiles

- Beaming patterns at 0.5 keV (left) and 1.0 keV (right):
Atmosphere models

- The model for $I'(E',\sigma')$.
- Iterative models solving simultaneously NS atmosphere structure and radiative transfer.
- Assumptions:
  - Composition
  - Ionization state
  - Thomson vs Compton scattering
  - Depth of heat release
  - Magnetic field strength

Bogdanov+2021
Atmosphere models

- Models typically too slow for direct inference:
  - Using pre-computed intensity tables for a variety of parameters (non-accreting):
    \[ E, \sigma, T_{\text{eff}}, \log(g) \]
Radiative transfer equation

\[
S(E, \mu) = \frac{k(x)}{\sigma(x, \mu) + k(x)} B_x + \frac{\kappa_e}{\sigma(x, \mu) + k(x)} \times \left(1 + \frac{C I(x, \mu)}{x^3}\right) x^2 \int_0^\infty \frac{dx_1}{x_1^2} \int_{-1}^1 d\mu_1 R(x, \mu; x_1, \mu_1) I(x_1, \mu_1)
\]

\[
x = E
\]

\[
I(E, \mu)
\]

\[
\mu = \cos \sigma'
\]

\[
\frac{dI(E, \mu)}{d\tau(E, \mu)} = I(E, \mu) - S(E, \mu)
\]
Atmosphere structure

Temperature as function of depth

Energy balance +
Surface flux corrections

Radiative transfer equation

\[ 2\pi \int_0^\infty dE \int_{-1}^{+1} [\sigma(E, \mu) + k(E)][I(E, \mu) - S(E, \mu)]d\mu = -Q^+ \]
Effects on M&R constraints for NICER

- Different models tested (Ho&Lai 2001, Ho&Heinke 2009, Salmi+2020):
  - Fully-ionized hydrogen (\texttt{nsxH}), used usually in NICER.
  - Fully-ionized helium (\texttt{nsxHe})
  - Partially-ionized hydrogen (\texttt{nsxHp})
  - Partially-ionized carbon (\texttt{nsxCp})
  - Fully-ionized hydrogen but externally heated and from an independent algorithm (\texttt{hatmH})

Salmi+2023 submitted
Effects on M&R constraints for NICER

- **Composition**: Hydrogen expected due to rapid sinking of heavier elements.... But helium (or heavier) possible if hydrogen was never accreted or there was nuclear burning.

- **Ionization state**: Accounting for it could affect but can be inaccurate for hotter neutron stars (due to limitations in opacity tables).

- **Deep-heating**: Accounting for non-deep-heating could affect if the bombarding particles are slow enough ($\gamma < 100$, Salmi+2020), but typically they are expected to be much faster (Harding&Muslimov 2011).
J0740: 2 circular hot spots (ST-U)

- High-mass pulsar J0740 (studied in Miller+2021; Riley+2021; Salmi+2022).
- All choices produce consistent M&R constraints.
- Only carbon atmosphere disfavored based on Bayesian evidence.

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J0030: 2 circular hot spots (ST-U)

- J0030 (studied in Miller+2019; Riley+2019).

- **Different M&R constraints, but not equally likely.**

- Deep-heating: No effect.

- Partial-ionization: Shift, but disfavored.

- C vs H: Shift, but disfavored.

- He vs H: Shift, evidence cannot distinguish.
  - 13-16 km vs 10-11 km.

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J0030: 1 circle and 1 crescent (ST+PST)

• Preferred model from Riley+2019.

• More computationally expensive, thus only 3 cases tested.

• Again, similar evidence for fully-ionized hydrogen and helium, but different radii (12-14 km vs 15-16 km).

• Partially-ionized hydrogen disfavored but better fitting ST-U solutions were not even found: Sampling with 10k MultiNest livepoints not enough?

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J0030: 2 circular hot spots and XMM

- Constraining NICER background by fitting simultaneously NICER and XMM data.
- Evidence favors He against H. But both hit 16 km upper limit when fully ionized.
- Partially-ionized hydrogen infers smaller R but evidence disfavored.
- Need studies with more complex spot shapes and independent background estimates.

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Discussion

Possible reasons why J0030 different compared to J0740:
- No external prior constraints for NS mass or geometry for J0030.
- Higher number of observed counts for J0030.
- Favoring/allowing hot spots that are only seen if photons emitted always at high angles (having largest difference in beaming).

Riley+2019
Conclusions and Future

- None of tested atmosphere assumptions affects M&R J0740 constraints.
- H vs He assumption affects M&R J0030 constraints, but He is considered less likely (although with higher evidence) and leads typically to unexpectedly high R for J0030.
- Other tested atmosphere assumptions either do not affect J0030 or they affect but have a much lower evidence.
- In future atmosphere models can be further explored and best ones inferred, especially with any new high-energy-resolution X-ray instruments.
Extra: Beaming parameterization

- Uncertainty in the predicted beaming pattern can also be parameterized:
- 4 new empirical beaming parameters, modifying the input from an atmosphere table.

\[ I(E, \mu, a, b, c, d) = I(E, \mu)_{\text{NUM}} f(E, \mu, a, b, c, d), \]  
\[ f(E, \mu, a, b, c, d) = C \left( 1 + a \left( \frac{E}{\text{keV}} \right)^c \mu + b \left( \frac{E}{\text{keV}} \right)^d \mu^2 \right) \]
Extra: J0030 with beaming

- Allowing max 5% correction to intensities below 60 deg emission angles (as typically between the atmosphere models):
  - Hydrogen solution same, helium a bit shifted.

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