THERMAL RADIATION FROM COOLING NEUTRON STARS

G. G. PAVLOV
Pennsylvania State University,
525 Davey Lab, University Park, PA 16802, USA
E-mail: pavlov@astro.psu.edu

V. E. ZAVLIN
Max–Planck–Institut für extraterrestrische Physik,
Giessenbachstr. 1, 85748 Garching, Germany
E-mail: zavlin@mpe.mpg.de

Observations of thermal radiation from neutron stars allow one to measure the surface temperatures and confront them with cooling scenarios. Detection of gravitationally redshifted spectral lines can yield the mass-to-radius ratio. In the few cases when the distance is known, one can measure the neutron star radius, which is particularly important to constrain the equation of state of the superdense matter in the neutron star interiors. Finally, one can infer the chemical composition of the neutron star surface layers, which provides information about formation of neutron stars and their interaction with the environments. We present the observational results on thermal radiation from active pulsars and radio-quiet neutron stars, with emphasis on the results obtained with the Chandra X-ray Observatory and discuss some implications of these results.

1. Introduction

Observations of thermal emission from the surface layers of isolated (non-accreting) neutron stars (NSs) is among most important tools to study the nature of these exotic objects. However, only a small fraction of the currently observable NSs allows direct observations of their surfaces. First of all, these are middle-aged ($\tau \sim 10^4$–$10^6$ yr) radio and/or gamma-ray pulsars, whose thermal radiation, with temperatures 0.3–1 MK, can dominate at soft X-ray and UV energies. In addition to active pulsars, a number of radio-quiet isolated NSs emitting thermal-like X-rays have been detected, with typical temperatures $\sim 0.5$–5 MK. Their radiative properties (particularly, multiwavelength spectra) are quite different from those of active
pulsars, but the presence of the thermal component in their emission provides a clue to understand the nature of these objects.

First thermally emitting isolated NSs were detected with *Einstein*. In 1990’s, *ROSAT* and *ASCA* detected more than 30 radio pulsars, including a few thermal emitters, and discovered several radio-silent NSs (see Becker and Pavlov for a review). The new era in observing X-ray emission from NSs has started with the launch of the *Chandra* and *XMM-Newton* X-ray observatories. In this brief review we present recent results on thermal X-ray emission from isolated NSs of various types observed with *Chandra*.

![Figure 1](image)

Figure 1. Left: Multiwavelength energy spectrum of the Vela pulsar. The solid line shows the NS hydrogen atmosphere plus PL fit to the observed *Chandra* spectrum. The dotted line is the unabsorbed model flux. The dash-dot lines show the extrapolated optical and EUV absorbed spectra. Right: Spectral flux for the three-component (TS+TH+PL) model for PSR B0656+14. The absorbed and unabsorbed spectra are shown with solid and dashed curves, respectively. The crosses show the IR-optical-UV fluxes.

2. Thermal emission from radio pulsars

X-ray emission of rotation-powered pulsars generally consists of two components — thermal and nonthermal. The nonthermal component, generated by relativistic particles in the NS magnetosphere, is expected to be strongly pulsed and characterized by a power-law (PL) spectrum. The thermal component, emitted from the NS surface, can be observed in X-rays if it is not
buried under the nonthermal component, as in very young pulsars, and if the temperature is not too low, as in old pulsars. Weak pulsations of the thermal emission can be caused by temperature nonuniformities along the NS surface and/or anisotropy of emission in a strong magnetic field. Some examples of thermal radiation of pulsars observed with Chandra are presented below (see Pavlov et al.\textsuperscript{2} for more details and references).

