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EFFECT OF AN ELECTRON SCATTERING CLOUD ON X-RAY OSCILLATIONS PRODUCED BY BEAMING

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ABSTRACT

We report the results of analytical and Monte Carlo calculations of the effect of a surrounding scattering cloud on the amplitude of oscillations produced by a rotating beam of X-rays. These results show that a cloud of optical depth τ_c reduces the amplitude of oscillations produced by a narrow pencil beam by a factor $\sim 1/(1 + \tau_c)$. The amplitude of oscillations produced by a broad beam or one with multiple lobes is reduced even more, becoming negligible for clouds of moderate optical depth if the beam has forward-backward symmetry. For asymmetric beams with n lobes, the amplitude of the oscillations emerging from a scattering cloud of optical depth greater than ~ 5 is a factor $\sim 1/n^2$ less than the amplitude of the oscillations that would be produced by a narrow pencil beam at the center of the same cloud. When combined with recent observational results, these theoretical results strongly suggest that the quasi-periodic oscillations observed in the X-ray intensities of some luminous low-mass X-ray binaries are caused by oscillations in the luminosity of the X-ray star. They also explain why periodic oscillations at the neutron star rotation frequency are so weak in these sources.

Subject headings: pulsars — radiative transfer — stars: accretion — stars: neutron — stars: X-rays — X-rays: binaries

I. INTRODUCTION

Relatively narrow peaks have recently been discovered in power spectra of X-ray intensity time series from more than a dozen luminous X-ray stars (see van der Klis 1987*a*, *b*). The stars exhibiting these so-called quasi-periodic oscillations (QPOs) are thought to be neutron stars accreting from disks in low-mass binary systems. Here we focus on those stars with QPO frequencies greater than 5 Hz and luminosities near the Eddington limit, since these fast, luminous oscillators (FLOs) appear most likely to form a uniform class.

Two types of models have been proposed to explain the oscillations in the intensities of these stars. In modulated accretion models, the QPOs are caused by oscillations in the luminosity of the star. An example is the so-called beat-frequency modulated accretion model (Alpar and Shaham 1985; Lamb *et al.* 1985; Lamb 1986; Shibazaki and Lamb 1987). In this model, the accretion rate and stellar luminosity oscillate at the beat frequency given by the difference between the orbital frequency of inhomogeneities in the inner disk and the rotation frequency of the star. In beaming models, on the other hand, the luminosity is approximately constant, but the intensity of the X-rays emerging from the system in our direction oscillates quasi-periodically due to changes in the distribution of matter within the system. Examples include beaming of radiation by luminous matter orbiting in the boundary layer at the surface of a nonmagnetic neutron star (Hameury, King, and Lasota 1985) and beaming by shock waves revolving at the magnetospheric boundary of a magnetic neutron star (Morfill and Trümper 1986). It has also been suggested that the QPOs are due to beaming of X-rays by disk oscillations (van der Klis *et al.* 1985, 1987) or self-luminous (van der Klis *et al.* 1985), scattering (Boyle, Fabian, and Guilbert 1986), or obscuring (van der Klis *et al.* 1985) matter orbiting in the inner disk.

The results of a recent analysis of *EXOSAT* data on the luminous QPO source Cyg X-2 (Hasinger 1987) have important implications for these models. This analysis shows that the QPOs observed at higher X-ray energies lag the QPOs at lower energies by a few milliseconds. When combined with the shape of the X-ray spectrum, this lag indicates that the oscillating X-rays are Comptonized by passing through a scattering cloud of radius ~ 200 km and electron scattering optical depth ~ 3–10. The presence of such a cloud is consistent with earlier observational results (Hirano *et al.* 1984; Shibazaki and Mitsuda 1984; Mitsuda *et al.* 1984; White, Peacock, and Taylor 1985; Hasinger *et al.* 1985, 1986) which indicated that central coronae with properties like these are present in luminous low-mass X-ray binaries, and with theoretical arguments (see Lamb 1986) which suggested that heat-

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ing of the surface of the inner disk should create such coronae. A somewhat smaller lag of the QPOs in higher energy X-rays has now also been reported in GX 5-1 (van der Klis 1987*b*). These new observational results indicate that the QPOs in these sources are produced well inside a moderately dense central corona.

