Gravitationally Redshifted Absorption Lines in the Burst Spectra of the Neutron Star in EXO 0748-676

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Bursting Neutron Stars

* One of the most direct methods of determining the composition of a neutron star is to measure the gravitational redshift at the surface. $z \propto M/R$
* Extensive searches have been conducted for gravitationally redshifted absorption features in isolated neutron stars.
  – Most neutron stars show no discrete spectral structure.
  – Only 1E1207.4-5209 shows absorption features, but these have not been uniquely identified.
* Bursting neutron stars are excellent targets for these searches:
  – During the bursts, the neutron star outshines the accretion-generated light by an order of magnitude.
  – Continuing accretion provides a constant source of heavy elements at the neutron star surface.
  – Low magnetic fields in LMXBs vastly simplify the spectral analysis.

XMM-Newton Observations of EXO 0748-676

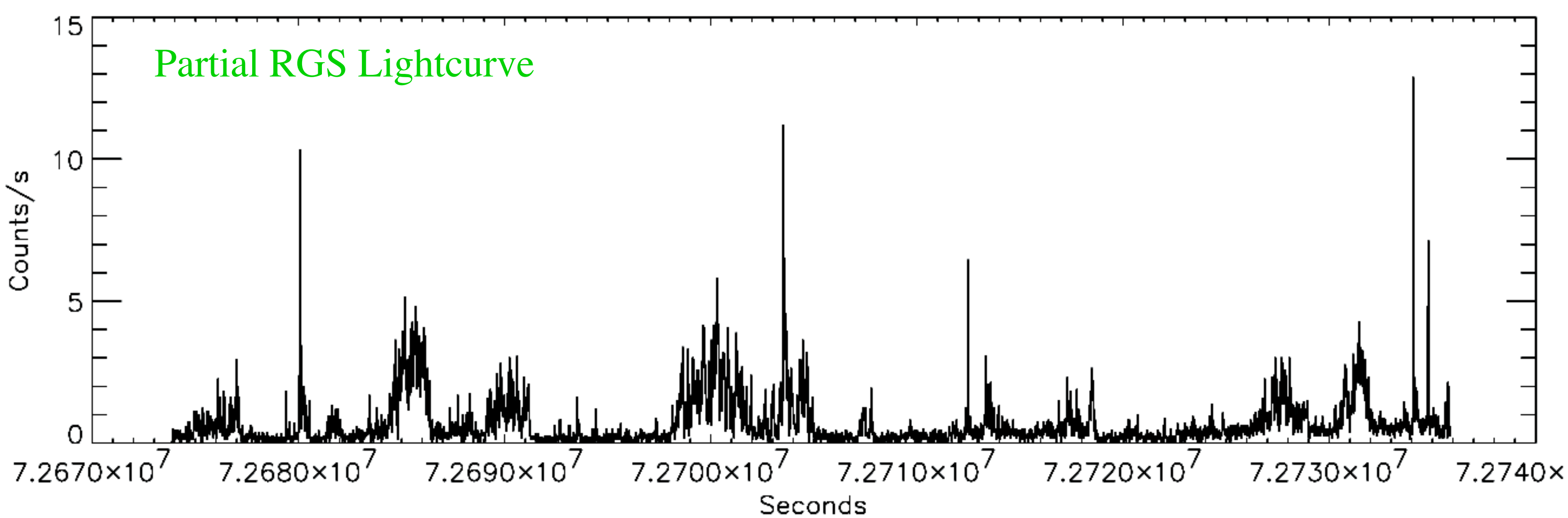
* EXO 0748-676 was observed with XMM-Newton during commissioning and calibration of the observatory:

Total Exposure: RGS: 335,000 s   EPIC: 39,000 s

* The RGS data contain 28 bursts, and EPIC data contain 3 bursts:

