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X-RAY SPECTRA OF Z SOURCES

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ABSTRACT

A physically consistent model has been proposed that seeks to explain in a unified way the X-ray spectra and rapid variability of the Z sources and other weakly magnetic neutron stars in low-mass systems. Here we describe a simple, four-parameter spectral model derived from the unified model that accurately reproduces the X-ray colors, spectra, and count rates of the Z sources. In this model, photons are produced primarily by electron cyclotron emission in the neutron star magnetosphere and are then Comptonized in the magnetosphere, hot central corona, and inward radial flow. In addition to explaining their Z tracks, the model explains several other previously unexplained properties of the Z sources.

Subject headings: radiation mechanisms: thermal — stars: neutron — X-rays: stars

1. INTRODUCTION

The six known Z sources (Hasinger & van der Klis 1989) are among the most luminous low-mass X-ray binaries. They are unique in tracing out Z-shaped tracks in X-ray color-color diagrams on timescales of minutes to hours (see van der Klis 1989; van der Klis & Lamb 1995). The tracks are thought to be produced by variations in the mass accretion rate, which appears to increase monotonically as a Z source moves from its horizontal to its normal and then to its flaring branch (see van der Klis & Lamb 1995). Power spectra of Z-source brightness variations show two types of quasi-periodic oscillations (QPOs) and three types of aperiodic flickering ("noise"). The properties of the QPOs and flickering vary systematically with the position of a source on its Z track.

The X-ray spectra of the Z sources and the origin of their Z-shaped tracks have been a puzzle. Increasingly complicated multicomponent models have been used in attempts to obtain statistically acceptable fits to the spectra of Z sources and other accreting neutron stars in low-mass systems (see, e.g., Swank & Serlemitsos 1985; Mitsuda et al. 1984; White, Stella, & Parmar 1988). In these works, the X-ray spectra were averaged over hours, the origin of the Z tracks of the Z sources was not addressed (in some cases the existence of the Z tracks was unknown at the time the work was done), and no attempt was made to relate the spectral properties of a source to its rapid X-ray variability. Several authors have shown that the tracks of one or two Z sources can be reproduced by varying the parameters in various spectral models (see, e.g., Schulz, Hasinger, & Trümper 1989; Hasinger et al. 1990; Schulz & Wijers 1993; Asai et al. 1994), but the required variations of the spectral parameters are typically erratic and unrelated to the other properties of the source.

A model that seeks to provide a unified, physically consistent explanation of the X-ray spectra and rapid X-ray variability of the Z sources and other low-mass binary systems containing weakly magnetic neutron stars has been proposed by Lamb (1989, 1995). In this "unified model," the Z sources are rapidly spinning neutron stars with magnetic fields $\sim 10^8$–10^9 G, accreting matter from their companions at $\sim$0.5–1.1 times the Eddington critical rate $\dot{M}_{\rm E}$ via a Keplerian disk. Matter flowing approximately radially inward from a corona above the inner disk at a radius $\sim 3 \times 10^7$ cm supplies $\sim$20% of the total mass flux. Interaction of the Keplerian and inward radial flows with the small (radius $\sim 3 \times 10^6$ cm) neutron star magnetosphere produces a slightly larger (radius $\sim 5 \times 10^6$ cm) hot central corona (HCC) around the magnetosphere. The temperature $T_e^{\rm HCC}$ of the electrons in the HCC is typically $\sim$6–10 keV, depending on the source and its position on its Z track.

Soft ($\sim$0.5–1 keV) photons produced within the magnetosphere by high-harmonic cyclotron emission and other processes are Comptonized by resonant and nonresonant electron scattering in the magnetosphere. Photons emerging from the magnetosphere into the HCC are Comptonized by the electrons there, losing energy to electron recoil but gaining energy from electron thermal and bulk motion. Since $T_e^{\rm HCC}$ is much greater than 1 keV, the spectrum of the radiation that emerges from the HCC above 2 keV is a slightly rounded power law that cuts off at about $T_e^{\rm HCC}$. The exponent of the power law depends primarily on $y^{\rm HCC} \equiv (4k_{\rm B}T_e^{\rm HCC}/m_e c^2)\,(\tau_{\rm es}^{\rm HCC})^2$, where $\tau_{\rm es}^{\rm HCC}$ is the electron scattering optical depth of the HCC. Interaction of the photons escaping from the HCC with the radial flow, which has an electron scattering optical depth $\tau_{\rm es}^{\rm RF} \sim 2$–10, does not affect the luminosity but does affect slightly the shape of the spectrum, increasing its curvature at $\sim$2–5 keV (see Lamb 1989, 1995). The radiation keeps $T_e^{\rm RF}$, the electron temperature in the flow, close to the local Compton temperature ($\sim$1 keV).

