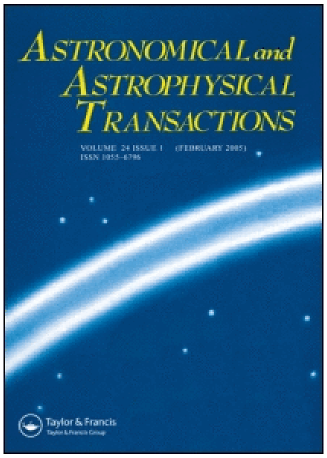

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MAGNETIC FIELDS OF NEUTRON STARS IN LOW MASS X-RAY BINARIES

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We report detailed radiation transport calculations which show that the shape of the 1–30 keV continuum spectrum of a weakly magnetic accreting neutron star depends on the strength of its magnetic field. We use this dependence to estimate the magnetic fields of several accreting neutron stars in LMXBs. We demonstrate that the magnetic field strengths estimated in this way correlate strongly with the properties of the 15–60 Hz magnetospheric QPOs and the kilohertz QPOs observed in many Z and atoll sources. We also find that sources currently accreting at high rates have higher magnetic field strengths than sources currently accreting at lower rates. This is an important constraint on models of the evolution of the magnetic field strengths of accreting neutron stars.

KEY WORDS Neutron stars, X-ray binaries, magnetic field

1 INTRODUCTION

Most low-mass X-ray binary systems (LMXBs) consist of a neutron star in orbit around a low-mass main sequence or giant star. They are thought to be the progenitors of the millisecond radio pulsars. The compact objects in these systems are therefore expected to be rapidly spinning (periods ~ 1 ms), weakly magnetic (fields $\sim 10^8$–10^{10} G) accreting neutron stars. Despite extensive efforts, no cyclotron lines or periodic X-ray oscillations have been detected in the persistent emission of most of these systems, making determination of their magnetic fields difficult.

During the last decade, observations of LMXBs made using several X-ray satellites with good spectral and fast timing capabilities have revealed a large number of phenomena occurring over many timescales. These include medium-frequency ($\sim$ 1–200 Hz; see Hasinger and van der Klis, 1989) and high-frequency ($\sim$ 1000 Hz; see van der Klis, 1989) quasi-periodic oscillations (QPOs) in the brightness of the persistent emission, as well as nearly coherent oscillations during type I (thermonuclear) X-ray bursts, which are thought to be produced by the spin of the neutron star. All the rapid variability characteristics of these sources are correlated with their X-ray spectral states.

The primary component of the 2–20 keV X-ray spectra of neutron-star LMXBs is a power-law with an exponential cut-off at high energies ($\gtrsim$ 10 keV; see White *et al.*, 1988). This is the characteristic spectral shape produced by Comptonization of soft ($\lesssim$ 1 keV) photons by hot electrons. In this case the hot electrons are thought to be in the accreting gas near the neutron star, in the magnetosphere and the inner accretion disc. Here we demonstrate that high-harmonic, self-absorbed cyclotron emission in the neutron star magnetosphere is the source of these soft photons. We also show that, for a given mass accretion rate, the X-ray spectrum of a source is determined by its magnetic field. We then use the observed spectral properties of neutron star LMXBs to estimate their magnetic field strengths.

2 RADIATION PROCESSES AND RADIATIVE TRANSFER

The slopes and cut-off energies of the power-law spectral component in LMXBs imply electron temperatures $\sim$ 5–20 keV, electron scattering optical depths $\sim$ 3–5, and electron densities $\sim 10^{19}$ cm^{-3}. For these conditions, the dominant radiation processes are thermal bremsstrahlung, cyclotron emission and absorption, and Compton scattering.

