MODELING SPECTRAL FEATURES FROM ISOLATED NEUTRON STARS

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Abstract We study several effects that influence the strength of the proton cyclotron and atomic features in the thermal spectra of magnetic neutron stars. Magnetic field variations over the neutron star surface leads to broadening of features. Vacuum polarization can strongly suppress spectral lines when $B \gtrsim 10^{14}$ G. The surface spectrum is unaffected by vacuum polarization when $B \lesssim 7 \times 10^{13}$ G; thus the proton cyclotron absorption line (and atomic lines) can have a large equivalent width, possibly explaining the features seen in some isolated neutron stars.

Keywords: stars:atmospheres – stars:magnetic fields – stars:neutron – X-rays:stars

1. Observations

Considerable observational resources have been devoted to the study of thermal emission from isolated neutron stars (NSs) and, in particular, to the search for spectral features in the radiation. Thermal radiation from the surface of isolated NSs can provide invaluable information on the physical properties and evolution of NSs (Zavlin 2005). For many NSs, the spectra are found to be featureless and often well fit by a blackbody (see Pavlov *et al.* 2002 for a review). However, absorption features have been found in the thermal emission of several isolated NSs. For example, the spectrum of the young NS 1E 1207.4 − 5209 shows features at 0.7 and 1.4 keV (Sanwal *et al.* 2002; Mori *et al.* 2004) and possibly at 2.1 and 2.8 keV (De Luca *et al.* 2004). Several of the dim, radio-quiet isolated NSs (Haberl 2004; Trümper 2005) have been observed to possess broad absorption features (Table 1). It is particularly striking

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that, although four of these have similar effective temperatures, the equivalent widths (EW) of their lines are very different.

Table 1. Spectral Features in Dim Isolated Neutron Stars

DINS	*Period (s)*	*kT (eV)*	E_{line} *(keV)*	*EW (keV)*	*Ref*
RX J1308.6 + 2127	10.3	86	0.2−0.3	0.15	1
RX J1605.3 + 3249	?	95	0.45	0.08	2
RX J0720.4 − 3125	8.4	85[a]	0.27	0.04	3
RX J0806.4 − 4123	11.4	96	0.41−0.46	0.03−0.06	4
RX J0420.0 − 5022	3.45 or 22.7	45	0.33	0.045	4

References—(1) Haberl *et al.* 2003; (2) van Kerkwijk *et al.* 2004; (3) Haberl *et al.* 2004a; (4) Haberl *et al.* 2004b

[a] see de Vries *et al.* 2004 and Vink *et al.* 2004 for long-term spectral changes

2. Partially Ionized Atmospheres and Vacuum Polarization Effect

Because the strong magnetic field significantly increases the binding energies of atoms, molecules, and other bound states (see Lai 2001 for a review), these bound states may have abundances appreciable enough to contribute to the opacity in the atmosphere. Recently, thermodynamically consistent equation of state (EOS) and opacities for a magnetized, partially ionized H plasma have been obtained by Potekhin & Chabrier (2003, 2004). These EOS and opacities have been implemented by Ho *et al.* (2003) and Potekhin *et al.* (2004, where we have included the effect of bound species on the polarization vectors of the photon modes) for modeling NS atmospheres. For models with "ordinary" magnetic field strengths (10^{12} G$\lesssim B \lesssim 7\times 10^{13}$ G), the spectral lines associated with bound species lie in the extreme UV to very soft X-ray energy bands and are difficult to observe. However, the opacities are sufficiently different from the fully ionized opacities that they can change the atmosphere structure and continuum flux, which can affect fitting of the observed spectra (e.g., Ho *et al.* 2004).

In a magnetized NS atmosphere, both the plasma and vacuum polarizations contribute to the dielectric property of the medium. A "vacuum resonance" arises when these two "compensate" each other (Ventura 2005). Away from the vacuum resonance, the photon modes (for $E \ll E_{Be} = 1.16\,B_{14}$ MeV, the electron cyclotron energy) are almost linearly polarized. Near the vacuum resonance, the normal modes become circularly polarized. When a photon propagates outward in the NS atmosphere, its polarization state will evolve adiabatically if the density variation is sufficiently gentle; thus, a photon of

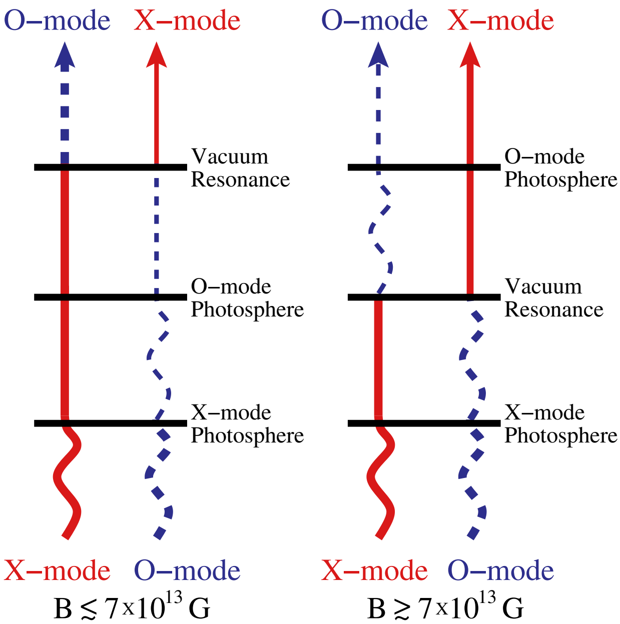

Figure 1. Diagram illustrating how vacuum polarization-induced mode conversion affects the emergent radiation from a magnetized NS atmosphere. The photosphere is defined by where the optical depth (measured from the surface) is 2/3 and is where the photon decouples from the matter. Left: In the "normal" field regime, the vacuum resonance lies outside the photospheres of the two modes. Right: In the "superstrong" field regime, the vacuum resonance lies between the two photospheres.

one mode will be converted into the other mode as it traverses the vacuum resonance (Fig. 1; Lai & Ho 2002, 2003).

At $B \gtrsim 10^{14}$ G, vacuum polarization can significantly affect the radiation spectrum from magnetized NS atmospheres: it softens the high-energy tail and suppresses the proton cyclotron feature and features due to bound species (Lai & Ho 2002; Ho & Lai 2003; Ho *et al.* 2003). The latter could provide an explanation for the non-detection thus far of lines in the observed thermal spectra of several magnetars (Israel 2004), which are thought to possess $B \gtrsim 10^{14}$ G. We note here that there have been spectral features seen in the *non-thermal* emission from magnetars (Rea *et al.* 2003; Ibrahim 2005).

At $B \lesssim 10^{14}$ G, vacuum polarization has little effect on the atmosphere emission spectra. Therefore, strong proton cyclotron or other atomic features may be present in the thermal spectrum. Our calculations of NS synthetic spectra, taking into account the line broadening effect due to magnetic field variation over the NS surface, show that the observed broad absorption features in the dim isolated NSs (Table 1) could be explained naturally as the proton cyclotron line, with possible blending from atomic lines of neutral hydrogen (Ho & Lai 2004). The variation in the strength of the observed spectral features in these sources is then due to different fractions of the surface with $B \lesssim 10^{14}$ G.

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VI

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