When the accretion rate is ~ 0.5–$0.9\dot{M}_{\rm E}$, interaction of the small magnetosphere with the accretion disk produces a quasi-periodic luminosity oscillation at the beat frequency between the stellar spin frequency and the orbital frequency of clumps near the inner edge of the disk (Alpar & Shaham 1985;

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Lamb et al. 1985; Shibazaki & Lamb 1987). This is the horizontal branch oscillation (HBO). When the mass accretion rate rises above $\sim 0.8\dot{M}_{\rm E}$, a soft, global, radiation-hydrodynamic mode of the radial flow becomes weakly damped and is therefore excited by fluctuations in the accretion flow, which causes the X-ray spectrum to oscillate quasi-periodically at a frequency approximately equal to the inverse of the inflow time from the outer radius of the flow (Lamb 1989, 1995; Fortner, Lamb, & Miller 1989; Miller & Lamb 1992). This is the normal/flaring branch oscillation (N/FBO). At still higher accretion rates, nonradial modes are expected to develop (Lamb 1989, 1995; Miller & Park 1995).

In this Letter we describe a simple, four-parameter spectral model that accurately reproduces the X-ray colors, spectra, and count rates of the Z sources. The variations of the four parameters with the position of a source along its Z track are consistent with the results of more detailed numerical calculations of the X-ray spectra of the Z sources. In addition to providing a simple, physically consistent explanation of the spectra of the Z sources, including their Z tracks, the model also explains other, previously unexplained properties of the Z sources.

2. SPECTRAL MODEL AND RESULTS

We have computed the spectrum of the radiation produced by the magnetosphere, hot central corona, and radial flow for several models of the inner disk (see Ghosh & Lamb 1992). These detailed numerical calculations take into account the variation of the magnetic field with radius in the magnetosphere, resonant and nonresonant scattering, cyclotron absorption and emission, the effects of induced processes (which typically dominate spontaneous processes by factors ~ 20 in the magnetosphere), the angle dependence of these processes, and the effects of Comptonization in the hot central corona and radial flow. The results of these calculations will be presented elsewhere (Psaltis, Lamb, & Miller 1995).

Here we present a much simpler spectral model that gives results similar to those produced by the more detailed computations. In this simplified model there are three nested regions, each of which is approximated as uniform: the magnetosphere, the HCC, and the radial flow. The effects of these three regions on the X-ray spectrum are treated sequentially, i.e., we assume that no radiation leaks back into the magnetosphere from the HCC or into the HCC from the inward radial flow.

The spectrum of the radiation emerging from the magnetosphere is approximated by a blackbody spectrum of temperature $T_e^{\rm M}$, cut off at energy $E_{\rm max}$ (see, e.g., Hartmann, Woosley, & Arons 1988). The effects of Comptonization in the HCC and radial flow are computed using the approach of Miller & Lamb (1992). The finite sizes and assumed spherical shapes of the HCC and radial flow are taken into account by specifying the probability distributions of the number of scatterings in the two regions, which depend, respectively, only on $\tau_{\rm es}^{\rm HCC}$ and $\tau_{\rm es}^{\rm RF}$. The effects of bulk motion are neglected. Then the effect of the HCC on the spectrum is completely determined by $T_e^{\rm HCC}$ and $\tau_{\rm es}^{\rm HCC}$, while the effect of the radial flow is determined by $T_e^{\rm RF}$ and $\tau_{\rm es}^{\rm RF}$. The radii of the magnetosphere, HCC, and radial flow do not enter, except that the magnetosphere is assumed to be inside the HCC and the HCC is assumed to be inside the radial flow.

The QPOs of the Z sources and the qualitative shapes of their X-ray spectra tightly constrain several of these parameters. The low upper limits on the amplitudes of any periodic X-ray brightness oscillations (Vaughan et al. 1994) require $\tau_{\rm es}^{\rm HCC} \gtrsim 5$ (Brainerd & Lamb 1987; Lamb 1989, 1995). The relatively flat shapes of Z-source X-ray spectra require $y^{\rm HCC} \lesssim 4$ (and hence $\tau_{\rm es}^{\rm HCC} \lesssim 10$) and $\tau_{\rm es}^{\rm RF} \lesssim 10$. The radiation-hydrodynamic model of the N/FBO further constrains $\tau_{\rm es}^{\rm RF}$ in Cyg X-2 to be ≈ 9 near the middle of the normal branch (Miller & Lamb 1992).

