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LETTERS

The optical/ultraviolet excess of isolated neutron stars in the resonant cyclotron scattering model *

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Abstract X-ray dim isolated neutron stars are peculiar pulsar-like objects, characterized by their Planck-like spectrum. In studying their spectral energy distributions, optical/ultraviolet (UV) excess is a long standing problem. Recently Kaplan et al. measured the optical/UV excess for all seven sources, which is understandable in the resonant cyclotron scattering (RCS) model previously addressed. The RCS model calculations show that the RCS process can account for the observed optical/UV excess for most sources. The flat spectrum of RX J2143.0+0654 may be due to contributions from the bremsstrahlung emission of the electron system in addition to the RCS process.

Key words: pulsars: individual (RX J0420.0–5022, RX J0720.4–3125, RX J0806.4–4123, RX J1308.6+2127, RX J1605.3+3249, RX J1856.5–3754, RX J2143.0+0654) — stars: neutron

1 INTRODUCTION

The seven X-ray dim isolated neutron stars (XDINSs) are puzzling pulsar-like compact stars. They are characterized by their Planck-like spectrum and are good specimens for neutron star cooling, as well as atmospheric and equation of state studies (Tong & Peng 2007; Tong et al. 2008; review Turolla 2009). Additionally, these sources may also have some relations with other classes of pulsar-like objects, e.g. magnetars and rotating radio transients (Tong et al. 2010).

The spectral energy distributions of XDINSs show that their optical and ultraviolet (UV) emissions are above the extrapolation of the X-ray blackbodies, i.e. optical/UV excess. This excess of XDINSs is a long standing problem which may be related to the equation of state of neutron stars (Xu 2002, 2009). Previously, only two sources (RX J1856.5–3754 and RX J0720.4–3125) have both optical and UV data (van Kerkwijk & Kaplan 2007). Recently, Kaplan et al. (2011) presented results of the optical and UV emission for all seven sources. They also found that the source RX J2143.0+0654 has a very flat spectrum ($F_\nu \propto \nu^\alpha$, $\alpha \sim 0.5$). This new observation requires updating the existing theoretical models.

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Tong et al. (2010) considered the resonant cyclotron scattering (RCS) in pulsar magnetospheres as the origin of optical/UV excess in XDINSs, i.e. the RCS model. This model can explain the observations of RX J1856.5–3754 and RX J0720.4–3125 (Tong et al. 2010). Considering the recent observational progress, we apply the RCS model to all seven XDINSs in this paper.

Section 2 is a summary of the RCS model, its application to XDINSs is treated in Section 3, and discussions and conclusions are presented in Section 4.

2 THE RCS MODEL: A SUMMARY

Tong et al. (2010) considered the RCS model for the origin of optical/UV excess in XDINSs. It has the following three key points.

(1) In analogy with a magnetospheric study of magnetars and rotating radio transients, similar to the "electron blanket" of neutron stars (Ruderman 2003), there may also be a dense electron system in the closed field line regions of XDINSs. We call it the "pulsar inner radiation belt" (since it is not far from the central star), in comparison with the "pulsar radiation belt" proposed by Luo & Melrose (2007). (It may be called the "pulsar outer radiation belt" since it is near the light cylinder far from the central star.)
(2) The scatterings between surface X-ray photons and the electron system are modeled three dimensionally using the Kompaneets equation method. Numerical calculations show both down scattering and up scattering of the RCS process. The existence of down scattering of the RCS process is crucial for its application to XDINSs.
(3) The application of down scattering of the RCS process to XDINSs can explain its optical/UV excess problem.

The Kompaneets equation (photon diffusion equation) for the RCS process is (Tong et al. 2010)

$$\left(\frac{\partial n}{\partial t}\right)_{\rm RCS} = \frac{kT_{\rm e}}{m_{\rm e}c^2}\frac{1}{x^2}\frac{\partial}{\partial x}\left\{x^4\frac{\tau_{\rm RCS}}{r_1-r_2}c\,g_\theta\left[\frac{\partial n}{\partial x}+n(1+n)\right]\right\}, \tag{1}$$

where n is the photon occupation number, and its evolution with time (which corresponds to spectral change) is determined by the right-hand side of Equation (1). Here x is the dimensionless photon frequency in units of electron temperature and $\tau_{\rm RCS}$ is the RCS optical depth. In order to calculate the RCS modified blackbody spectrum, four input parameters are needed: the neutron star surface temperature, the temperature and density of the electron system, and a normalization constant.

