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NSMAXG: A new magnetic neutron star spectral model in XSPEC

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Abstract. The excellent sensitivity of X-ray telescopes, such as Chandra and XMM-Newton, is ideal for the study of cooling neutron stars, which can emit at these energies. In order to exploit the wealth of information contained in the high quality data, a thorough knowledge of the radiative properties of neutron star atmospheres is necessary. A key factor affecting photon emission is magnetic fields, and neutron stars are known to have strong surface magnetic fields. Here I briefly describe our latest work on constructing magnetic ($B \geqslant 10^{10}$ G) atmosphere models of neutron stars and the NSMAXG implementation of these models in XSPEC. Our results allow for more robust extractions of neutron star parameters from observations.

Keywords. radiative transfer, stars: atmospheres, stars: magnetic field, stars: neutron

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Thermal X-ray radiation has been detected from many radio pulsars and radio-quiet neutron stars. Thermal emission can provide invaluable information on the physical properties and evolution of neutron stars, such as the mass M, radius R, and surface temperature T, which in turn depend on poorly constrained physics of the deep interior, such as the nuclear equation of state and quark and superfluid and superconducting properties at supranuclear densities. In addition, neutron stars are known to possess strong magnetic fields: from $B \approx 10^8 - 10^9$ G in the case of millisecond pulsars to $B \approx 10^{10} - 10^{13}$ G in the case of normal pulsars and even $B \gtrsim 10^{14}$ G in magnetars (see Zavlin 2009; Kaspi 2010; Harding 2013, for reviews).

The observed thermal radiation originates in a thin atmospheric layer (with scale height ~ 1 cm) that covers the stellar surface. Atmosphere properties, such as magnetic field, chemical composition, and radiative opacities, directly determine the characteristics of the observed spectrum. While the surface composition of neutron stars is generally unknown, a great simplification arises due to the efficient gravitational separation of light and heavy elements (Alcock & Illarionov 1980; Hameury *et al.* 1983). A pure hydrogen atmosphere is expected even if a small amount of accretion occurs after neutron star formation; the total mass of hydrogen needed to form an optically thick atmosphere can be less than $\sim 10^{16}$ g. Alternatively, a helium or carbon atmosphere may be possible as a result of nuclear burning on the neutron star surface (Chang & Bildsten 2003; Chang *et al.* 2010). Finally, a heavy-element atmosphere may exist if no accretion takes place or if all the accreted matter is consumed by nuclear reactions.

Steady progress has been made in modeling neutron star atmospheres (see Zavlin 2009, for more detailed discussion and references). Since the neutron star surface emission is thermal in nature, it has been modeled at the lowest approximation with a blackbody spectrum. Early works on more realistic spectra assumed emission from unmagnetized light-element atmospheres, and the resultant spectra exhibit distinctive hardening relative to a blackbody. The inclusion of magnetic fields has many important effects. For example, the presence of a magnetic field causes emission to be anisotropic and polarized (see Mészáros 1992, for review). At $B > e^3 m_{\mathrm{e}}^2 c/\hbar^3 = 2.35 \times 10^9$ G, the binding energy of atoms, molecules, and other bound states increases significantly, and abundances can be appreciable in the atmosphere of neutron stars (see Lai 2001, for review). When field strengths approach and exceed the quantum electrodynamics field $B_{\rm QED} = m_{\rm e}^2c^3/e\hbar = 4.41 \times 10^{13}$ G, vacuum polarization effects, such as switching between photon polarization modes, become relevant (Lai & Ho 2002; van Adelsberg & Lai 2006), and the atmosphere may even cease to exist as plasma condenses onto the surface (Medin & Lai 2007; Potekhin *et al.* 2012). Most calculations of magnetic neutron star atmospheres focus on a fully ionized hydrogen plasma. Only relatively recently have self-consistent atmosphere models using the latest equation of state and opacity results for strongly magnetized and *partially ionized* hydrogen and mid-Z elements been constructed (Potekhin *et al.* 2004; Mori & Ho 2007).

In previous work, we implemented into XSPEC (Arnaud 1996) our theoretical neutron star magnetic atmosphere X-ray spectra, under the model name NSMAX (Ho *et al.* 2008). These atmosphere spectra are obtained using the partially ionized results of Potekhin *et al.* (2004) and Mori & Ho (2007). Two sets of models are provided: One set with a single surface $\mathbf{B}$ and $T_{\rm eff}$ and a second set which is constructed with $\mathbf{B}$ and $T_{\rm eff}$ varying across the surface according to a magnetic dipole geometry. Magnetic fields and effective temperatures of the models span the range $B = 10^{12} - 3 \times 10^{13}$ G and $\log T_{\rm eff}\,({\rm K}) \approx 5.5 - 6.7$, respectively. Note that other neutron star atmosphere spectra in XSPEC are either non-magnetic (NSAGRAV: Zavlin *et al.* 1996; NSSPEC: Gänsicke *et al.* 2002; NSATMOS: McClintock *et al.* 2004; Heinke *et al.* 2006) or magnetic but fully ionized hydrogen (NSA: Pavlov *et al.* 1995); the last at only two fields: $B = 10^{12}$ and 10^{13} G. We also note the open source non-magnetic model McPHAC (Haakonsen *et al.* 2012).

We recently implemented into XSPEC a new set of neutron star magnetic atmosphere X-ray spectra, under the model name NSMAXG, which replaces NSMAX. The new model is nearly identical to the old model but with two important differences. The first difference is the inclusion of atmosphere spectra for weaker magnetic fields ($B = 10^{10} - 10^{11}$ G). These spectra are constructed using the method described in Ho *et al.* (2008), and references therein, supplemented by Potekhin & Chabrier (2003) for calculating Gaunt factors and Suleimanov *et al.* (2012) to account for thermal effects (see also Pavlov & Panov 1976; Potekhin 2010; Suleimanov *et al.* 2010). Examples of these spectra are shown in Ho (2013). Note that these weak magnetic field spectra assume a fully ionized hydrogen atmosphere; partially ionized spectra are the subject of current work.