For simplicity we set $T_e^M = T_e^{\rm HCC}$ and $\tau_{\rm es}^{\rm HCC} = 6$. We choose $y^{\rm HCC}$ as the adjustable parameter in the simplified model because the predicted *EXOSAT* count rate spectrum is insensitive to $T_e^{\rm HCC}$ and $\tau_{\rm es}^{\rm HCC}$ taken separately. We determine $T_e^{\rm RF}$ by solving the electron kinetic equation in the radial flow. The *shape* of the X-ray spectrum at the source then depends only on $E_{\rm max}$, $y^{\rm HCC}$, and $\tau_{\rm es}^{\rm RF}$. The shape at Earth also depends on the neutral hydrogen column $N_{\rm H}$. To compare count rate spectra given by the model with the spectra observed by *EXOSAT*, we use the interstellar absorption cross section of Morrison & McCammon (1983) and the response matrix of the *EXOSAT* ME detector (see Turner, Smith, & Zimmerman 1981) at the epoch of the observation.

The *normalization* of the spectrum, and hence the predicted *EXOSAT* count rate, depends on the luminosity of the source and its distance. We assume that the luminosity is proportional to $\dot{M}$ and choose $\dot{M}$ as the fourth adjustable parameter of the model. Since the distances to the Z sources are not accurately known, we scale $\dot{M}$ by its value at the junction of the normal and flaring branches. In the unified model, the radiation flux through the radial flow at this junction is very nearly the critical radiation flux (see Lamb & Miller 1995), so we denote the mass flux here by $\dot{M}_E$. This is consistent with the measured X-ray fluxes of the Z sources and current estimates of their distances.

We specify the position of a Z source on its track by a *rank number*, defined to be 1.0 at the junction of the horizontal and normal branches and 2.0 at the junction of the normal and flaring branches (see van der Klis & Lamb 1995). The four parameters $\dot{M}$, $E_{\rm max}$, $y^{\rm HCC}$, and $\tau_{\rm es}^{\rm RF}$ of the simplified spectral model can be determined as functions of rank number by fitting the observed X-ray spectra and count rates.

As an example, we fitted the model to *EXOSAT* data on Cyg X-2 using the following procedure. First, $y^{\rm HCC}$ and $\tau_{\rm es}^{\rm RF}$ at rank number 1.6 were fixed at the values (1.76 and 9, respectively) that give the source spectrum found by Miller & Lamb (1992) to be consistent with the radiation-hydrodynamic model of the N/FBO and *Ginga* observations of the N/FBO at this rank number. Next, $E_{\rm max}$ at rank number 1.6 was determined by fitting the shape of the 0.9–12 keV count rate spectrum predicted by the model to an *EXOSAT* count rate spectrum at this rank number; in this step $N_{\rm H}$ was determined once and for all. We determined $\dot{M}$ at rank number 1.6 and $\dot{M}$, $E_{\rm max}$, $y^{\rm HCC}$, and $\tau_{\rm es}^{\rm RF}$ at the two vertices and the two endpoints of the Z track by making the plausible assumption that $\tau_{\rm es}^{\rm RF}$ is proportional to $\dot{M}$ and fitting the model to the count rate at rank number 1.6 and the colors and count rates at the other four rank numbers. The constant of proportionality between $\tau_{\rm es}^{\rm RF}$ and $\dot{M}/\dot{M}_{\rm E}$ was found to be 9.2.

Figure 1 shows the spectrum, colors, and count rates given by the model, while Figure 2 shows the inferred values of the model parameters as functions of rank number. These sequences are typical of the sequences obtained by fitting Z-source data. The inferred accretion rate increases monotonically from $0.7\dot{M}_E$ to $1.02\dot{M}_E$ as the rank number increases from 0.5 to 2.5, consistent with the requirements of the unified model.

3. DISCUSSION

The parameter behavior found in § 2 is consistent with our more detailed modeling (Psaltis et al. 1995) if the neutron star in Cyg X-2 has a dipole field $\sim 7 \times 10^9$ G and the electron density in the magnetosphere increases with rank number from $\sim 10^{19}$ to $\sim 10^{20}$ cm^{-3}. The parameter behavior can be understood as follows.

As $\dot{M}$ increases from $0.7\dot{M}_E$ to $0.9\dot{M}_E$ (rank numbers 0.5–1.0), E_{max} remains nearly constant because it depends primarily on the magnetic field at ~2 stellar radii, which remains almost unchanged (E_{max} depends only weakly on the electron scattering optical depth of the magnetosphere, which varies little). The electron temperature, and hence y^{HCC}, must therefore rise to keep the luminosity proportional to the accretion rate. The increase in the radial mass flux with rank number causes τ_{es}^{RF} to increase. The result is an approximately horizontal track in both color-color and hardness–count rate diagrams.