Thermal bremsstrahlung. The absorption coefficient for thermal bremsstrahlung at a photon energy E is (Rybicki and Lightman, 1979)

$$\begin{aligned} \chi^{\mathrm{TB}} &\simeq 3\times10^{-5} Z^2 g(T_e,E)\left(\frac{T_e}{10\ \mathrm{keV}}\right)^{-1/2}\left(\frac{E}{1\ \mathrm{keV}}\right)^{-3} \\ &\times \left(\frac{n_i}{10^{19}\ \mathrm{cm}^{-3}}\right)\left(1-\mathrm{e}^{-E/T_e}\right) n_e\sigma_T, \end{aligned} \tag{1}$$

where T_e and n_e are the electron temperature and density, n_i is the ion density, σ_T is the Thomson scattering cross-section, Z is the average atomic number of the ions in the flow, and $g(T_e, E)$ is the energy-dependent Gaunt factor, which is of order unity.

Cyclotron emission and absorption. The energy of the fundamental electron cyclotron frequency in the neutron star magnetosphere is

$$E_c = \hbar\omega_c \equiv \frac{B_m e}{m_e c} \simeq 0.012\left(\frac{B_m}{10^9\ \mathrm{G}}\right)\ \mathrm{keV}, \tag{2}$$

where B_m is the magnetospheric field strength. Cyclotron emission is self-absorbed if (Bekefi, 1965)

$$\Lambda \equiv \frac{\omega_p^2 R}{\omega_c c} = 4\pi e n_e R B^{-1} \simeq 1.8\times10^7\left(\frac{B_m}{10^9\ \mathrm{G}}\right)^{-1}\tau_{\mathrm{es}} \gg 1, \tag{3}$$

where ω_p is the plasma frequency, R is the characteristic dimension of the emitting region, and τ_{es} is the electron scattering optical depth, which we have approximated

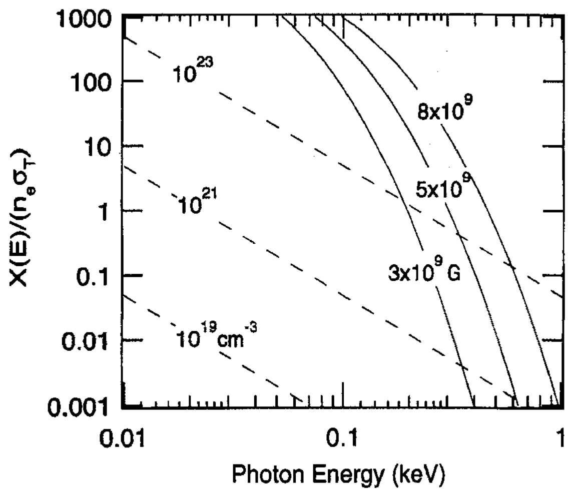

Figure 1 Coefficients, in units of the coefficient for electron scattering, for cyclotron absorption (solid lines) and inverse thermal bremsstrahlung (dashed lines), for an electron temperature of 10 keV and several magnetic field strengths and electron densities.

by $\tau_{\rm es} \simeq n_e \sigma_T R$, where σ_T is the Thomson scattering cross-section. Equation (3) shows that cyclotron emission in the magnetosphere is heavily self-absorbed for the magnetic field strengths and electron scattering optical depths typical of neutron-star LMXBs.

A characteristic feature of cyclotron absorption is the strong dependence of the absorption coefficient on photon energy. Let $E_{\rm max}$ be the photon energy that corresponds to the maximum of the spectrum produced by cyclotron emission; $E_{\rm max}$ is comparable to the energy at which the cyclotron absorption optical depth is equal to 1 and depends on the parameter Λ, the electron temperature T_e, and the geometry of the emitting region (see Bekefi, 1965). At energies below $E_{\rm max}$ the optical depth is very high and hence, when electron scattering in the emitting region is negligible, the photon energy spectrum follows the Planck spectrum very closely at these energies. At energies above $E_{\rm max}$ the optical depth is almost zero and the energy spectrum falls rapidly. If electron scattering is not negligible and $E_{\rm max}$ is smaller than the electron temperature, some of the photons are upscattered by resonant and non-resonant scattering with the hot electrons and form a power-law tail at photon energies higher than $E_{\rm max}$.

