Comptonization in the X-ray Spectra of Radio Millisecond Pulsars

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Abstract. The majority of X-ray-detected rotation-powered millisecond pulsars (MSPs) appear to exhibit predominantly thermal emission, believed to originate from the heated magnetic polar caps of the pulsar. In the nearest MSP, J0437–4715 a faint PL is also observed at >3 keV, usually associated with magnetospheric emission processes. However, the hard emission in this and other similar MSPs may instead be due to weak Comptonization of the thermal polar cap emission by energetic electrons/positrons of small optical depth most likely in the pulsar magnetosphere. This spectral model implies that all soft X-rays are of purely thermal origin, which has important implications in the study of neutron stars.

1. Introduction

With the advent of the current generation of X-ray telescopes, Chandra and XMM-Newton, it has become apparent that the population of rotation-powered millisecond pulsars (MSPs) possesses very diverse spectral properties. The most energetic ($\dot{E} \sim 10^{36}$ erg s$^{-1}$), “Crab-like” MSPs, B1937+21, B1821–24 (in the globular cluster M28), and J0218+4232, exhibit strongly pulsed non-thermal X-rays with $L_X \sim 10^{33}$ ergs s$^{-1}$, which are attributed to non-thermal radiation processes in the pulsar magnetosphere (Nicastro et al. 2004; Becker et al. 2003; Rutledge et al. 2004; Webb, Olive, & Barret 2004). Several binary MSPs are observed at X-ray energies (with $L_X \sim 10^{31}$ ergs s$^{-1}$) due to interaction of their energetic particle wind ($\dot{E} \sim 10^{34–35}$ ergs s$^{-1}$) with matter from a close stellar companion (Grindlay et al. 2002; Stappers et al. 2003; Bogdanov, Grindlay, & van den Berg 2005). The bulk of X-ray detected MSPs show predominantly thermal spectra with $L_X \sim 10^{30–31}$ ergs s$^{-1}$ (see Becker & Trümper 1999; Zavlin 2006; Bogdanov et al. 2006; review talk by J. E. Grindlay). This thermal emission is widely believed to arise due to heating of the magnetic polar caps by a backflow of relativistic particles from the magnetosphere (see e.g. Harding &Muslimov 2002; Zhang & Cheng 2003 and references therein).

Thermal radiation from neutron stars (NSs) is of great interest in astrophysics as it serves as a probe of the environment near the surface of these compact objects. In particular, the study of this emission may shed light on the poorly understood properties of the stellar interior, thus, providing constraints on the elusive NS equation of state (EOS). Pavlov & Zavlin (1997) have shown that X-ray spectral and timing observations of MSPs can be used to measure fundamental NS parameters such as the mass-radius ratio ($M/R$) of the underlying NS. These objects are much better suited for such an analysis than other NS systems such as X-ray binaries, isolated NSs, and normal pulsars. In the latter objects there are numerous complications arising due to the effect of the strong magnetic field on the emergent radiation (Zavlin et al. 1995), the unknown temperature distribution across the surface, severe reprocessing of the thermal radiation by the magnetosphere, the uncertain altitude above the NS surface (e.g. in X-ray bursts, see Cottam et al. 2002), etc. Their low magnetic fields ($\sim 10^{8–9}$ G), point-like emission regions (<3 km), and “clean”, non-variable emission make MSPs potential laboratories for tests of fundamental NS physics.

However, it is important to realize that the thermal photons originating at the surface of the NS must propagate through the tenuous plasma present in the pulsar magnetosphere and wind before reaching the observer. Thus, it is essential to examine the effect of this plasma on the thermal photons as it may impede efforts to constrain the NS properties described above.