For photons in a certain frequency range, e.g. from optical to soft X-ray, only electrons in a specific radius range will contribute to the RCS process. The electron system may extend to a much larger radius, however the electrons there will not contribute to the RCS process (Tong et al. 2010). On the other hand, the electrons will radiate thermal bremsstrahlung emissions, which indeed depend on the radial extension of the electron system. The inclusion of the thermal bremsstrahlung process in addition to the RCS process will result in a flat optical spectrum.

3 APPLICATION OF THE RCS MODEL TO X-RAY DIM ISOLATED NEUTRON STARS

The application of the RCS model to RX J1856.5–3754 is shown in Figure 1. Model calculations for the other six sources are shown in Figure 2. The input parameters of the RCS model are given in Table 1. The neutron star surface temperature $T_{\rm x}$ is chosen as the temperature of the X-ray blackbody (from table 2 in Kaplan et al. 2011) and is kept fixed during the fitting process. The normalization is the radius of the radiation region over the source distance. For example, for RX J1856.5–3754, $R/d = 10/0.16\,$km kpc^{-1}. This means that for a source distance of $0.16\,{\rm kpc}$ the radius of the radiation region is $10\,{\rm km}$. All distance data are from table 4 in Kaplan & van Kerkwijk (2009). The electron temperature $T_{\rm e}$ is about $0.5\,T_{\rm x}$ or lower. The electron number density $N_{\rm e}$ is around

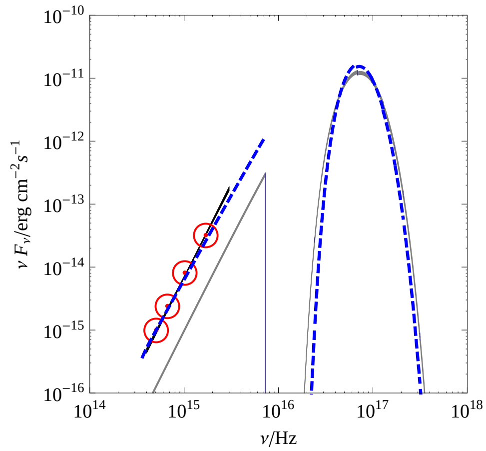

Fig. 1 Spectral energy distributions of RX J1856.5–3754 and RCS model calculations. The gray region is the X-ray blackbody and its extrapolation to the optical and UV range, including 1-σ uncertainties. The black region is the power law fit to the optical and UV data, including 1-σ uncertainties. The circles are observational data points; only central values are included. All the observational data are from Kaplan et al. (2011). The gap between optical/UV and X-ray is due to neutral hydrogen absorption. The dashed line is the RCS model calculation (Tong et al. 2010).

Table 1 Input Parameters of the RCS Model

Source	$T_{\rm x}$ (eV)	R/d (km/kpc)	$T_{\rm e}$ (eV)	$N_{\rm e}$ ($10^{12}\,{\rm cm}^{-3}$)	$N_{\rm H,rcs}$ ($10^{20}\,{\rm cm}^{-2}$)	$r_{\rm out}$ (10^9 cm)
J0420	45.0	9/0.345	22.5	2.0	3.0	< 1.2
J0720	88.4	9/0.36	35.4	1.6	2.1	< 2.2
J0806	87.2	3.5/0.25	43.6	1.6	2.6	< 1.2
J1308	102	5.5/0.5	51	1.4	2.7	< 1.8
J1605	92.6	7.5/0.39	23.2	1.8	2.0	1.2
J1856	63.5	10/0.16	25.4	1.8	1.7	< 1.5
J2143	104	4.5/0.43	10.4	1.5	4.6	2.2

Columns 1–7 are source name, neutron star surface temperature, normalization, electron temperature, electron density, neutral hydrogen column density and outer radius of the electron system, respectively. See text for details.