Burst Exposure: RGS: 3200 s   EPIC: 250 s

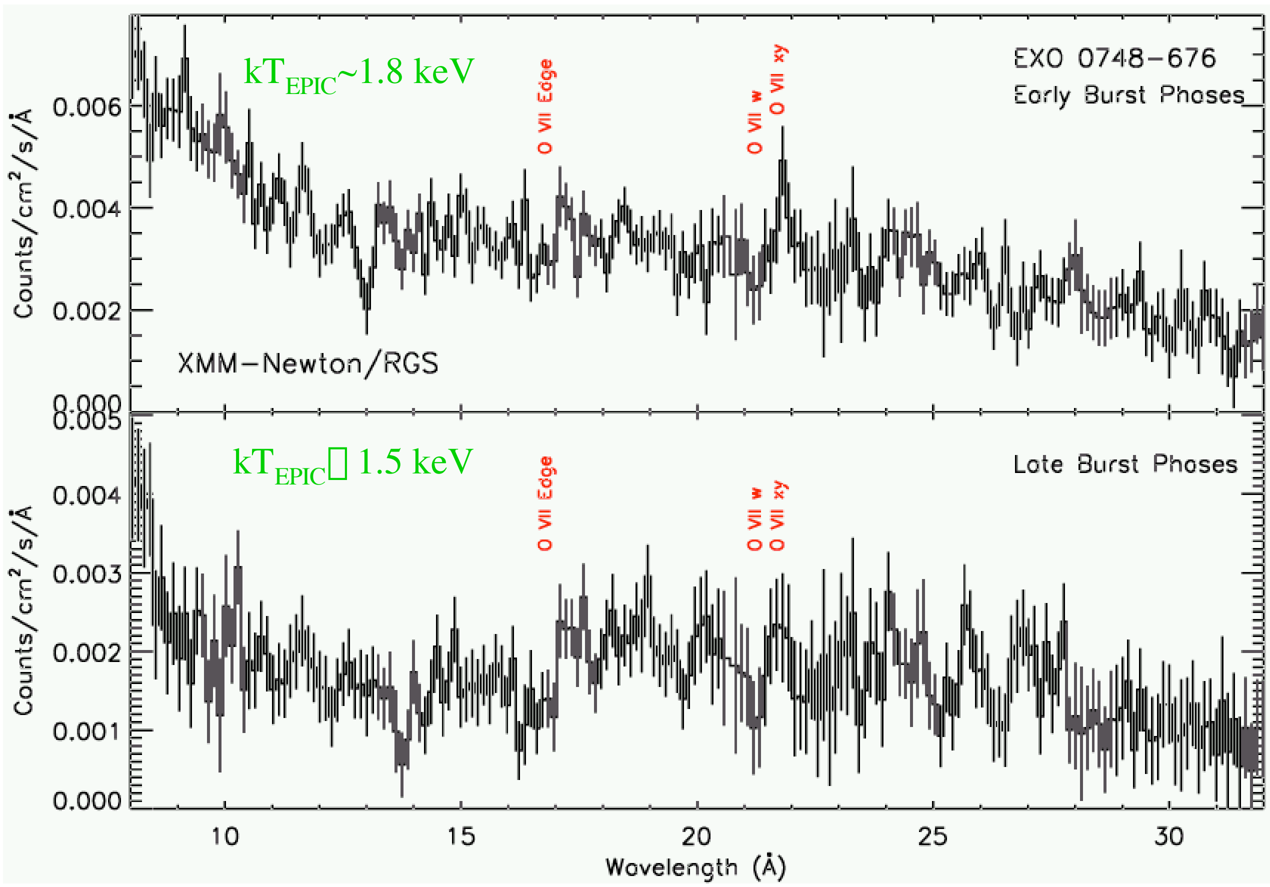
⟹ Excellent data set to search for absorption features in the neutron star photosphere



Averaged Burst Spectra

* The EPIC data show evidence of spectral evolution during the bursts:
  – Fitting to a black body plus power-law we find kT_{EPIC}~1.8 → 1.5 keV.

We therefore separated the RGS data into early and late burst phases.

