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EUV/Soft X-ray Spectra for Low B Neutron Stars

By Roger W. Romani[1], Mohan Rajagopal[1]
Forrest J. Rogers[2], AND Carlos A. Iglesias[2]

[1]Department of Physics, Stanford University, Stanford, CA 94305-4060, USA
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Recent ROSAT and EUVE detections of spin-powered neutron stars suggest that many emit 'thermal' radiation, peaking in the EUV/soft X-ray band. These data constrain the neutron stars' thermal history, but interpretation requires comparison with model atmosphere computations, since emergent spectra depend strongly on the surface composition and magnetic field. As recent opacity computations show substantial change to absorption cross sections at neutron star photospheric conditions, we report here on new model atmosphere computations employing such data. The results are compared with magnetic atmosphere models and applied to PSR J0437-4715, a low field neutron star.

1. Introduction

Thermal radiation from neutron star surfaces is of continuing interest to the X-ray community because it provides important clues to the compact objects' evolution and to the physics of the high density interior. Model atmosphere calculations for low field neutron stars (Romani 1987) with effective temperatures $5.0 < \log(T_{eff}) < 6.5$ and a variety of surface compositions showed that the emergent spectra could differ strongly from a Planck function. Extension of these results to atmospheres with strong ($> 10^{12}$G) fields has proved possible for pure H models (Pavlov *et al.* 1994). Satisfactory opacities in strong fields (Miller 1992) are not yet available for heavy elements, but the effects should be significantly weaker for a given field than in the H atmosphere case.

In the last few years there has been a dramatic improvement in our ability to probe neutron star thermal fluxes with a number of strong ROSAT detections (Ögelman 1994) and, more recently, some detections with EUVE (Edelstein, Foster & Bowyer 1995). These results include measurements of millisecond pulsars and other low field neutron stars. With the availability of flux ratios and some low resolution spectra it is important to compare the observations with models of varying surface composition; iron is of particular interest since it is the surface element for a BPS composition run. Recently it has also been realized that previous opacity computations, *eg.* the Los Alamos Opacity Library results, based on DCA (detailed configuration accounting) were not sufficiently accurate. In particular, new opacities by the OPAL (Rogers & Iglesias 1994) and OP (Seaton *et al.* 1994) groups, including configuration term structure, have significantly modified the contribution of Fe and other heavy elements. The most important changes are due to M shell transitions near 100eV, which provide large increases (up to four-fold) in solar abundance opacities. These modifications have already solved a number of outstanding stellar physics puzzles. For the neutron star thermal spectrum problem the new opacities are even more significant, since these objects can have pure Fe atmospheres, with strong surface gravities and temperatures $\log(T_{eff}) \sim 5-6$ ensuring that the emergent spectrum forms precisely in the region where the opacity changes have a maximal effect.

These two developments have prompted us to recompute atmosphere structures and

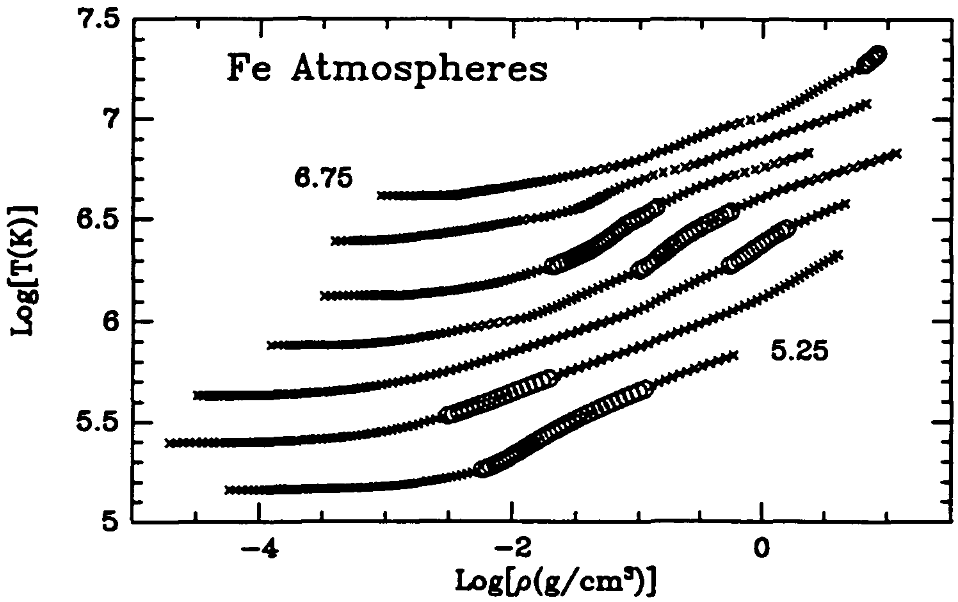

Figure 1: Fe model atmosphere structures. Convectively unstable regions are shown with open circles.

emergent spectra for weakly magnetized neutron stars. Here we report on preliminary results using OPAL H and Fe opacities. Improved equation of state data also allow us to investigate the atmospheric stability. We compare the new Fe spectra with emergent spectra for light elements and show how the sensitivity of recent observations can constrain the atmospheric properties of some pulsars.