$1.5 \times 10^{12}\,{\rm cm}^{-3}$. The neutral hydrogen column density $N_{\rm H,rcs}$ is one-and-a-half or two times that of the blackbody fit to the X-ray data. For all seven XDINSs, their surface magnetic field, surface temperature, radiation region, X-ray luminosity, and distance are similar to each other (Kaplan & van Kerkwijk 2009). Meanwhile, they all have an optical/UV excess on the order of 10 (Kaplan et al. 2011). Hence, these seven sources are similar to each other observationally, and as a consequence of this, the RCS model parameters for these sources are also similar to each other.

The two sources, RX J1605.3+3429 and RX J2143.0+0654, have flat optical/UV spectra (especially RX J2143.0+0654). For most sources, a power law fit to the optical/UV data gives $F_\nu \propto \nu^\alpha$, with $\alpha \sim 2$ implying a thermal origin, while for RX J2143.0+0654, $\alpha \sim 0.5$ (table 5 in Kaplan et al. 2011). The flat spectrum of RX J2143.0+0654 indicates that nonthermal processes are involved in its optical/UV emission. Noting that the bremsstrahlung emission has a flat spectrum, we propose that the flat spectrum of RX J2143.0+0654 may be due to the thermal bremsstrahlung emission of the electron system in addition to the RCS process.