2. The power-law tail

The most suitable object for such a study is the nearest and brightest radio millisecond pulsar known, PSR J0437–4715 (Johnston et al. 1993; van Straten et al. 2001; Hotan, Bailes, & Ord 2006). This MSP was the first to be detected at X-ray energies in the ROSAT all-sky survey (Becker & Trümper 1993). Subsequent ROSAT, Chandra, and XMM-Newton observations (Zavlin & Pavlov 1998; Zavlin et al. 2002; Zavlin 2006) have revealed that the 0.1–10 keV emission consists of two thermal components,
Fig. 1. (top) Comptonized blackbody model spectrum for $T_{\text{eff}} = 2.5$ MK, $kT_e = 100$ keV, and $\tau = 0.1$. (bottom) Comptonized H-atmosphere model spectrum for $T_{\text{eff}} = 1.3$ MK, $kT_e = 100$ keV, and $\tau = 0.1$. The photon energies have been corrected for the gravitational redshift assuming $R = 10$ km and $M = 1.4 \, M_{\odot}$. The dotted lines correspond to different viewing angles relative to the surface normal ($\cos \theta = 0.5$, 0.25, and 0.1, from top to bottom, respectively), while the solid line is for $\cos \theta = 1$. In both panels the dashed line represents the initial (unscattered) thermal spectrum.

Fig. 2. *Chandra* ACIS-S and *XMM-Newton* MOS1/2 spectra of PSR J0437–4715 fitted with a two-temperature Comptonized thermal spectrum (see Bogdanov, Grindlay, & Rybicki 2006 for best fit parameters).

Fig. 3. Model for the broadband spectrum of PSR J0437–4715 as inferred from X-ray and FUV data for this pulsar. The two hard thermal components (observed in X-rays) originate from the heated magnetic polar caps of the pulsar, while the softest ($\sim 10^5$ K) component (seen in the FUV) is due to emission from the rest of the NS surface (see Kargaltsev, Pavlov, & Romani 2004). Note the PL tail for each thermal component due to Comptonization.

and a faint power-law (PL) tail, with photon index $\Gamma \sim 2$. The latter can only be clearly seen in the spectrum for $>2.5$ keV. Due to the limited photon statistics beyond $\sim 3$ keV, the nature of this X-ray component is ambiguous but is usually attributed to non-thermal emission processes in the pulsar magnetosphere. However, for J0437–4715 this model encounters difficulties when extrapolated to lower energies where it is in disagreement with the FUV data for this pulsar (Kargaltsev, Pavlov, & Romani 2004) unless a break exists in the PL below 0.1 keV. Shock emission can also ruled out as the strength of the pulsar wind ($\dot{E} = 3.8 \times 10^{33}$ ergs s$^{-1}$) is insufficient to have a significant effect on the He-WD companion. A third thermal component is also rather implausible as it requires a peculiarly small emission area ($\sim$ a few meters) and high surface temperature ($T_{\text{eff}} > 8 \times 10^6$ K).

One physical mechanism for production of a PL spectrum in pulsars that is often overlooked is inverse Compton scattering (ICS). As a thermal photon emitted at the NS surface propagates through the tenuous (low optical depth) magnetospheric plasma and the particle wind of the pulsar, it may be scattered by energetic $e^\pm$ and in the process acquire energy. In the low optical depth ($\tau < 1$) regime, repeated ICS of thermal seed photons produces a PL distribution of photons (see Rybicki & Lightman 1979; Nishimura, Mitsuda, & Itoh 1986). Figure 1 illustrates the effect of Comptonization on an initially thermal spectrum for both blackbody and unmagnetized hydrogen atmosphere (Romani 1987; Zavlin, Pavlov, & Shibanov 1996;
The Comptonization model available in XSPEC\cite{heasarc} is quite successful at reproducing the observed shape of the X-ray spectrum of J0437–4715. Note that unlike the non-thermal (NT) and Comptonized photons, respectively.

The scattering $e^\pm$ are, therefore, most likely non-thermal (PL). Nonetheless, the model we have used remains valid since a PL photon spectrum is produced for an arbitrary distribution of $e^\pm$ energies. Note that unlike the non-thermal emission PL, the Comptonization PL does not extend into the FUV (see Fig. 3), thus, avoiding any conflict with optical/UV data encountered by the alternative model.