In the present *Letter* we report the results of analytical and Monte Carlo calculations that provide a first quantitative estimate of the effect of such a corona on the amplitude of oscillations in the X-ray intensity produced by a rotating pattern of radiation emitted at the center. Our results show that a moderately dense corona is very effective in reducing the amplitude of oscillations produced by beaming. They therefore strongly suggest that the QPOs in the fast, luminous sources, which have amplitudes as large as 20%, are caused by oscillations in the luminosity of the X-ray star and not by beaming. Our results also suggest that the observed weakness of periodic oscillations at the rotation frequencies of these neutron stars is caused by scattering in the central corona.

Although motivated by interest in the effect of coronae on the amplitudes of quasi-periodic and periodic oscillations in the QPO sources, our results can also be used to estimate the effect of scattering on X-ray pulsations produced by canonical accretion-powered pulsars that, like Her X-1, are embedded in coronae (see Mason 1986); on X-ray oscillations that may be produced by other accretion-powered sources inside scattering clouds, such as Cyg X-3 (Holt and McCray 1985; Mason 1986); and on X-ray pulsations produced by rotation-powered pulsars that happen, like the Vela pulsar, to be surrounded by a cloud of plasma (see Pravdo *et al.* 1978).

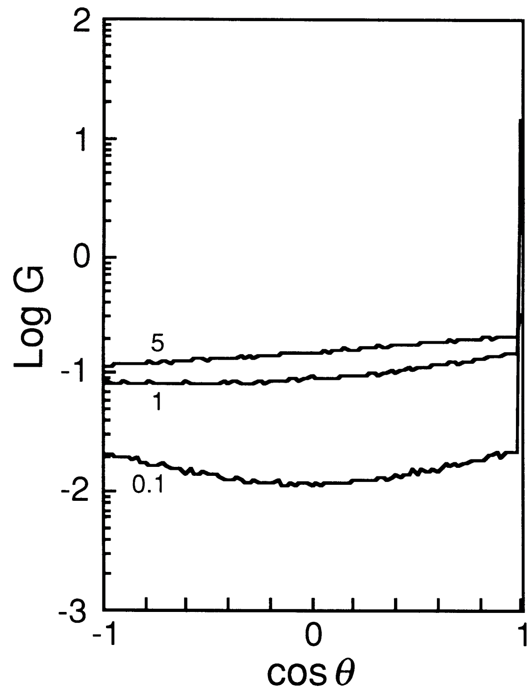

FIG. 1.—Monte Carlo results for the scattering Green's function G as a function of $\cos\theta$, for clouds of optical depth $\tau_c = 0.01$, 1, and 5. Note the peak at $\cos\theta = 1$ due to unscattered radiation and the nearly linear dependence of G on $\cos\theta$ for $\tau_c = 5$ (the variation of G with $\cos\theta$ is sufficiently small that the plotted variable $\log G$ is also linear in $\cos\theta$). The peak at $\cos\theta = 1$ makes only a small contribution to the integrated intensity for $\tau_c \gtrsim 1$. Its prominence in these plots is a consequence of the large number of bins in $\cos\theta$ used here.

II. THEORETICAL MODEL AND RESULTS

In our calculations we modeled the scattering cloud as a uniform density sphere of radius r_c and electron scattering optical depth τ_c measured from the center to the surface. We assumed Thomson scattering and neglected absorption. Thus, there was no need to keep track of the energy of the photons. We modeled the source as an anisotropic distribution or "beam" of radiation emerging from a point at the center of the scattering cloud. This beam was assumed to be axisymmetric about a nominal "beam direction," which was chosen as the axis of the polar coordinate system. With these assumptions, the relevant properties of the radiation emitted by the source are completely specified by the source beam pattern $I_0(\theta)$, which is the same in any plane containing the beam direction. The resulting intensity distribution $I(\theta, \phi, \tau_c)$ at infinity is of course also independent of the azimuthal angle ϕ. A variety of beam patterns was investigated.