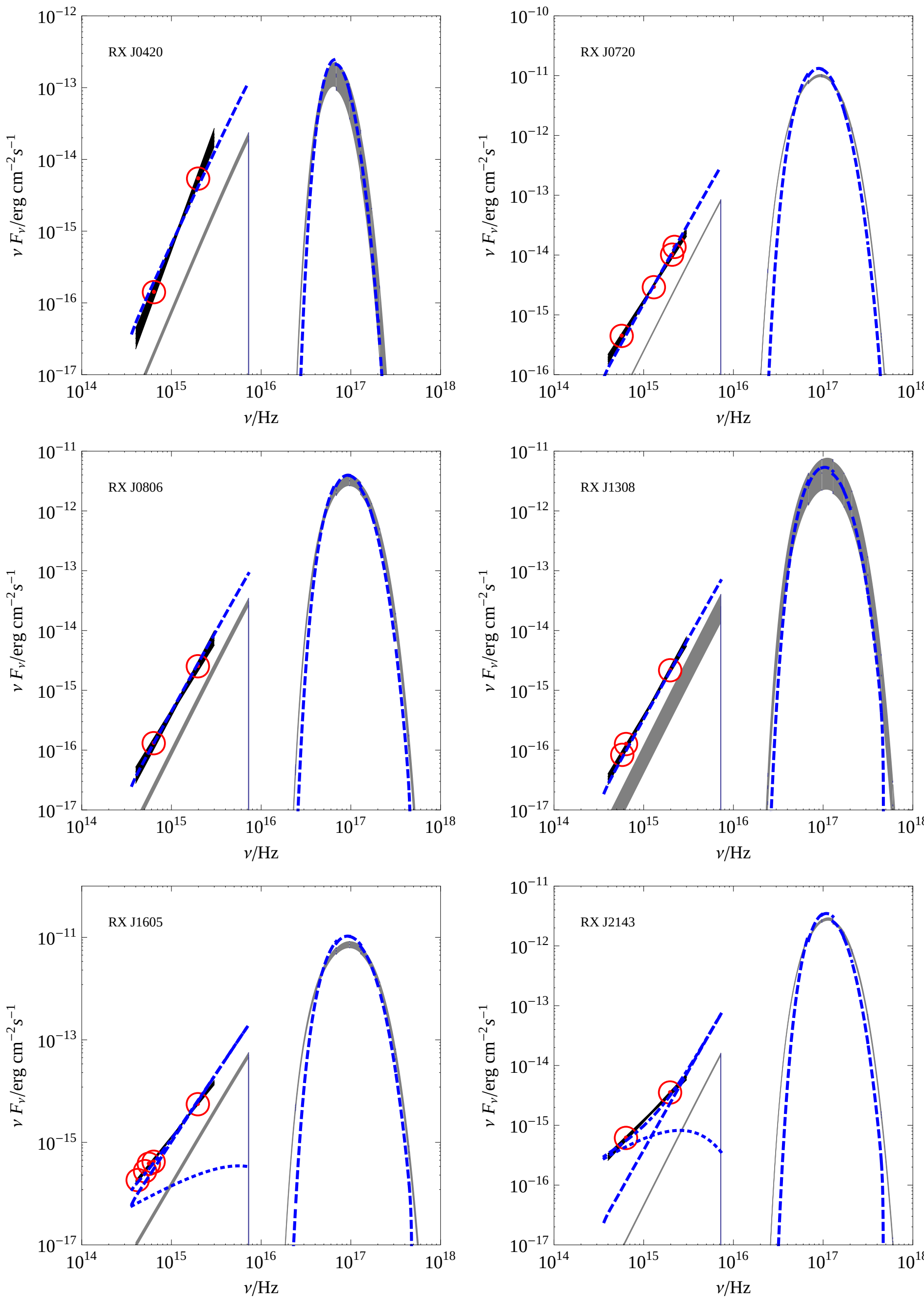

Fig. 2 Calculations for RX J0420.0–5022, RX J0720.4–3125, RX J0806.4–4123, RX J1308.6+2127, RX J1605.3+3249 and RX J2143.0+0654. Like Fig. 1, all observational data are from Kaplan et al. (2011). The dashed line is the RCS model calculation (Tong et al. 2010). The dotted line is the contribution from electron thermal bremsstrahlung. The dot-dashed line is the sum of the bremsstrahlung and RCS components. The bremsstrahlung component is needed only in the case of RX J1605.3+3249 and RX J2143.0+0654.

From Table 1, the temperature and density of the electron system are known. Once its radial extension is given, we can calculate its bremsstrahlung flux at Earth (Rybicki & Lightman 1979). The outer radius of the electron system $r_{\rm out}$ determines the relative importance of the bremsstrahlung component. For RX J1605.3+3429 and RX J2143.0+0654, $r_{\rm out}$ is determined in order to obtain a flat optical spectrum. For the other five sources, no bremsstrahlung component is needed. Therefore, an upper bound on $r_{\rm out}$ is given. The rotation periods of XDINSs are about $10\,{\rm sec}$. Therefore, the radial extension of the electron system is at most five percent of the light cylinder radius, near the central star. This is why we call it the "pulsar inner radiation belt." When the electron number density varies with radius, e.g. $N_{\rm e}(r) = N_{\rm e} \times (r/R_{\rm ns})^{-\alpha}$, where $R_{\rm ns}$ is the neutron star radius, the fitting results will be different from the uniform density case considered above. For electrons in a large space range all contributing to the bremsstrahlung process, the power index α should not be significantly larger than 1, i.e. $0 < \alpha < 1$ is required for RX J1605.3+3249 and RX J2143.0+0654, but for the other five sources, we do not see such a bremsstrahlung component. This is due to either a small radial extension of the electron system, or the electron number density there decreasing with radius very rapidly, i.e. $\alpha > 1$. The formation of the electron system is discussed in the appendix.

4 DISCUSSIONS AND CONCLUSIONS

In the discussion section of Kaplan et al. (2011), they also mentioned the RCS process, where they referred to the paper by Lyutikov & Gavriil (2006). However, as pointed out in Tong et al. (2010), the one-dimensional treatment of Lyutikov & Gavriil (2006) can only result in up scattering, whereas the optical/UV excess of XDINSs is "soft excess" in nature, which requires the down scattering process. This is the reason that Tong et al. (2010) modeled the RCS process three-dimensionally and employed the Kompaneets equation method.