Chandra observations of the famous Vela pulsar ($\tau_c \equiv P/2\dot{P} = 11$ kyr, $d \simeq 300$ pc) made it possible to resolve the pulsar from its surroundings. The analysis of the Chandra data revealed that the pulsar’s soft X-ray emission, at $E < \sim 1.8$ keV, is dominated by a thermal component (Fig. 1, left panel). The parameters of this component are noticeably different for the blackbody (BB) fit, $T^\infty_{bb} \simeq 1.4$ MK and $R^\infty_{bb} \simeq 2.6$ km, and the NS hydrogen atmosphere fit, $T^\infty_{eff} \simeq 0.7$ MK and $R^\infty \simeq 18$ km (the superscript $\infty$ denotes the quantities as measured by a distant observer). Such strong difference is explained by the fact that the hydrogen atmosphere spectra are harder than the BB ones at the same effective (surface) temperature\textsuperscript{3}.

The lack of significant spectral lines in the spectrum indicates that there are no heavy elements in the radiating layers. On the other hand, even strongly magnetized hydrogen does not have spectral features in the investigated energy band. The two-component X-ray model involving the NS hydrogen atmosphere fits well the optical data on the pulsar (Fig. 1). In this interpretation, the effective temperature of the Vela pulsar is well below the predictions of the “standard” models of NS cooling\textsuperscript{4,5}.

The analysis of the Chandra data on PSR B0656+14 ($\tau_c = 110$ kyr) showed no significant lines in the source spectrum. A three-component model is required to fit the data in the 0.2–6 keV range (Fig. 1, right panel). The high-energy tail ($E \gtrsim 2$ keV) fits best with a PL spectrum with a slope close to that of the optical spectrum. The low-energy part of the spectrum ($E \lesssim 0.7$ keV) fits well with a BB model (thermal soft; TS), with temperature $T^\infty_s \sim 0.85$ MK and radius $R^\infty_s \sim 17$ km (for $d = 700$ pc). This thermal soft (TS) component is presumably emitted from the whole visible NS surface. To fit the spectrum at intermediate energies, an additional component is needed. A good fit is obtained by adding a thermal hard (TH) component, with a temperature $T^\infty_h \sim 1.65$ MK (as given by the BB model), presumably emitted from pulsar’s polar caps of radius $R^\infty_{pc} = R^\infty_h \sim 1.4$ km heated by relativistic particles streaming down from the pulsar acceleration zones. The bolometric luminosity of the TS component is a factor of 10 higher than that for the TH component. This three-component model fits the data from IR through X-ray energies.
The analysis of the Chandra data on PSR B1055–52 ($\tau_c = 540$ kyr) yields results very similar to those obtained for PSR B0656+14. The high-energy tail of the spectrum ($E > 2$ keV) is best described with a PL, which approximately matches the optical and gamma-ray data. The spectrum at lower energies fits well with two thermal (BB) components, soft and hard. The best-fit model parameters for the phase-integrated spectrum are $T^\infty_s = 0.75$ MK and $R^\infty_s = 13$ km for the soft thermal component, $T^\infty_h = 1.4$ MK and $R^\infty_h = 1.2$ km for the hard thermal component (for $d = 700$ pc). Interestingly, the temperature of the soft thermal component is approximately the same for these pulsars, although the characteristic age, $\tau_c$, is a factor of 5 larger for B1055–52. A possible explanation of this fact is that these NSs have different properties (e.g., the mass of B1055–52 is lower$^5$). An alternative explanation$^2$ is that the true ages of these pulsars can be much closer to each other than the characteristic ages.

### Table 1. Examples of compact central objects in SNRs with best-fit parameters for the BB and NS hydrogen atmosphere models of the thermal component.

| Object      | Host SNR   | Age    | Period | $T^\infty_{bb}$ | $R^\infty_{bb}$ | $T^\infty_{eff}$ | $R^\infty_{eff}$ |
|-------------|------------|--------|--------|-----------------|-----------------|-----------------|-----------------|
| J2323+5848  | Cas A      | 0.32 kyr | ...    | 5.7             | 0.5             | 3.5             | 1              |
| J0852–4617  | G266.1–1.2 | ~1     | ...    | 4.6             | 0.3             | 3.1             | 1.5            |
| J0821–4300  | Pup A      | 1–3    | ...    | 4.4             | 1.4             | 2.0             | 10             |
| J1210–5226  | G296.5+10.0| 3–20 ms | 424 ms | 2.9             | 1.6             | 1.6             | 11             |