As $\dot{M}$ increases from $0.9\dot{M}_E$ to $1.0\dot{M}_E$ (rank numbers 1.0–2.0), τ_{es}^{RF} continues to increase. The magnetic field remains almost unchanged, but the rise in $\dot{M}$ and the rapid decrease of the inflow velocity caused by the increase in the outward radiation force cause the electron scattering optical depth of

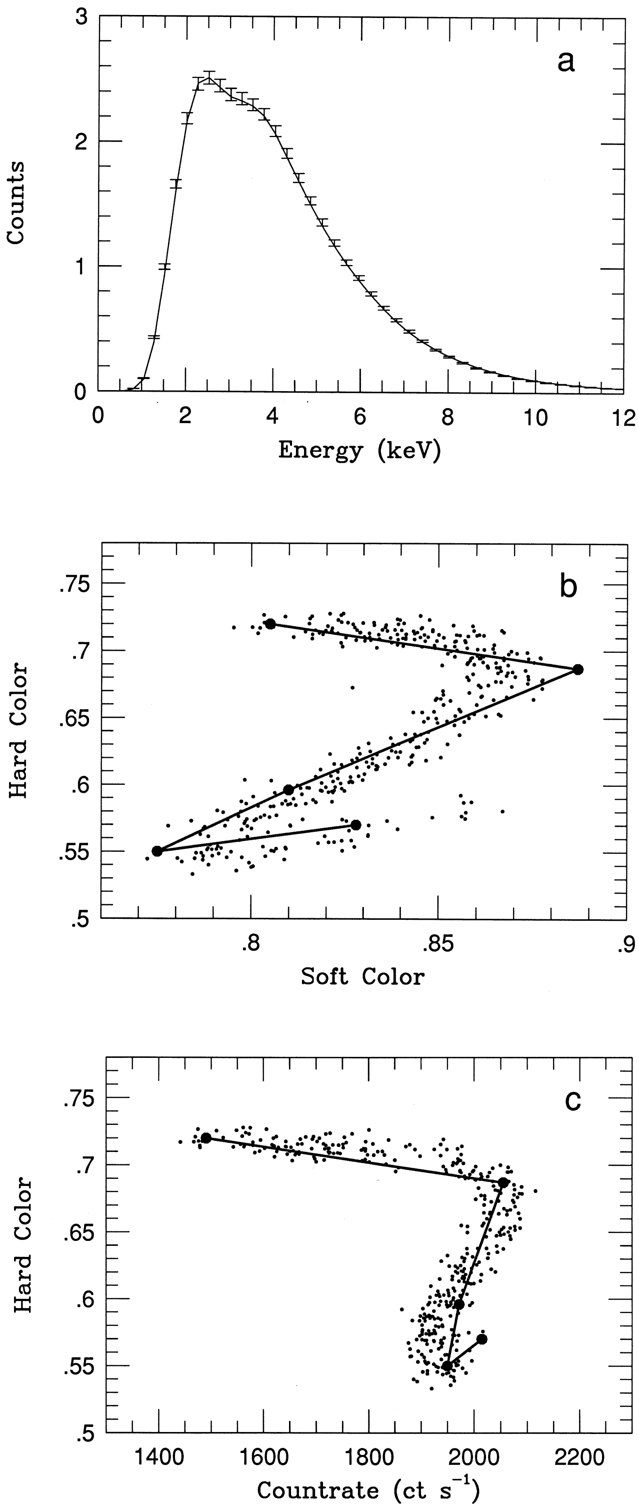

FIG. 1.—(*a*) Two-parameter fit of the model count rate spectrum at rank number 1.6 to a time-averaged *EXOSAT* count rate spectrum of Cyg X-2 near the middle of the normal branch; χ^2/dof = 2.4 with 36 dof. (*b*) Comparison of the color-color track produced by the spectral parameters shown in Fig. 2 with Cyg X-2 data from *EXOSAT*. (*c*) Similar comparison of the hardness–count rate track. As usual for *EXOSAT* data, the flaring branch lies almost on top of the normal branch in the hardness–count rate diagram. The energy bands are those used by Hasinger & van der Klis (1989).