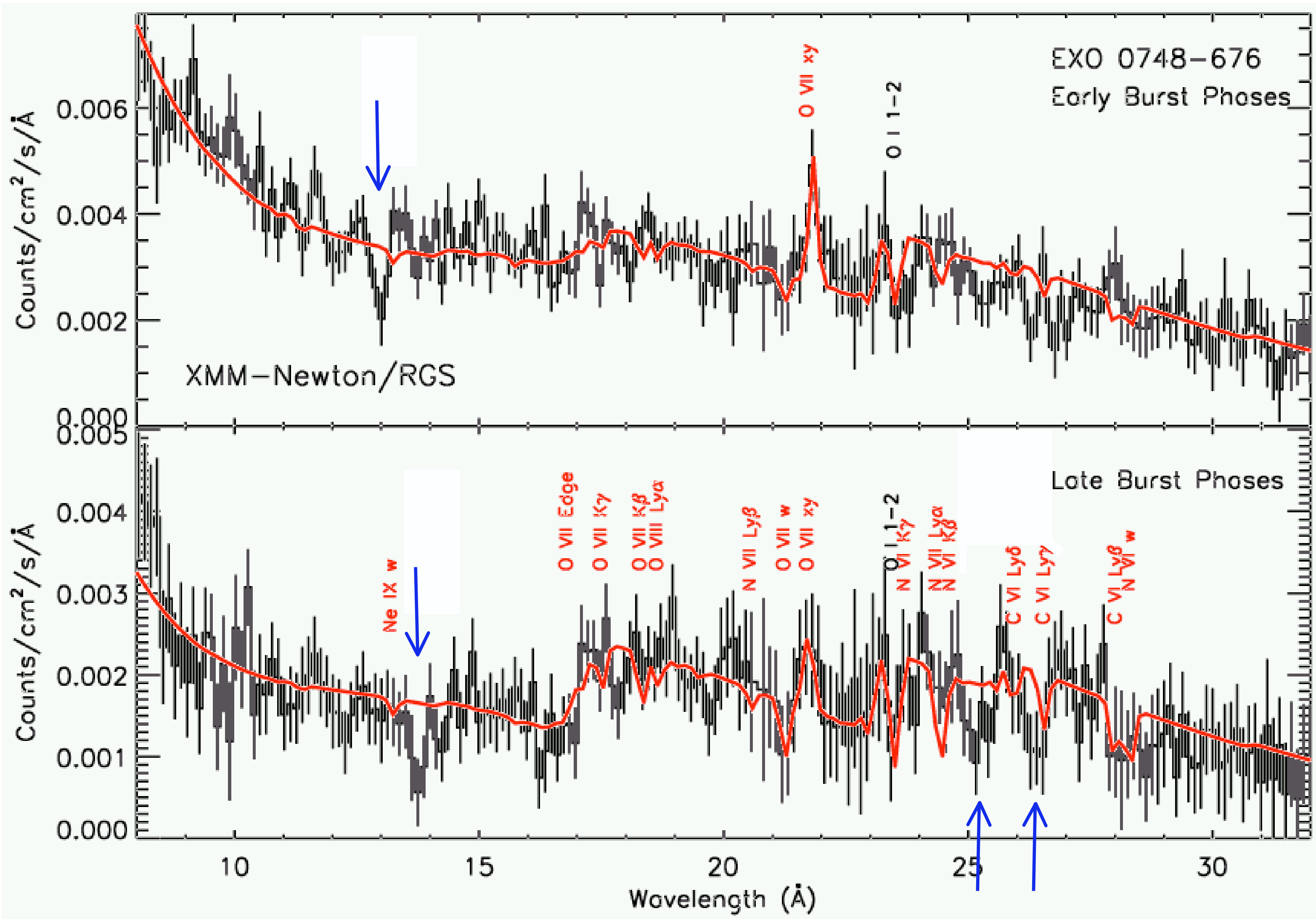


Circumstellar Absorption Spectra

* In order to identify features associated with the neutron star, we must first account for circumstellar absorption.
  – O VII emission line ratios suggest high density photoionized gas
  – O VII absorption features are blue-shifted by v~5000 km/s suggesting bulk outflow
  – Evolution in the absorption-to-emission ratios are consistent with changes in geometry from spherical to increasingly flat

* We can then use the measured O VII parameters to model the global absorption spectra.
  – The observed ratio of O VII/O VIII constrains the ionization parameter to □= L/nR^2 □ 10
    □ ionization balance for K-shell C, N, O, Ne, Mg, Si & L-shell Fe
  – Assume solar abundances □ ion column densities
  – Assuming a constant temperature, the velocity structure for each ion scales from the O VII values