2. Model Atmosphere Computations

For the iron atmospheres a pure Fe equation of state table was computed in the range $4.5 < \log(T) < 8$, $-14 < \log(\rho) < 5$, covering $\log(R = \rho/T^3) < -18$. The upper cut-off in density was imposed to keep relativistic corrections small. For this pure Fe gas 'monochromatic' opacities were computed as 10^4 Rosseland group means spaced linearly over $0 < u = \frac{E}{k_B T} < 20$. To extend to high energies in the final emergent spectrum, this was supplemented by 10^4 Planck mean opacities spaced linearly in energy to 10keV. As a representative light element, pure H equations of state and Planck mean 'monochromatic' opacities extending to 10keV were also computed. We have grids for solar abundance compositions as well; computations of these atmospheres are in progress.

The atmosphere calculations were started from models obtained by imposing hydrostatic equilibrium on the exact gray atmosphere solution. Typically 100 grid zones were utilized, extending to a Rosseland mean optical depth $\tau_R \sim 300$. Mean opacities at $\sim 10^3$ frequencies were computed and the transfer equations were solved at each energy group to compute the atmospheric flux. At large monochromatic τ_ν, the Milne integrals were replaced by diffusion to preserve convergence to the exact grey solution. The atmospheric temperature runs were corrected using an adaptive Lucy-Unsöld proceedure; convergence to the radiative zero solution within 1% was achieved throughout. Final emergent spectra were then computed from $> 10^4$ Planck mean subgroups and binned down to the desired resolution.

Atmospheric stability was checked by computing the energy gain ratio for a convection

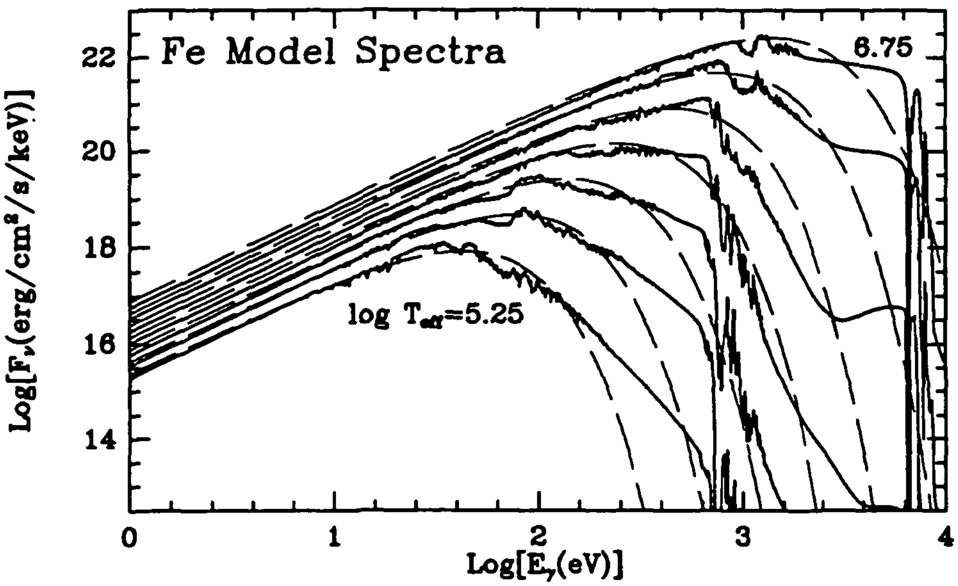

Figure 2: Emergent spectra for 10km, $1.4M_\odot$, Fe atmosphere neutron stars computed from OPAL opacities. Blackbody spectra are shown with dashed lines.

cell along the radiative solution, $dT/dz|_{rad}$:

$$\Gamma \approx \frac{\kappa_{cm} k_B^2}{24\sigma\mu^2 m_H^2}\rho(dT/dz|_{rad} - dT/dz|_{ad})^{1/2} C_P/(T g)^{3/2} \tag{2.1}$$

where the local adiabatic gradient was determined from the EOS computations. Although the atmospheres become formally convective at large depth the very large surface gravity ensures that convection is weak in most cases, since $\Gamma \propto 1/g$. For the coldest iron atmospheres $\log(T_{eff}) \lesssim 5.25$ the convective flux transport contributes only a few percent change to $T(\rho)$; for the other models corrections are smaller (Fig. 1). For H, convection can be significant at large depth for $\log(T_{eff}) \lesssim 5.5$, although atmospheric B fields will provide some further suppression. Spectral modifications due to photospheric convection are not included here; these decrease the flux above the thermal peak slightly.