### 3. Compact central objects in supernova remnants

Among the radio-quiet NSs, there is an interesting subclass dubbed ‘compact central objects (CCOs) in supernova remnants’. Four examples of such objects, studied with Chandra, are listed in Table 1. Although the spectra of CCOs are very similar to each other, it does not necessarily mean that they represent a uniform class of objects. If we adopt a plausible hypothesis that the thermal component of their radiation can be adequately described by the same spectral model (e.g., BB or hydrogen NS atmosphere), then we have to conclude that the temperature is decreasing with age while the emitting area is increasing. If the radiation emerges from a hydrogen atmosphere, then the effective radius is consistent with a NS radius for two oldest CCOs, J0821–4300 and J1210–5226, being smaller for two youngest ones, J2323+5848 and J0852–4617.

A recent review on CCOs has been presented by Pavlov et al.$^6$. Here we describe briefly only the the best-investigated CCO, J1210–5226.
(=1E 1207.4–5209) at the center of G296.5+10.0 (=PKS 1209–51/52), the first isolated NS which shows spectral lines.

First Chandra observation\(^7\) of J1210–5226 resulted in the discovery of the period, \(P \simeq 424\) ms, which proved that the source is a NS. Second Chandra observation\(^8\) and an XMM-Newton observation\(^9\) provided an estimate for the period derivative, \(\dot{P} \approx 3 \times 10^{-14}\) s s\(^{-1}\). This estimate implies that the characteristic age of the NS, \(\tau_c \approx 200\) kyr, is much larger than the 3–20 kyr age of the SNR, while the “canonical” magnetic field (assuming a centered-dipole configuration), \(B \approx 4 \times 10^{12}\) G, is typical for a radio pulsar.

![Figure 2.](image)

The analysis of the Chandra spectra\(^{10}\) shows that continuum models (e.g., BB, PL, fully ionized NS atmosphere) fail to fit the source spectrum, revealing two absorption features near 0.7 keV and 1.4 keV, with equivalent widths of \(\sim 0.1\) keV (Fig. 2). Most likely, the observed features are atomic lines formed in the NS atmosphere. The lines cannot be explained as emerging from a hydrogen atmosphere because, at any magnetic field and any reasonable gravitational redshift, there is not a pair of strong hydrogen spectral lines whose energies would match the observed ones. Sanwal et al.\(^{10}\) suggested that these features are the strongest lines of once-ionized helium in a superstrong magnetic field, \((1.4–1.7) \times 10^{14}\) G. Such a high value can be explained by a strong off-centering of the magnetic dipole or by the presence of a strong non-dipolar component. In this interpretation, the observed line energies correspond to the gravitational redshift \(z = 0.12–0.23\), which corresponds to \(R/M = 8.8–14.2\) km \(M_\odot^{-1}\). Hailey & Mori\(^{11}\) suggested an alternative interpretation, that these line are due to He-like ions of oxy-
gen or neon in a magnetic field somewhat below $10^{12}$ G. Which (if any) of the two interpretations is correct will be shown by future observations with high spectral resolution.

