Part 9

Population and Neutron Star Properties

Section B. Thermal Evolution of Pulsars and Their Companion

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Neutron Star Atmospheres

George G. Pavlov

The Pennsylvania State University, Department of Astronomy & Astrophysics, 525 Davey Lab, University Park, PA 16802, USA

V. E. Zavlin

Max-Planck-Institut für Extraterrestrische Physik, 85740 Garching, Germany

Abstract. Properties of the thermal radiation emitted by neutron stars (NSs) are determined by thin plasma layers (atmospheres) at their surfaces. The NS atmospheres are very different from those of usual stars due to the immense gravity and huge magnetic fields. Current models of hydrogen NS atmospheres show that the spectra deviate substantially from blackbody spectra of the same temperatures. Comparison of the model spectra with recent observations of soft X-ray and UV-optical radiation of NSs yields the surface temperatures considerably lower than those obtained from the blackbody fits. This conclusion have important implications for theories of NS cooling and for understanding fundamental properties of the superdense matter in the NS interiors.

1. Introduction

All our knowledge about the properties of usual stars comes from the analysis of spectra emitted from their atmospheres. Although the star's spectrum is, on average, close to the Planck spectrum with the effective temperature $T_{\rm eff}$, local deviations from the Planck spectrum can be quite substantial, including spectral lines and photoionization jumps. If neutron stars (NS) also have atmospheres, one should use atmosphere models to analyze their thermal radiation.

Do neutron stars (NSs) indeed have atmospheres? It depends on *surface temperature*, *magnetic field*, and *chemical composition*. For instance, if the surface is covered with *hydrogen*, it is in a condensed state for $T \lesssim 0.1$, 0.5, 1 MK at $B = 10$, 100, 500 Teragauss (TG), respectively (Lai & Salpeter 1997). This means that the hydrogen is in the gaseous phase at observable temperatures, $T \gtrsim 0.1$ MK, for typical magnetic fields of radio pulsars, ~ 0.1–10 TG, but it may condense in magnetic fields of magnetars, $\sim 10^2 - 10^3$ TG.

The actual chemical composition of the NS surface layers depends on NS history. If even a small amount of hydrogen is present at the NS surface (e.g., due to accretion from the ISM or fallback of a fraction of the envelope ejected during the SNR explosion), the NS atmosphere would be comprised of pure H because of gravitational separation of elements.

There are two main reasons why we cannot use standard stellar atmosphere models for NSs. First, the *gravity* at the NS surface is enormous, $g \sim 10^{14}$ cm^2 s^{-1}, about 10 orders of magnitude greater than for usual stars. As a result, NS atmospheres are strongly compressed — a typical height scale, $\sim$ 0.1–10 cm, is very small, and the density, $\sim$ 0.1–100 g cm^{-3}, is very high, which leads to strong nonideality effects (pressure ionization, smoothed spectral features). Second, *huge magnetic fields* make NS atmospheres essentially anisotropic and drastically change the properties of the atmospheric matter. For instance, the electron cyclotron energy, $\hbar\omega_c = 11.6(B/1$ TG) keV, strongly exceeds the thermal energy, $kT \sim 0.01$—1 keV, i.e., the transverse motion of "free" electrons is quantized. Since the ratio of the cyclotron energy to the Coulomb energy, $\beta = \hbar\omega_c/(Z^2\mathrm{Ry}) = 852Z^{-2}(B/1$ TG), is very large, the structure of atoms is strongly distorted by the magnetic fields. In particular, the ionization potential is increased by a factor of $\sim (\ln\beta)^2$, which substantially modifies ionization equilibrium. Moreover, spectral opacities are essentially modified (e.g., they are anisotropic and polarization-dependent), which means that *the spectrum, angular distribution and polarization of thermal radiation depend on magnetic field.* Another important effect is that the nonuniform magnetic field leads to a nonuniform surface temperature distribution because of anisotropic heat conduction, which enhances *pulsations of thermal radiation* due to NS rotation.

Why studying NS atmospheres is needed? Comparing observed thermal NS spectra with atmosphere models allows one to infer *chemical composition and properties of NS surface layers* ($T_{\rm eff}$, B, g). Measuring $T_{\rm eff}$ for NSs of different ages allows one to trace thermal evolution of these objects and to evaluate the radius-to-distance ratio, thus putting constraints on the *equation of state*, *nucleon superfluidity*, and *composition* of the superdense NS matter.