Burst Spectra with Circumstellar Model



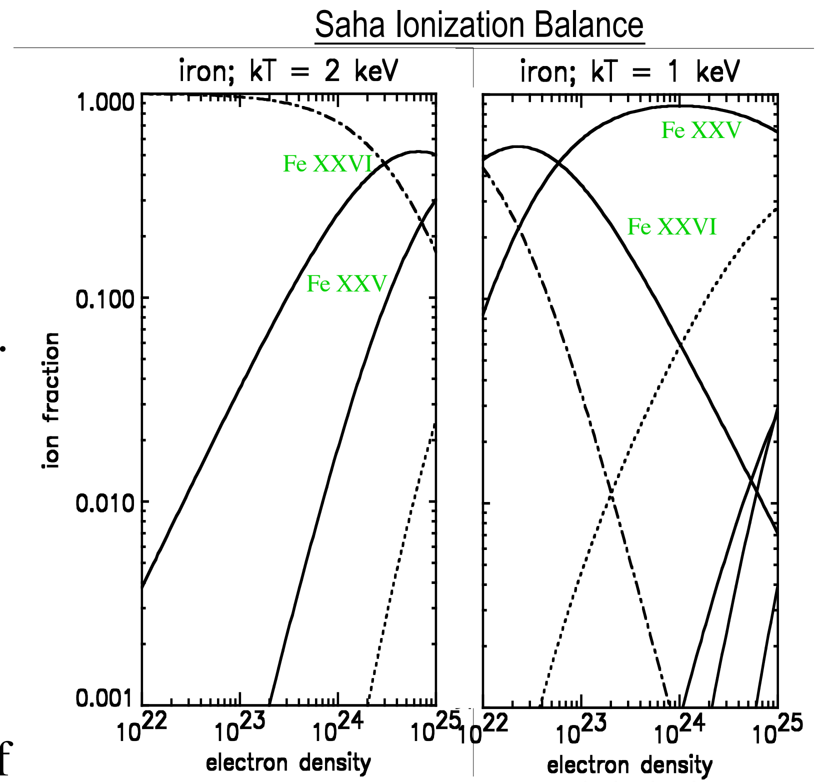
Residual Spectral Features

* There are significant residual spectral features at
  - Early: 13.0 Å (25.3, 26.3, 26.9 Å)
  - Late: 13.75 Å, 25.2 Å, 26.4 Å (17.8, 19.7 Å)
* Excluding instrumental explanations
  – The features appear in both RGS instruments
  – The features appear in the early- and late- phase spectra separately
  – There are no similar features in deep exposures of Mrk 421, 3C273, PKS2155-304
* Excluding circumstellar explanations
  – The features are inconsistent with absorption in ions at higher ionization parameters:
    • To account for the features, separate ions present at the same □ would have different, random velocities and a strange ionization balance
    • For a given line identification, the higher n-level lines and/or the associated edges are not observed

$\Longrightarrow$ Features must be associated with the Neutron Star

Identifying Absorption Features

* Features are not consistent with simple absorption in the Lyman series of any ion.
* Evolution of the spectral features is key to their identification.
  – Early: Fe XXVI dominates ion balance.
    • Identifying 13.0 Å with transitions of Fe XXVI n=2-3 □ z=0.35
    • Higher order n □ 2 transitions would lie at □<9.7 Å
  – Late: Fe XXV dominates ion balance.
    • Identifying 13.75 Å with transitions of Fe XXV n=2-3 □ z=0.35
    • Higher order n □ 2 transitions would lie at □<10.2 Å

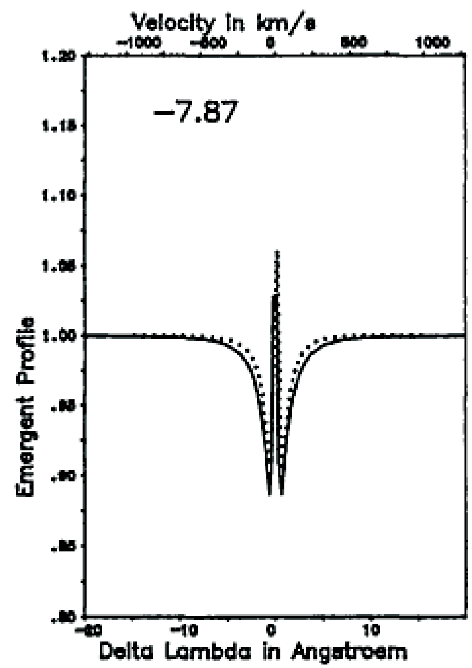


⇨ Two absorption features both at redshift z=0.35

Identifying Absorption Features (Cont.)

- Only other ion that might be present with sufficient abundance is O VIII
  - – Redshifting O VIII Ly□ by z=0.35 would produce a feature centered between the 25.3, 26.4 Å features
  - – Perhaps the double-peaked structure is self-reversed absorption in an extended outflowing atmosphere.
- Alternately, these features may be higher-order Fe XXV transitions.
  - – Fe XXV n □ 3 transitions cannot be made to fit with a single redshift.
  - – Features might be consistent with Fe XXV n □ 3 transitions if include additional redshifts due to the Stark effect.