Our products are grids of Fe and H atmospheres computed with the surface gravity of a $1.4M_\odot$, 10 km neutron star (*e.g* Fig. 2). Emergent spectra (with zero redshift) are computed for $5 < \log(T_{eff}) < 6.75$. To compare with observations these must be redshifted to infinity; spectra for various neutron star radii and masses are adequately represented by varying this redshift. These spectra are available for comparison with EUV/soft X-ray observations of neutron stars. (Contact: rwr@astro.stanford.edu)

3. Application to PSR J0437-4715

Using the ROSAT PSPC Becker and Trümper (1993) have studied the nearby (140pc), low field (B=2.5×10^8G) millisecond pulsar PSR J0437-4715, detecting pulsed X-rays in the 0.1-2.4 keV band. They find that the time averaged spectrum is fit by a composite model of a powerlaw plus blackbody. The pulse fraction peaks at $\sim$ 1 keV, indicating that pulsation is due to variation in the 'blackbody' component.

We have re-analyzed the PSPC data, phasing to the radio pulse ephemeris (Manchester, private comm.). We find that the X-ray pulse arrives in phase with the radio emission (residual ROSAT clock errors, however, allow a phase error $\Delta\phi \sim 0.1$), supporting the

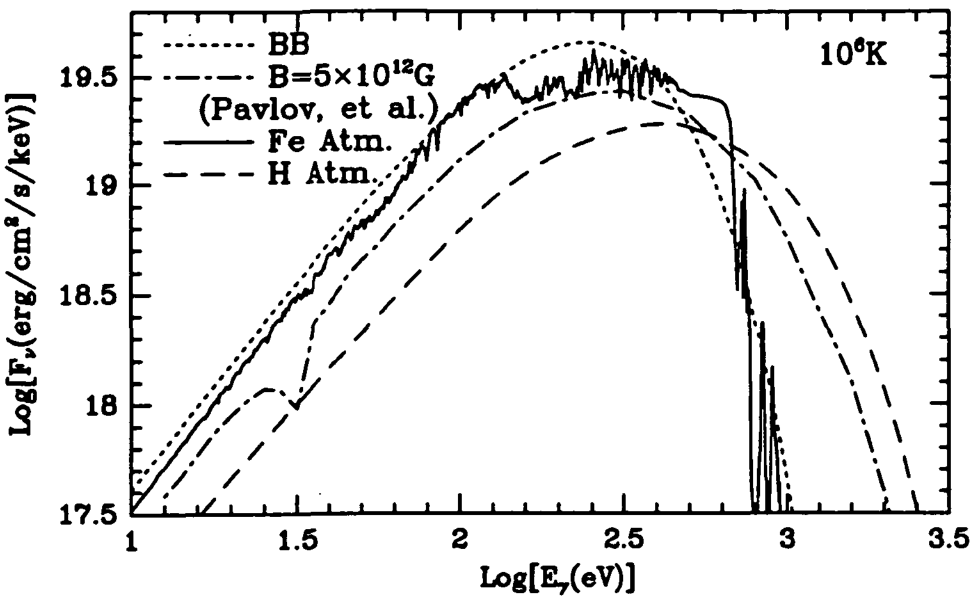

Figure 3: Variation with surface composition and magnetic field at $T=10^6$K. H and Fe spectra are from the present work; the H atmosphere with $B=5 \times 10^{12}$G is from Pavlov *et al.* 1994. Note that all spectra depart significantly from the equivalent blackbody.