The calculations were performed using standard Monte Carlo methods for treating random walk problems (Cashwell and Everett 1959). Beams of photons were launched from the center of the cloud in directions chosen according to the assumed source intensity distribution. The probability of escape was calculated, and this fraction of the beam assumed to escape. The distance to the first scattering was determined from the scattering probability distribution along the path of the beam. The scattering angle was calculated using the angular distribution for Thomson scattering. The procedure was then repeated until less than 0.1% of the initial beam remained. For each initial angular distribution, 10^5 beams were followed. The angular distribution of radiation at infinity was computed by binning the final beam directions in 100 equal bins in $\cos\theta$, since this is the natural variable for many purposes.

Of particular interest is the intensity distribution $G(\theta, \phi, \tau_c)$ at infinity produced by the source beam pattern $I_0(\theta) = \delta(\cos\theta - 1)/2\pi$, since this distribution is the Green's function for an arbitrary beam. Figure 1 displays Monte Carlo results for G as a function of $\cos\theta$ for cloud optical depths of 0.1, 1, and 5. G was also calculated for cloud optical depths of 10 and 20. The fractional rms error in G is $\sim 10\%$ for $\tau_c = 0.1$ and $\sim 3\%$ for large τ_c. The distribution of the *unscattered* radiation is $I_0(\theta)e^{-\tau_c}$ and produces the peak evident at $\cos\theta = 1$. The Monte Carlo results suggest that the distribution of the *scattered* radiation may be expressed as $I_{sc}(\theta, \phi, \tau_c) \approx a(\tau_c) + b(\tau_c)\cos\theta + c(\tau_c)\cos 2\theta$, as expected from the angle dependence of the Thomson cross section. The variation of G with θ diminishes rapidly with increasing cloud optical depth. For $\tau_c \gtrsim 2$, a is much larger than either b or c and essentially constant. For $\tau_c \gtrsim 5$, $c \lesssim 0.1b \lesssim 0.02a$ and hence $G(\theta, \phi, \tau_c) = a + b(\tau_c)\cos\theta$ to a good approximation, as may be seen by inspecting the $\tau_c = 5$ curve in Figure 1.

The dependence of b on τ_c may be conveniently explored by considering the dependence of the ratio $R \equiv (I_f - I_b)/(I_f + I_b)$ on τ_c, since when c is negligible, $R = b/2a$. Here I_f is the intensity integrated over the forward hemisphere and I_b is the intensity integrated over the backward hemisphere. R

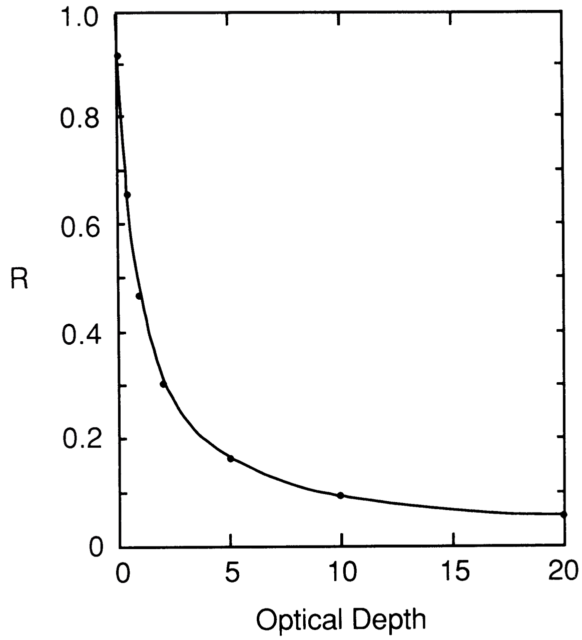

FIG. 2.—(*data points*) Monte Carlo results for the forward-backward ratio R produced by a δ-function beam embedded in a spherical cloud of optical depth τ_c. (*solid curve*) The two-stream result $R = 1/(1 + \tau_c)$ for the forward-backward ratio R produced by a δ-function beam at the center of a slab of optical depth τ_c.

falls rapidly with increasing τ_c, as indicated by the Monte Carlo results plotted in Figure 2.