4. “Dim” isolated neutron stars

ROSAT discovered seven objects which are often called “dim” or “truly isolated” NSs (see Haberl\textsuperscript{12} for a recent review). These sources are characterized by blackbody-like X-ray spectra with temperatures around 1 MK. Low values of hydrogen column density, $n_H \sim 1 \times 10^{20}$ cm$^{-2}$, suggest small distances to these objects. Their X-ray fluxes, $f_x \sim 10^{-12} - 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, correspond to rather low (bolometric) luminosities, $L \sim 10^{30} - 10^{31}$ erg s$^{-1}$ for a fiducial distance of 100 pc. The fluxes do not show variations on either short (minutes-hours) or long (months-years) time scales, and they are much higher than the optical fluxes, $f_x/f_{opt} > 10^3$. Such properties strongly suggest that these objects are isolated, nearby NSs. Two of them, RX J0720.4–3125 and J1308.8+2127, show periodic variations, with surprisingly long periods $P \approx 8.4$ s and 10.3 s, respectively. The source powering the thermal radiation of these NSs has been a matter of debate. Two main options considered are the internal heat of a cooling NS and accretion of material from the interstellar medium. Large proper motions measured for RX J1856.5–3754\textsuperscript{13} and RX J0720.4–3125\textsuperscript{14} (about 330 and 105 mas yr$^{-1}$, respectively) imply high velocities of these objects, that makes accretion an implausible source of energy for the thermal radiation from these objects. Moreover, first estimates of the period derivative for RX J0720.4–3125\textsuperscript{15,16} also favor models invoking a young (or middle-aged) cooling NS (a pulsar?) rather than an old accreting NS for this object because the corresponding strong magnetic field ($B \sim 10^{13}$ G) is believed to prevent the accretion of material onto the NS surface.

The most famous (and best-investigated) object of this class, \textit{RX J1856.5–3754} (J1856 hereafter), discovered by Walter et al.\textsuperscript{17}, has been observed with \textit{Chandra} for 505 ks with high spectral resolution. Detailed analyses of these observations revealed no spectral lines. The combined X-ray and optical data rule out all the available NS atmosphere models: light-element models overpredict the actual optical fluxes\textsuperscript{18}, whereas heavy-element models do not fit the X-ray spectrum. The spectrum fits well a BB model of $T_{\infty}^{BB} = 0.73$ MK and $R_{\infty}^{BB} = 4.4$ km for a distance $d = 120$ pc, as measured from the optical data (the “hard BB” component in Fig. 3, left panel).
Search for pulsations from J1856 at periods $P > 20$ ms has yielded no positive result. Several attempts have been made to reconcile various heavy-element atmosphere models with the X-ray data on J1856, assuming fast rotation ($P < 10$ ms), which smears spectral features, or very low metal abundances, but none of them succeeded. Thus, we have to admit that the BB spectrum remains the best model for the X-ray spectrum of J1856. However, the radius of the emitting area, $R_{\text{bb}} \approx 4$–5 km, is too small to be the NS radius. Moreover, the X-ray BB model underpredicts by a factor of 7 the optical fluxes detected from J1856 (Fig. 3). One may assume\textsuperscript{19} that the X-ray radiation is emitted from a hot area on the NS surface, while the optical radiation is emitted from the rest of the surface of the NS with a radius $R_{\text{bb},s} > 16$ km and a temperature, $T_{\text{bb},s} < 0.4$ MK (“soft BB” component in Fig. 3, left panel). In this two-temperature picture, it is tempting to interpret the hot area as a pulsar polar cap. This interpretation is supported by the discovery\textsuperscript{20} of the H$_{\alpha}$ nebula surrounding J1856, presumably a bow-shock in the ambient medium created by the supersonic motion of the NS with a relativistic (pulsar?) wind. However, the hot spot is unusually large and luminous for an ordinary pulsar. On the other hand, a large polar cap would be expected if J1856 were a mil-
lisecond pulsar, with a period $P \sim 2$–5 ms. Since the surface magnetic field is low in millisecond pulsars, it does not prevent the heat released by relativistic particles to propagate from the “core” of the polar cap along the NS surface, so that the surface temperature decreases gradually away from the core (see Zavlin and Pavlov\textsuperscript{21} and Zavlin et al.\textsuperscript{22}). To model such a case, we assumed that a nonuniform temperature distribution over the NS surface can be approximated as $T^\infty = T^\infty_{hs}[1 + (\theta/\theta_0)^\gamma]^{-1}$, where $\theta$ is magnetic colatitude, $T^\infty_{hs}$ and $\theta_0$ are characteristic temperature and angular size of the hot spots, respectively. We found that such a model, with the spin axis perpendicular to the line of sight, angle $\alpha = 15^\circ$ between the spin and magnetic axes, $kT^\infty_{hs} = 82$ eV, $\theta_0 = 38^\circ$, $\gamma = 2.1$, and $R^\infty = 16.8$ km, satisfactorily fits the multiwavelength data on J1856 (see Fig. 3, right panel). In such a model, the nondetection of nonthermal X-ray and radio emission from J1856 is caused by unfavorable orientation of the radiating beams, whereas the thermal X-rays are detected from peripheries of the polar cap(s). To check this hypothesis, the source should be observed in X-rays with high temporal resolution.