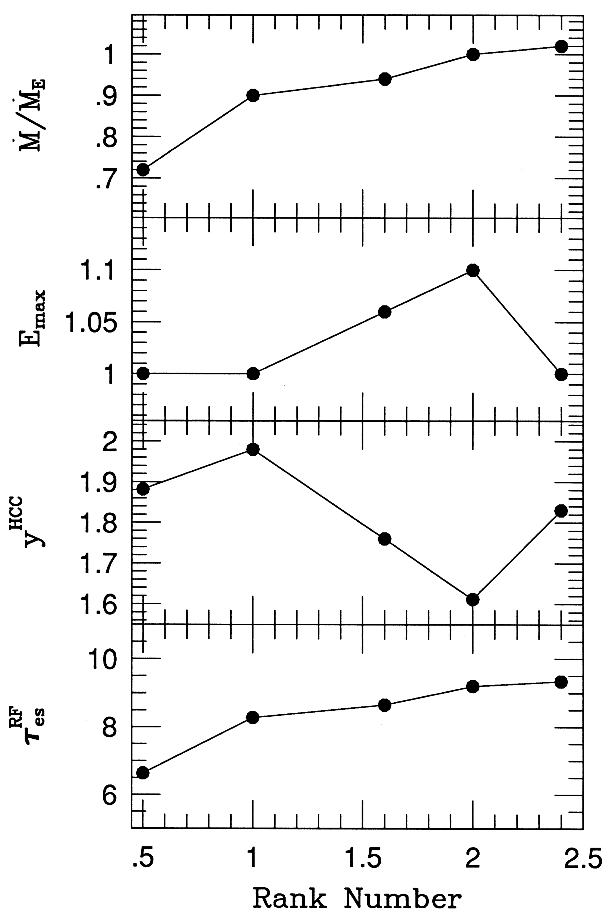

FIG. 2.—Values of $\dot{M}$, E_{max}, y^{HCC}, and τ_{es}^{RF} derived using the procedure described in the text.

the magnetosphere to rise steeply, increasing E_{max}. The electron temperature, and hence y^{HCC}, must therefore fall to keep the luminosity from increasing faster than the accretion rate. As y^{HCC} decreases, fewer cyclotron photons are scattered up into the *EXOSAT* energy range, and hence the count rate decreases even though the luminosity is increasing.

The character of the accretion flow when $\dot{M}$ exceeds $\dot{M}_E$ (rank numbers >2.0) is uncertain, but the flow is probably aspherical and time dependent, with matter flowing inward in some regions and outward in others (Lamb 1989, 1995). In such a situation, radiation escapes primarily through regions of lower optical depth, which causes E_{max} to decrease and y^{HCC} to increase; τ_{es}^{RF} increases with $\dot{M}$. The result is a flaring branch that is nearly parallel to the normal branch but extends to a slightly greater soft color.

Analysis of archival *EXOSAT* data (Kuulkers 1995) suggests that the Z sources can be divided into two subclasses: the Cyg-like sources (Cyg X-2, GX 5-1, and GX 340+0) and the Sco-like sources (Sco X-1, Sco X-2, and GX 17+2). The spectral model described here reproduces the spectral behavior of the Cyg-like sources if E_{max} is $\sim$0.6–1.0 keV and reproduces qualitatively the spectral behavior of the Sco-like sources if E_{max} is always $\lesssim 0.5$ keV. The shape of the spectrum of the Sco-like sources in the *EXOSAT* energy range is then insensitive to changes in E_{max}, so the increase in τ_{es}^{RF} with increasing $\dot{M}$ on the horizontal branch causes this branch to slope downward to the right in color diagrams, while the increase of T_e^{HCC} and τ_{es}^{RF} on the flaring branch causes the flaring branch to extend to higher count rates in hardness–count rate diagrams, as in *EXOSAT* observations of the Sco-like sources.

The lower value of E_{max} needed to reproduce the Z tracks of the Sco-like sources implies that their magnetic fields are smaller than the magnetic fields of the Cyg-like sources. This is consistent with the fact that no HBO has been detected in Sco X-1 or Sco X-2 and that the HBO observed in GX 17+2 is very weak. Moreover, according to the unified model the logarithmic derivative of the HBO centroid frequency with respect to count rate should be greater for neutron stars with lower magnetic fields (Ghosh & Lamb 1992), in agreement with the observed behavior of the GX 17+2 HBO, which has a derivative $\sim$3 times larger than the derivatives of the Cyg-like sources (see Hasinger & van der Klis 1989).

Finally, we mention that the spectral model presented here can reproduce the observed X-ray colors of the atoll sources if their magnetic fields are as weak as those of the Sco-like Z sources or weaker and their mass accretion rates are $\sim$0.01–$0.1\dot{M}_E$.

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