From which objects and in which energy ranges can one observe the NS thermal radiation? In very young, active pulsars (e.g., Crab, B0540–69) nonthermal radiation dominates in any energy range, i.e., their thermal radiation is virtually unobservable. In *middle-aged pulsars* ($10^4 - 10^6$ yr) thermal radiation is observable in soft X-ray and UV ranges. *Old pulsars* are too cold to be seen in X-rays, but their thermal radiation is observable in the optical-UV range. Fortunately (for investigators of NS thermal radiation, not for radio pulsar astronomers), the number of *radio-silent NSs* (some of them are "dead pulsars") greatly exceeds the number of radio pulsars. Their thermal radiation could be observed in optical/UV/X-rays, depending on temperature (age). However, observational identification of these objects is complicated. Finally, many NSs reside in close binaries and emit thermal X-rays due to accretion onto the NS surface. Of particular interest for studying surface layers of NS are observations of soft X-rays from *NS transients in quiescence* (Rutledge et al. 1999).

2. Atmosphere Models

2.1. Low-field Atmospheres

Magnetic fields of millisecond (recycled) pulsars and other very old NSs are as low as $\sim 10^8$–10^9 G, so that $\hbar\omega_c \ll kT$ and $\omega_c \ll \omega$ (for X-rays). This means than one can neglect magnetic effects on the NS atmosphere properties. Most recent low-field NS atmosphere models have been studied by Rajagopal &

Romani (1996) and Zavlin, Pavlov, & Shibanov (1996), who constructed a set of models for pure H, He and Fe atmospheres. The main features of these models can be summarized as follows.

- The H and He atmosphere spectra are considerably harder than the blackbody spectrum in the soft X-ray range. This means that fitting the observed spectra with the blackbody model gives the (spectral) temperature exceeding the true effective temperature (typically, by a factor of 2).
- The Fe atmosphere spectra show numerous spectral features in the soft X-ray range; some of them are observable with low-resolution (e.g., CCD) spectrometers. Blackbody fits of these spectra give temperatures close to the true $T_{\rm eff}$.
- The angular distributions of the atmosphere radiation (limb-darkening effect) are quite different for the Fe and H/He atmospheres and depend on energy.
- The spectral shape of the observed radiation depends on direction of emission (which is particularly important if the radiation is emitted from hot spots on the NS surface, like in millisecond pulsars).

2.2. High-field Atmospheres

Hydrogen NS atmospheres with strong magnetic fields have been considered in several papers (see Pavlov et al. 1995; Pavlov 1998; Pavlov & Zavlin 1998 for reviews). The main results can be summarized as follows.

- The magnetic atmosphere spectra are softer at X-ray energies than the low-field spectra, but still harder than the blackbody spectra with the same effective temperatures.
- The angular distributions are strongly anisotropic, with "pencil" and "fan" components.
- The pulse profiles are much sharper than those emitted from low-field atmospheres. Their shape strongly depends on the mass-to-radius ratio due to the gravitational effects.
- Spectral lines become prominent at $T_{\rm eff} \lesssim 0.5$ MK. They are strongly broadened by the motional Stark effect (Pavlov & Potekhin 1995). The strongest line is at $E \sim 0.1 \ln(B/5~{\rm TG})$ keV.
- The radiation is strongly polarized; the degree of polarization depends on E, B, and M/R - see Zavlin & Pavlov (this volume) for details.

Magnetic Fe atmospheres were considered by Rajagopal, Romani, & Miller (1997). These models are still rather approximate because of complicated properties of Fe ions in strong magnetic fields. The model spectra show many prominent spectral features. Observing these features (e.g, with *Chandra* and *XMM*) would be very useful to measure the magnetic field and the mass-to-radius ratio. The Fe atmosphere spectra are, on average, closer to blackbody than the H atmosphere spectra.

3. Observational Implications

3.1. Soft X-ray Observations

Fitting the observed soft X-ray spectra of isolated NSs with NS atmosphere models gives the following results.

- The effective temperatures inferred from fitting the soft X-ray spectra of *middle-aged pulsars* and *radio-quiet NSs in SNRs* with magnetic H atmospheres (e.g., Zavlin, Pavlov, & Trümper 1998) agree with modern NS cooling theories, contrary to the temperatures obtained from the blackbody fits. The best agreement was achieved for the "standard" cooling models with allowance for superfluidity. From the comparison of the model cooling curves with the inferred temperatures, Yakovlev, Levenfish, & Shibanov (1999) estimated the following critical superfluidity temperatures for neutrons and protons: $T_{\rm cn} = 200$ MK, $T_{\rm cp} = 130$ MK.
- The soft X-ray radiation from the brightest *millisecond pulsar* J0437–4715 can be interpreted as thermal emission from hot ($T \approx 1$ MK) polar caps ($R \approx 1$ km) covered with hydrogen (Zavlin & Pavlov 1998), although a nonthermal origin (Becker & Trümper 1999) cannot be firmly excluded yet.
- The faint X-ray radiation from *old pulsars* (e.g., B1929+10, B0950+08 — Wang & Halpern 1997) is likely emitted from very small ($A \sim 100$ m^2), hot ($T \sim 3$ MK) regions (polar caps?). This is a challenge to many models of radio pulsars, which predict polar cap luminosities much higher than observed.