In this paper we use the cyclotron absorption coefficients derived by Robinson and Melrose (1984) and generalized by Hartmann *et al.* (1988) for a relativistic Maxwellian distribution of electrons. These absorption coefficients were calculated in the continuum approximation (i.e., with no harmonic structure) and were found to be very accurate at the high harmonic numbers ($\gtrsim$ 8; see Chanmugam *et al.*, 1989) that are relevant for the magnetospheres of LMXBs.

Figure 1 compares the absorption coefficient for cyclotron self-absorption (in units of the inverse photon mean-free-path for electron scattering) with the absorption coefficient for thermal bremsstrahlung, for an electron temperature of $T_e = 10$ keV and magnetic field strengths and electron densities that are typical of the surface layers of the neutron stars and the hot central coronae that are thought to surround them (Lamb, 1991; Psaltis *et al.*, 1995; Psaltis, 1997). When the electron temperature is higher than 10 keV, the coefficient for cyclotron absorption at a given energy increases, whereas the coefficient for inverse thermal bremsstrahlung decreases. For an electron scattering optical depth of 5, cyclotron emission is self-absorbed up to a photon energy $\sim 0.8(B/10^{10}$ G) keV, i.e., up to a harmonic number ~ 10.

Compton scattering. In the following calculations we model Compton scattering by solving iteratively the radiative transfer equation and its zeroth and first moments derived by Psaltis and Lamb (1997), using a generalization of the method of variable Eddington factors (Psaltis, 1997; see also Mihalas, 1978, 1980). For a static, spherically symmetric medium, the zeroth and first moments of the transfer equation are, to first order in E/m_ec^2 and T_e/m_ec^2,

$$\begin{aligned} \frac{\partial H_E^r}{\partial r} + \frac{2}{r} H_E^r &= \eta_E - \chi_E J_E \\ &+ n_e\sigma_T \left[E\frac{\partial}{\partial E}\left(\frac{4k_BT_e - E}{m_ec^2}\right) + \frac{k_BT_e}{m_ec^2}E^2\frac{\partial^2}{\partial E^2}E\right] J_E \end{aligned} \tag{4}$$

and

$$\begin{aligned} \frac{\partial K_E^{rr}}{\partial r} + \frac{3}{r}(K_E^{rr} - J_E) &= -\chi_E H_E^r - n_e\sigma_T H_E^r - \frac{2}{5} n_e\sigma_T \left[\left(\frac{k_BT_e - 3E}{m_ec^2}\right) \right. \\ &+ \left. E\frac{\partial}{\partial E}\left(\frac{4k_BT_e - E}{m_ec^2}\right) + \frac{k_BT_e}{m_ec^2}E^2\frac{\partial^2}{\partial E^2}E\right] H_E^r, \end{aligned} \tag{5}$$

where J_E, H_E^r, and K_E^{rr} are the zeroth, first, and second moments of the monochromatic specific intensity of the radiation field and η_E and χ_E are the emission and absorption coefficients for thermal bremsstrahlung and cyclotron emission and absorption. We close the system of equations by introducing the variable Eddington factors $f_E = K_E^{rr}/J_E$. We first solve the moment equations for the zeroth and first moments of the specific intensity of the radiation field, using an initial guess for the variable Eddington factors. We then solve the radiative transfer equation (eq. [A8] of Psaltis and Lamb, 1997), having evaluated the scattering integral using the moments of the specific intensity of the radiation field obtained as described above. Finally, we update the variable Eddington factors and repeat this procedure until convergence is achieved.

Figure 2 shows the results of detailed calculations of radiation transport in the vicinity if the neutron star, taking into account thermal bremsstrahlung and cyclotron emission and absorption, as well as Compton scattering. In these calculations we assumed for simplicity a spherically symmetric emitting region and a dipolar neutron star magnetic field. For a given neutron star magnetic field, the shape of the X-ray spectrum at photon energies below the high-energy cutoff depends almost exclusively on the parameter $y \equiv 4T_e\tau^2/(m_ec^2)$ that describes