Table 1: Fits to PSR J0437-4715 PSPC data

Model	$T_{eff}(10^6$K)	A_{eff}(cm^2)	χ^2/DOF
BB	1.4	9.8×10^9	1.33
H	0.56	4.0×10^{11}	0.85
Fe	1.0	3.8×10^{10}	2.0

idea that the thermal pulsed component is associated with a heated polar cap. We therefore extract the off-pulse spectrum and find the best fit powerlaw to represent the unpulsed, presumably plerionic, emission. This fit is acceptable, but shows significant residuals. To test the effect of surface composition on the polar cap flux, we then fit the on-pulse spectrum by adding a thermal component. Results are summarized in Table 1. While the blackbody is statistically acceptable, the implied polar cap area is very small. The Fe atmospheres, having a sharp L edge at ~0.9keV, cannot provide a good fit to the data. Light element, eg. H, atmospheres produce a significantly better fit than the best blackbody due to the excess above the thermal peak (Figure 3). The large emission region implied by the lower temperature is in better agreement with theoretical expectations as well; the cap radius for an aligned vacuum dipole is $r_{cap} = (2\pi r_{NS}^3/Pc)^{1/2}$ giving an area 1×10^{11}cm^2 while the cap size inferred for surface core emission ($r_{cap} \sim 0.043 r_{NS} P^{-1/2}$, Rankin 1990) gives an area of 9×10^{11}cm^2.

Similarly, the presence of a light element atmosphere simplifies interpretation of the recent detection of PSR J0437-4715 in the 100Å filter of the EUVE deep survey instrument (Edelstein, Foster & Bowyer 1995). The EUVE flux for an absorbing column of $N_H \sim 10^{20}$cm^{-3}pc is in agreement that expected from an H atmosphere with an effective temperature of $T_{eff} \sim 6 \times 10^5$K and an emitting area of $2 - 3 \times 10^{11}$cm^2.

4. Conclusions

Computations of Fe and H atmospheres with revised opacity and equation of state data provide a baseline set of atmospheres to compare with observed spectra of neutron stars. While for most young pulsars strong $\sim 10^{12}$G magnetic fields ensure that magnetic atmospheres are needed for detailed comparison, the gross differences between the H and Fe spectra in the present spectra still provide a useful probe of the surface composition. Moreover, these spectra are directly applicable to millisecond pulsars and other low field neutron stars.

For the Fe atmospheres, improvements to the atmospheric computations and the OPAL opacity data have resulted in significant changes to the absorption edge and line strengths in the emergent spectra, especially at energies in the EUV/Soft X-ray range, $\sim 50-300$eV. These new spectra should be used to illustrate the effects of heavy element atmospheres. For the H atmospheres computation of stability criteria along the radiative zero solution indicates that there can be significant convective energy transport for low T_{eff}, although the high surface gravity and the presence of magnetic fields suppresses the convection. In the light element atmospheres the trend towards 'harder' spectra for a given T_{eff} with excess emission above the Wien peak is clear. For high magnetic fields this excess is somewhat suppressed (Pavlov *et al.* 1994).

Because of the strong broad-band features in these models, phase resolved X-ray spectral data, even of low resolution, can constrain the composition of neutron star surfaces. Comparison of our models with PSR J0437-4715 PSPC observations suggests that, as for other soft X-ray pulsars, 'thermal' spectra harder than the equivalent blackbody provide the best description of the data; a light element surface can provide such a spectrum. The change in the inferred T_{eff} has significant effect on the thermal history and on the inferred EOS at supernuclear densities. By inference, application of magnetic H atmospheres to high-field young neutron stars may be appropriate, as well. This is fortunate, since magnetic opacities for heavy elements will be difficult to compute.

Thus phase resolved soft X-ray spectra can isolate thermal surface emission from pulsar magnetospheric or plerionic flux. Phase resolved fluxes from EUVE images can also provide important constraints. We note that spectral results from EUVE would be even more revealing if moderate age ($\log(T_{eff}) \gtrsim 5.5$) pulsars can be found with weak interstellar absorption $N_H \lesssim 10^{19}\mathrm{cm}^{-3}$pc. In this case measurement of spectral lines and breaks can strongly probe the surface composition and redshift. Future AXAF and XMM observations should be able to effect such tests for more distant objects.

Becker, W. & Trümpler, J. 1993 *Nature*, **365**, 528.

Edelstein, J., Foster, R. & Bowyer, S. 1995 *ApJ* , submitted; see also Foster, these proceedings.

Miller, M.C. 1992 *MNRAS* **255**, 129.

Ögelman, H. 1994 In *Lives of Neutron Stars* (ed. J. van Paradijs & A. Alpar). Kluwer.

Pavlov, G.G. *et al.* 1994 In *Lives of Neutron Stars* (ed. J. van Paradijs & A. Alpar). Kluwer.

Rankin, J.M. 1990 *ApJ* **352**, 247.

Rogers, F.J. & Iglesias, C.A. 1994 *Science* **263**, 50.

Romani, R.W. 1987 *ApJ* **313**, 718.

Seaton, M.J. *at al.* 1994 *MNRAS* **266**, 805.