Using a simple calculation we can get a sense of the density and physical size of the scattering medium necessary to have a significant effect on the thermal spectrum. Assuming a Goldreich-Julian (GJ) charged particle density in the MSP magnetosphere, we obtain $n = n_{\text{GJ}} \sim 0.07 B / P = 4 \times 10^9 \text{ cm}^{-3}$ \cite{goldreich69}, where we have assumed $B \sim 10^8 \text{ G}$, and $P = 5.76$ ms, appropriate for J0437–4715. The optical depth is given by $\tau_s = n L \sigma$, where $L$ is the path length through the scattering medium and $\sigma$ is the scattering cross section. For $L$ equal to the light cylinder radius ($r_{lc} = c P / 2 \pi = 275 \text{ km}$ for J0437–4715) and $\sigma$ equal to the Thomson cross section ($\sigma_T = 0.24 \times 10^{-24} \text{ cm}^2$) we find $\tau \sim 7 \times 10^{-8}$, too low to have an observable effect on the X-ray spectrum. However, the actual particle density in the vicinity of a pulsar may greatly exceed the GJ density, e.g., due to pair production cascades by high energy photons. Thus, $n > n_{\text{GJ}}$ and/or $L > r_{lc}$ are necessary to produce a sufficient scattering optical depth to account for the PL tail in J0437–4715.

Insight into the geometry of the Comptonizing plasma may, in principle, be obtained by observing the behavior of the PL radiation as a function of the spin phase of the MSP. Figure 3 shows lightcurves of J0437–4715 folded at the MSP spin period for the 0.3–1 keV and 3–6 keV energy ranges. Unfortunately, the currently available timing data do not permit any useful constraints on the properties of the Comptonizing medium. The future generation of X-ray facilities (\textit{Constellation-X} and XEUS) should be able to shed more light via phase-resolved spectroscopy at energies beyond 10 keV.

3. Conclusion

We have shown that the faint PL tail in the spectrum of the millisecond pulsar PSR J0437–4715 could be the observable signature of weak Comptonization of the thermal X-ray photons by particles in the pulsar magnetosphere and wind. Deep multiwavelength (X-ray and optical/UV) observations of other MSPs, such as the nearby isolated PSRs J0030+0451 and J2124–3358, would allow an important test of the Comptonization model. For these MSPs, due to the limited count statistics in the currently available data, the presence of a PL tail cannot be established (see Fig. 4). The absence of a stellar companion for J0030+0451 and J2124–3358 has allowed very deep optical observations, which have found no emission down to $V \sim 27 \pm 28$ \cite{koptsevich03, migiani03}. Such observations, coupled with more detailed models describing the spatial and energy distribution of the particles populating the pulsar magnetosphere and wind will lead to a more complete picture of the pulsar environment and reveal the true nature of the PL emission from J0437–4715.

If Comptonization is indeed the mechanism responsible for the PL emission, X-ray spectra of MSPs can potentially serve as a valuable diagnostic of the charged particle population near the pulsar, thus, providing important constraints for pulsar models. Perhaps more importantly, the

\begin{figure}[h]
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\caption{XMM-Newton EPIC-pn lightcurves of J0437 in the 0.3–1 keV (top) and 3–6 keV (bottom) bands. In the Comptonization model these bands contain purely thermal (unscattered) and Comptonized photons, respectively. The dotted line in the bottom panel shows the background level.}
\end{figure}
Fig. 5. (top) XMM-Newton MOS1/2 spectra of PSR J0030+0451. (bottom) Chandra ACIS-S and XMM-Newton MOS1/2 spectra of PSR J2124-3358. In both cases the data are fitted with a two-temperature blackbody spectrum.

Comptonization model implies that all soft emission (<1 keV) from J0437–4715 is purely thermal (unscattered) radiation, which has profound applications in the study of NS structure.

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References
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