The second important difference between NSMAXG and NSMAX is a change in XSPEC fit parameters. Most XSPEC neutron star atmosphere models (NSA, NSAGRAV, and NSATMOS) use the fit parameters $T_{\rm eff}$, M, R, and either distance d or flux normalization A. The last two are equivalent since $A \propto R^2/d^2$. On the other hand, the fit parameters of NSMAX are $T_{\rm eff}$, A, and gravitational redshift $1+z_{\rm g}$ $[= (1-2GM/c^2R)^{-1/2}]$. There are two reasons for this different choice for NSMAX. The first is that *all* models in XSPEC are calculated assuming that emission arises from the entire visible surface of the neutron star, i.e., $R = R_{\rm NS}$. Thus the same value of R must be used to calculate $z_{\rm g}$. The second reason is that NSMAX is constructed for particular values of surface gravity g $[= (1+z_{\rm g})GM/R^2]$ (similarly NSA is calculated using a single value of g, as well as assuming a fully ionized plasma, which is in contrast to the partially ionized plasma of NSMAX). Thus allowing M and R to vary as fit parameters would not produce consistent results, i.e., the derived values of M and R would not necessarily correspond to the value of g that is used to compute the atmosphere spectrum (see Heinke *et al.* 2006, for comparisons between NSA and NSATMOS). We rectify this second issue by calculating spectra for a range of surface gravities, i.e., $\log g\,({\rm cm\ s^{-2}}) = 13.6 - 15.4$, thus allowing NSMAXG to use M and R as consistent fit parameters. Note that NSATMOS

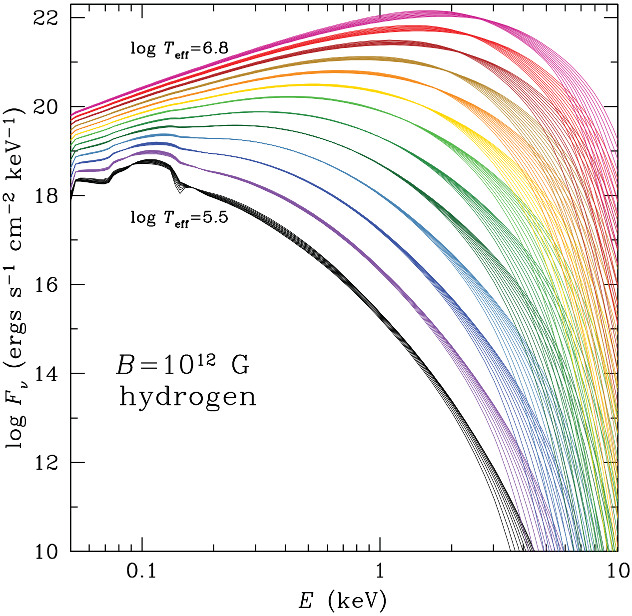

Figure 1. Partially ionized hydrogen atmosphere model spectra for effective temperatures $\log T_{\rm eff} = 5.5-6.7$, surface gravities $\log g = 13.6-15.4$, and magnetic field $B = 10^{12}$ G.

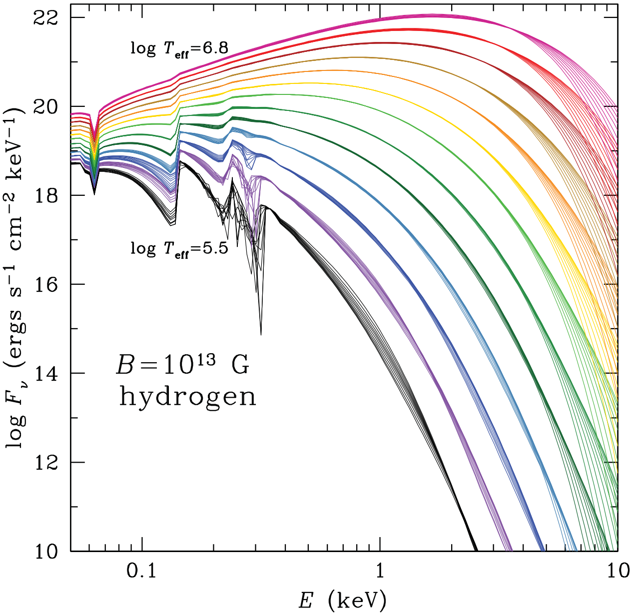

Figure 2. Partially ionized hydrogen atmosphere model spectra for effective temperatures $\log T_{\rm eff} = 5.5-6.7$, surface gravities $\log g = 13.6-15.4$, and magnetic field $B = 10^{13}$ G.

and NSAGRAV are also calculated for a range of g; however recall that these two are non-magnetic models. Figures 1 and 2 show the resulting NSMAXG spectra for $B = 10^{12}$ and 10^{13} G, respectively. Incidentally, the spectral tables of NSMAX and NSMAXG can easily be made compatible for use with the other XSPEC neutron star fitting routines.

The spectra shown in Figs. 1 and 2 only describe emission from either a local patch of the stellar surface with a particular effective temperature and magnetic field or a star with a uniform temperature and radial magnetic field of uniform strength. By taking into account surface magnetic field and temperature distributions, we can construct more physical models of neutron star emission, which can be used for interpreting and decoding observations (see Ho 2007; Ng *et al.* 2012, for details and examples).

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