Modelled He II 4686 Å line profile in outflowing stellar atmosphere



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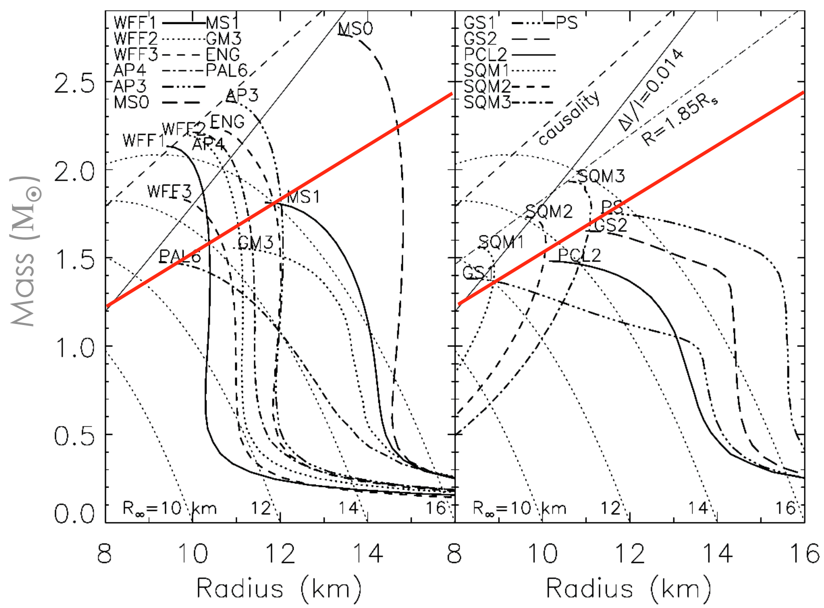
Immediate Implications

* Measurement of the gravitational redshift imposes quantitative constraints on the equations of state for cold, dense nuclear matter. A redshift of z=0.35 is consistent with most models of normal nuclear matter:

$M=1.4\text{-}1.8\ M_{\odot}$ $R=9\text{-}12$ km

For astrophysically reasonable neutron star masses, it is marginally consistent or excludes some models containing more exotic matter.



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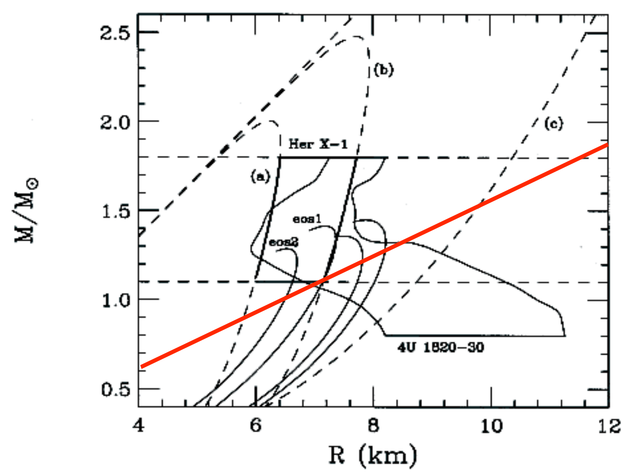

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Detailed Line Spectroscopy

* The Fe absorption lines are resolved and have large equivalent widths:

$EW_{FeXXVI} = 0.13$Å $EW_{FeXXV} = 0.18$Å

* We can calculate upper-limits to the equivalent widths for thermal Doppler broadening by assuming features are formed at □≤ 1. For atmosphere at solar abundance and T ~ 10^7 K we get EW □0.013 Å. To match measured value iron must be overabundant $A \geq 100A_{\odot}$

□ Need an additional source of line broadening.

* We can estimate the line broadening due to the Stark Effect. For a characteristic density of $n_e = 10^{23}cm^{-3}$ we find □E ~ 0.1 Å.

□ Positive evidence of Stark broadening!

Detection of multiple transitions in a single ion provide a measure of electron density and gravitational acceleration, g □ M/R^2

* The higher-order transitions should lie just below our current detection limits:

Lyman: $W_{□}$ = 30 eV
Balmer: $W_{□}$ = 0.03Å ($W_{meas} \leq$ 0.04Å)
Paschen: $W_{□}$ = 0.2Å, $W_{□}$ = 0.1 □ particularly sensitive

* These measurements are independent of the rotation period.

Future Work

* Further high-resolution observations of bursting neutron stars should be performed using XMM-Newton, Chandra, ASTRO-E2, and particularly Constellation X, in order to increase the sample size.

* Further Observations of EXO 0748-676 are needed. Deeper observations that detect higher-order transitions will confirm line identifications and potentially provide a measure of the electron density. This could provide a simultaneous spectroscopic measure of the mass and radius of a neutron star.

* Further calculations are required to fully utilize the spectroscopic information. We need to calculate the Stark broadening in the regime where the Stark split is comparable to the fine structure split. These calculations depend critically on the density and temperature distribution in the neutron star atmosphere during burst.