3.2. UV-Optical Observations

The capabilities of modern optical telescopes, particularly, the *Hubble Space Telescope* (*HST*), has opened a new window for studying NSs. Here are some results.

- IR-optical radiation from *middle-aged pulsars* (e.g., B0656+14, Geminga) is nonthermal; their thermal radiation should dominate in UV (Pavlov, Welty, & Córdova 1997; Mignani, Caraveo, & Bignami 1998; Golden & Shearer 1999).
- Optical radiation from *old pulsars* (B1929+10, B0950+08) is apparently thermal, although more observations are needed to confirm it. The temperatures inferred ($T \sim 0.1$ MK — Pavlov, Stringfellow, & Córdova 1996) allow one to constrain *heating mechanisms* (Larson & Link 1999; Miralles, Urpin, & Konenkov 1998).
- Optical-UV radiation from *radio-silent isolated NSs* (RX J1856–3754 — Walter & Matthews 1997; RX J0720–3125 — Motch & Haberl 1998; Kulkarni & van Kerkwijk 1998) looks thermal. The nature of these NSs (age, magnetic field, period for J1856–3754) remains unclear. The joint analysis of the X-ray and optical data may provide a clue (Pavlov et al. 1996b).

4. Future Work

4.1. Theory

To develop realistic NS atmosphere models for broad ranges of temperature, magnetic field, chemical composition, the following work is to be done:

- Calculations of atomic structure for various atoms and ions in strong and superstrong ($B > 10^{14}$ G) magnetic fields.
- Investigations of molecules, molecular chains, phase transitions (particularly, for lower temperatures and/or stronger magnetic fields).
- Calculations of opacities of nonideal plasma and condensed matter.

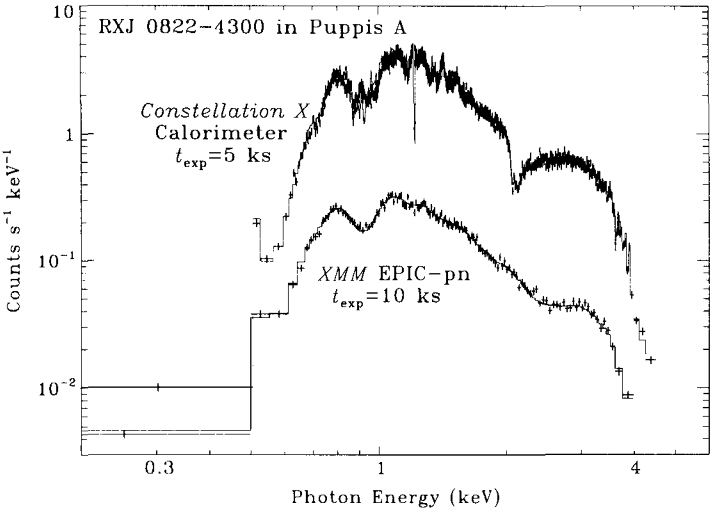

Figure 1. Simulated low-field Fe atmosphere spectra of the radio-quiet NS in the Puppis A SNR (Zavlin, Trümper, & Pavlov 1999), for future observations with the *XMM* and *Constellation X* observatories.

- Developing improved atmosphere/surface models, with allowance for new results of atomic calculations.

4.2. Observations

The forthcoming observations of thermally radiating NSs with the new generation of X-ray observatories is expected to be a breakthrough in our understanding of these objects.

- Observations with *Chandra* and *XMM* will achieve much higher energy resolution ($E/\Delta E$ up to 1000) than presently available and would allow one to detect atmospheric spectral features (see an example in Fig. 1). From the analysis of these features, it would be possible to determine chemical composition, magnetic fields, and M/R for several middle-aged pulsars and radio-quiet NSs in SNRs.
- Observations with the recently launched *Chandra* X-ray Observatory provide very high spatial resolution, $\lesssim 1''$. Importance of that has been demonstrated by the detection of the compact central object of the Cas A SNR in the *Chandra* First Light Observation, which probably is an isolated NS with hot polar caps (Pavlov et al. 1999). Although this source has been found in the *ROSAT* HRI and *Einstein* HRI data after the *Chandra* discovery, it is completely diluted by the SNR diffuse radiation in the low-resolution *ASCA* images.

We expect most interesting results in the UV/optical range from observations of nearby pulsars and NSs with the *HST*/STIS/MAMA detectors. These observations would provide

- separation of the thermal component in radiation of middle-aged pulsars, based on the UV-optical spectra and pulse shapes;
- optical-UV spectra and pulsations of the presumably thermal radiation from old pulsars and radio-silent isolated NSs.

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