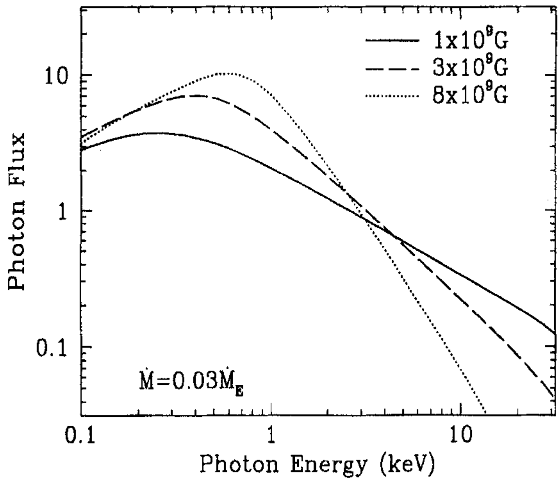

Figure 2 Photon energy spectra of neutron stars accreting at $0.03\dot{M}_E$, where $\dot{M}_E$ is the Eddington critical mass accretion rate, for three different surface magnetic field strengths.

the increase in the average energy of a photon caused by scattering in the medium. Hence, for a given mass accretion rate the Compton parameter y can be determined by equating the luminosity emerging from the system to the luminosity supplied by accretion.

For a wide range of electron temperatures and scattering optical depths, high harmonic, self-absorbed cyclotron emission is the dominant source of soft photos. Figure 2 demonstrates that for a given mass accretion rate, stars with weaker magnetic fields have significantly harder X-ray spectra. This is so because when the neutron star magnetic field is weak, cyclotron emission and cyclotron cooling in the magnetosphere are inefficient (cf. Figure 1). As a result, the electrons in the magnetosphere are hotter, the average energy gain per scattering is larger, and the X-ray spectra are harder. This *anticorrelation* between spectral hardness and magnetic field strength is a very robust qualitative feature of the spectra produced by Comptonizing media in which cyclotron emission is the dominant source of photons. In particular, this result is insensitive to the geometry of the emission region.

3 DISCUSSION

We have shown that self-absorbed cyclotron emission in the magnetosphere of a weakly magnetic accreting neutron star can be the dominant source of soft photons. These photons gain energy by scattering with hot electrons near the neutron star surface, producing the X-ray spectra of such stars. In previous work (Psaltis *et al.*, 1995; Psaltis, 1997), detailed numerical models of this process were shown to be in excellent agreement with the observed count-rate spectra of several LMXBs at different mass accretion rates. Here we study the general properties of the X-ray

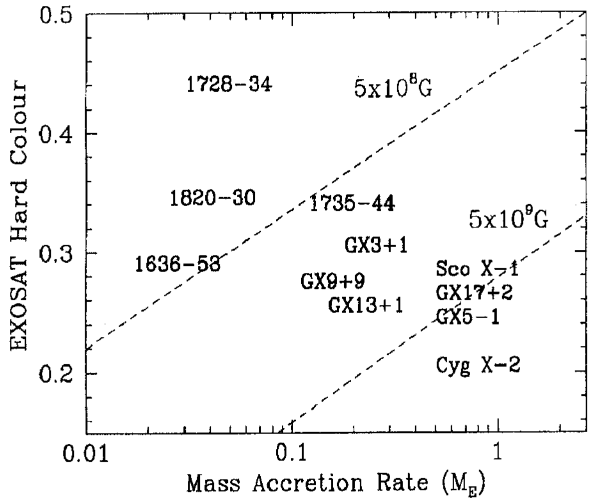

Figure 3 Average EXOSAT hard colours and mass accretion rates for eleven LMXBs and their magnetic field strengths inferred from the spectral modelling described in the text.

spectra of the population of luminous LMXBs and in particular their dependence on the magnetic field strength of the neutron star.

Using HEAO-1 data, van Paradijs and van der Klis (1994) found an anticorrelation between the hardness of the count-rate spectra of LMXBs and their average mass accretion rates, inferred in ways that are distance independent. Figure 3 shows that there is a similar anticorrelation between EXOSAT hard colours (as defined by Schulz *et al.*, 1989) and mass accretion rate.