Another possible hypothesis\textsuperscript{24} is that the NS surface is composed of a solid matter (according to Lai and Salpeter\textsuperscript{23}, this can happen even at high temperatures if the magnetic field is very strong at the surface, $B \gtrsim 10^{14}$ G). The shape of the emission spectrum from the solid surface could mimic the BB spectrum in the relatively narrow energy range, 0.1–1 keV, but the emissivity would be lower, so the radius inferred would be larger, compatible with being a NS radius. Although there are no reliable calculations for such a model, we expect that it will give a UV-optical flux even lower than the BB model, increasing the discrepancy with the observed flux.

5. Concluding remarks

Because of the limited space available, we presented only a few examples of thermal radiation from NSs. We did not even touch several important subclasses of thermally emitting NSs, such as “old” pulsars, which apparently emit thermal X-rays from their polar caps\textsuperscript{1}, radio-quiet “magnetars”, which show thermal components\textsuperscript{25}, likely due to decay of a superstrong magnetic field, $B \sim 10^{14}$–$10^{15}$ G, and transiently accreting NSs in quiescence, whose thermal emission is due to the heat released by pycnonuclear reactions in the compressed accreting material\textsuperscript{26}. Multiwavelength observations of the diverse population of NS have convincingly shown that thermal emission indeed dominates in the soft X-ray and/or UV-optical radiation of various
classes of NSs. The analysis of this emission allows one to measure the NS temperatures and, in some cases, to estimate the radii or mass-to-radius ratios. An interesting result of the temperature measurements in middle-aged pulsars and CCOs, which are supposed to be passively cooling NSs with relatively well known ages, is that the age dependence of temperature cannot be described by a single cooling curve, at least if the current age estimates are not off too much. It indicates that NSs are not all alike, but at least some of their properties, responsible for cooling, are different. Yakovlev et al.\textsuperscript{5} explain the different cooling behavior as due to different NS masses. Main cooling regulators in NSs younger than 1 Myr are the neutrino emission mechanisms (e.g., modified [slow] and direct [fast] URCA mechanisms at low and high NS core densities, respectively) and the baryon superfluidity that, generally, reduces the neutrino emissivity, depending on the poorly known critical temperatures $T_c(\rho)$ for different types of superfluidity. Low-mass NSs (e.g., PSR B1055–52) have lower central densities and cool slower than high-mass NSs with higher central densities (e.g., Vela). Moreover, these authors conclude that, for NSs with nucleon cores, superfluidity is required to reconcile the observations with the cooling models, although there is not enough data yet to infer $T_c(\rho)$ and measure the masses of individual NSs.

The observational data on the NS thermal emission indicate that the simple picture of a NS with a centered dipole magnetic field and a uniform surface temperature is, most likely, an oversimplification. We have seen several examples of nonuniform temperature distributions, in both active pulsars and radio-quiet NSs. Moreover, the radius of X-ray emitting area is often considerably smaller than the “canonical” NS radius. The example of J1210–5226 shows that the characteristic age of a pulsar can differ from its true age by a large factor, and the conventional “pulsar magnetic field” can be quite different from the actual magnetic field at the NS surface. Therefore, any inferences on the properties of NSs and the superdense matter obtained without taking this into account should be considered with caution.

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