The RCS model can explain the spectral energy distributions of XDINSs in a wide parameter space. Meanwhile, since the surface X-ray photons are scattered by a shell of electrons, this will naturally result in a low pulsation amplitude. The X-ray spectra are Planck-like with no high energy tails. This may imply that XDINSs are possibly quark stars (Xu 2002, 2009). At the same time, the possible features may be proton cyclotron lines or electron cyclotron lines far in the magnetosphere (Turolla 2009). From figure 3 in Kaplan et al. (2011) we see that for RX J2143.0+0654 we only have two data points at present. Future optical and UV data will tell us whether its spectrum is really so flat or not. Moreover, with more data points we can know whether there is curvature in the optical/UV spectrum and whether there are more spectral components in addition to the power law component. The electron thermal bresstrahlung component has a flat spectrum in the IR/optical range, with a flux of about 0.1 μJy for RX J2143.0+0654. This flux is much lower than the H-band flux upper limit (1.6 μJy at 1.65 μm, Lo Curto et al. 2007). Therefore in order to verify whether the flat spectrum of RX J2143.0+0654 is due to the thermal bremsstrahlung process, deeper optical/UV and IR observations are required.

The electron system cools down via the bremsstrahlung process (possibly also via free-bound transitions, like the recombination process). The central star therefore has to continually heat the electron system and ionize it. This is similar to the "Strömgren sphere" around early-type stars (Dyson & Williams 1980). The size of the ionized region is $(3S/4\pi N_{\rm e}^2 \beta_2)^{1/3}$ (Dyson & Williams 1980), where S is the ionizing photon number flux of the central star, $N_{\rm e}$ is the electron number density (assuming fully ionized hydrogen plasma) and β_2 is the recombination coefficient. Similar calculations show that the size of the ionized region is $\sim 10^{10}\,{\rm cm}$, to the order of magnitude consistent with the outer radius used in Table 1.

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Appendix A: FORMATION OF THE ELECTRON SYSTEM

The electron system may be formed similarly to the "injection through ionization" process (Luo & Melrose 2007). Assuming there is a neutron star whose mass is $1.4\,M_\odot$, radius $10\,\mathrm{km}$ and spatial velocity $100\,\mathrm{km\,s^{-1}}$, it will accrete interstellar media or circumpulsar material at a rate $\dot{M} = 2\pi(GM)^2 V^{-3}\rho_{\mathrm{ISM}} \sim 2\times10^8\,\mathrm{g\,s^{-1}}$ (Frank et al. 2002), where the density of the interstellar medium is assumed to be $10^{-24}\,\mathrm{g\,cm^{-3}}$. Since the accretion rate is rather low, the corresponding Alfvén radius $r_{\mathrm{m}} \sim 4\times10^{11}\,\mathrm{cm}$ is larger than the light cylinder radius and corotation radius. Only a small fraction of the accreted matter can fall onto the neutron star through a diffusion process, similar to the propeller case (Ertan et al. 2007). Since we are considering diffusion processes along magnetic field lines, the diffusion properties are not affected by the presence of a magnetic field. Assuming the plasma deflection length as the typical mean free path (Frank et al. 2002), the particle flux of the diffusion process is $F = D|\nabla n_{\mathrm{ISM}}| \sim \frac{1}{3}\lambda v_{\mathrm{rms}}\frac{n_{\mathrm{ISM}}}{r_{\mathrm{m}}} \sim 10^6\,\mathrm{cm^{-2}\,s^{-1}}$, where D is the diffusion coefficient, λ the mean free path $\sim 10^{12}\,\mathrm{cm}$, v_{rms} the typical particle velocity $\sim 10\,\mathrm{km\,s^{-1}}$, and n_{ISM} the interstellar medium number density $\sim 1\,\mathrm{cm^{-3}}$. With such a diffusion flux, the corresponding accretion rate is about 200 times smaller than the total Bondi-Hoyle accretion rate given above. The time scale for the formation of the electron system is about $4\times10^3\,\mathrm{yr} \ll \tau_c$, where τ_c is the pulsar's characteristic age $\approx 4\times10^6\,\mathrm{yr}$ for RX J2143.0+0654. When the diffused plasma comes to the vicinity of the neutron star, it will diffuse across magnetic field lines and enter the pulsar's closed field regions. The plasma system of the RCS model may be formed. The maximum particle number density that can be confined by the magnetic field at r_{out} is (i.e. the kinematic and magnetic energy densities are in equilibrium): $B(r_{\mathrm{out}})^2/(8\pi kT_{\mathrm{e}}) \sim 10^{16}\,\mathrm{cm^{-3}} \gg N_{\mathrm{e}}$. The plasma system can be confined by the magnetic field.

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