We showed above that, for a given mass accretion rate, the hardness of the X-ray spectrum of a LMXB is roughly anticorrelated with its magnetic field strength. The anticorrelation shown in Figure 3 therefore implies that systems with stronger magnetic fields generally have higher mass accretion rates, and vice versa. Note that the position of a source on the plot shown in Figure 3 is only indicative of its average accretion rate and colour. In particular, the hard colour of a source accreting at near-Eddington rates varies considerably with accretion rate (Hasinger and van der Klis, 1989; Psaltis *et al.*, 1995) and therefore the relative positions of these near-Eddington sources in Figure 3 may not reflect their relative magnetic field strengths precisely.

The above conclusion is in agreement with the rapid X-ray variability characteristics of LMXBs (see Figures 4 and 5 and Hasinger and van der Klis, 1989). The horizontal branch oscillations (HBOs; see van der Klis, 1989), which are QPOs believed to be magnetospheric in origin (Alpar and Shaham, 1985; Lamb *et al.*, 1985) are indeed *stronger* in systems with *stronger* inferred magnetic fields. In contrast, the kilohertz QPOs (van der Klis, 1989), which are expected to occur only when the magnetic field is weak enough that the Keplerian accretion flow penetrates close to

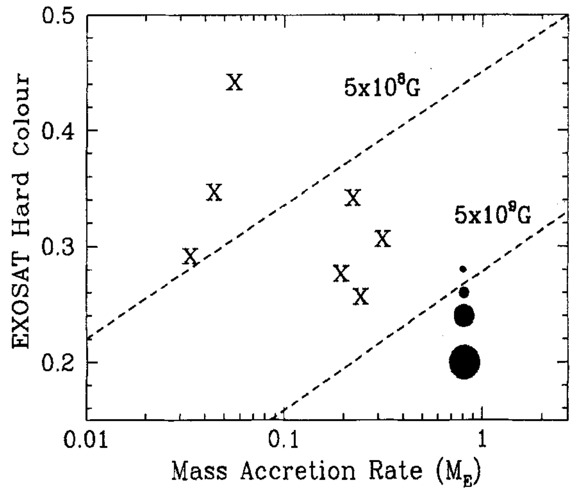

Figure 4 Correlation of the observed amplitudes of HBOs (shaded circles) with the inferred magnetic field of the neutron star (dashed lines). The sources plotted are the sames ones as in Figure 3. The areas of the circles are proportional to the observed amplitudes of the QPOs. The X's indicate that no QPO has been detected.

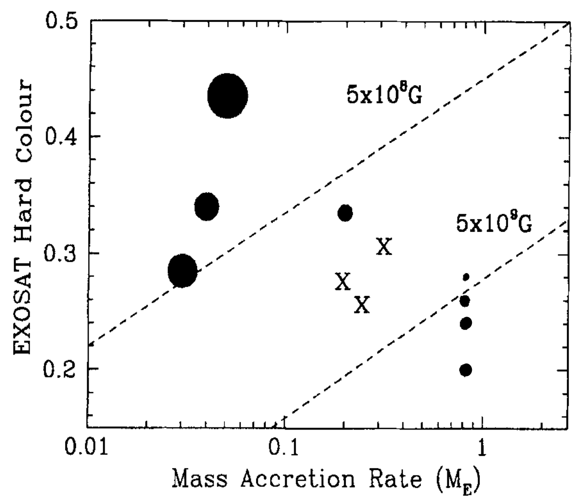

Figure 5 Correlation of the observed amplitudes of kilohertz QPOs (shaded circles) with the inferred magnetic field of the neutron star (dashed lines). The areas of the circles are proportional to the observed amplitudes of the QPOs. The X's indicate that no QPO has been detected.

the neutron star surface (Miller *et al.*, 1998), are *stronger* in systems with *weaker* inferred magnetic fields. This correlation between mass accretion rate and magnetic field strength may be responsible for the similarity of the inferred neutron star spin frequencies in sources with very different mass accretion rates (White and Zhang, 1997).

Acknowledgements

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