An analytical expression for the dependence of R on τ_c may be obtained by considering in the two-stream approximation the scattering of radiation beamed in the forward direction from the center ($\tau = 0$) of a uniform slab of total optical depth $2\tau_c$. The equations describing the variation of I_f and I_b with τ are

$$\frac{dI_f}{d\tau} = -\frac{1}{2}I_f + \frac{1}{2}I_b + F_0\delta(\tau) \qquad (1a)$$

$$\frac{dI_b}{d\tau} = -\frac{1}{2}I_f + \frac{1}{2}I_b, \qquad (1b)$$

where F_0 is the total flux and τ increases in the direction of the beam. The appropriate boundary conditions are $I_f(-\tau_c) = 0$ and $I_b(\tau_c) = 0$. The solution with these boundary conditions is

$$R(\tau_c) = \frac{1}{1 + \tau_c}. \qquad (2)$$

This result may be understood as follows. Photons emitted by the source typically travel one mean free path in the direction of the beam before scattering. Since each scattering is typically through a large angle, the photon distribution after the first scattering is approximately isotropic, but centered on a point approximately one mean free path from the center of the slab. As a result, slightly more photons leak out in the forward direction than in the backward direction.[3]

[3] This explanation was suggested by Middleditch and Priedhorsky (1985) and confirmed by analytical work of N. Shibazaki (1985, unpublished).

The analytical result (2) is compared with our Monte Carlo results in Figure 2. As may be seen, the agreement is excellent. Thus, although the Monte Carlo results alone are not sufficient to establish the precise τ-dependence of b, we expect $b \propto 1/(1 + \tau_c)$. This result and the Monte Carlo results for the angular dependence of I_{sc} suggest that in the limit $\tau_c \to \infty$, the scattering Green's function approaches

$$G(\theta, \phi, \tau_c) = \frac{1}{4\pi}\left[1 + \left(\frac{2}{1 + \tau_c}\right)\cos\theta\right]. \qquad (3)$$

When convolved with the source intensity distribution $I_0(\theta)$, this Green's function gives analytical intensity distributions that agree well for $\tau_c \gtrsim 5$ with our Monte Carlo results for a wide variety of source beam patterns, supporting this conjecture.

Under the physical conditions that exist in the FLOs, radiation is expected to emerge from the neutron star magnetosphere in many directions, producing an initial beam with multiple lobes (see § III). For such a beam, scattering may be expected to reduce the angular anisotropy of the radiation emerging from the central corona more than for a δ-function beam. In order to explore this effect, we considered source beam patterns of the form $I_0(\theta) = N(1 + \cos n\theta)F_0$, where $n = 1, 2, \ldots$ and N is a normalization factor chosen so that the integral of $I_0(\theta)$ over θ and ϕ is F_0. These beams form a complete, linearly independent set of axisymmetric functions and may therefore be used to represent any axisymmetric initial beam.

We have calculated the intensity distribution at infinity produced by these source beam patterns for $1 \le n \le 6$ and $0.1 \le \tau_c \le 20$, using the Monte Carlo method. Figure 3 shows the results for $n = 1$, 3, and 5 and cloud optical depths of 0.1, 1, and 5. Note the change in the sign of the $\cos\theta$-dependence between $n = 1$ and $n = 3$ for $\tau_c = 5$. The intensity distribution predicted by the Green's function (3) is

$$I(\theta, \phi, \tau_c) = \begin{cases} \frac{1}{4\pi}\left[1 + \left(\frac{1}{4 - n^2}\right)\left(\frac{2}{1 + \tau_c}\right)\cos\theta\right]F_0, & n \text{ odd;} \\ \frac{1}{4\pi}F_0, & n \text{ even.} \end{cases} \qquad (4)$$

Note that the term proportional to $\cos\theta$ changes sign for $n > 1$, as expected from the Monte Carlo results. The analytical expression (4) agrees well with our Monte Carlo results for $\tau_c \gtrsim 5$.

These analytical and Monte Carlo results show that for source beam patterns with forward-backward symmetry (n even), the angular anisotropy of the radiation emerging from the cloud decreases with increasing τ_c much more rapidly than $1/\tau_c$. For clouds of moderately large optical depth, all asymmetric (n odd) source beam patterns produce distributions at infinity $\propto a + b\cos\theta$, just like the δ-function beam except that the amplitude of the variation with θ is much smaller. Indeed, b falls off as $1/n^2$ for large n.

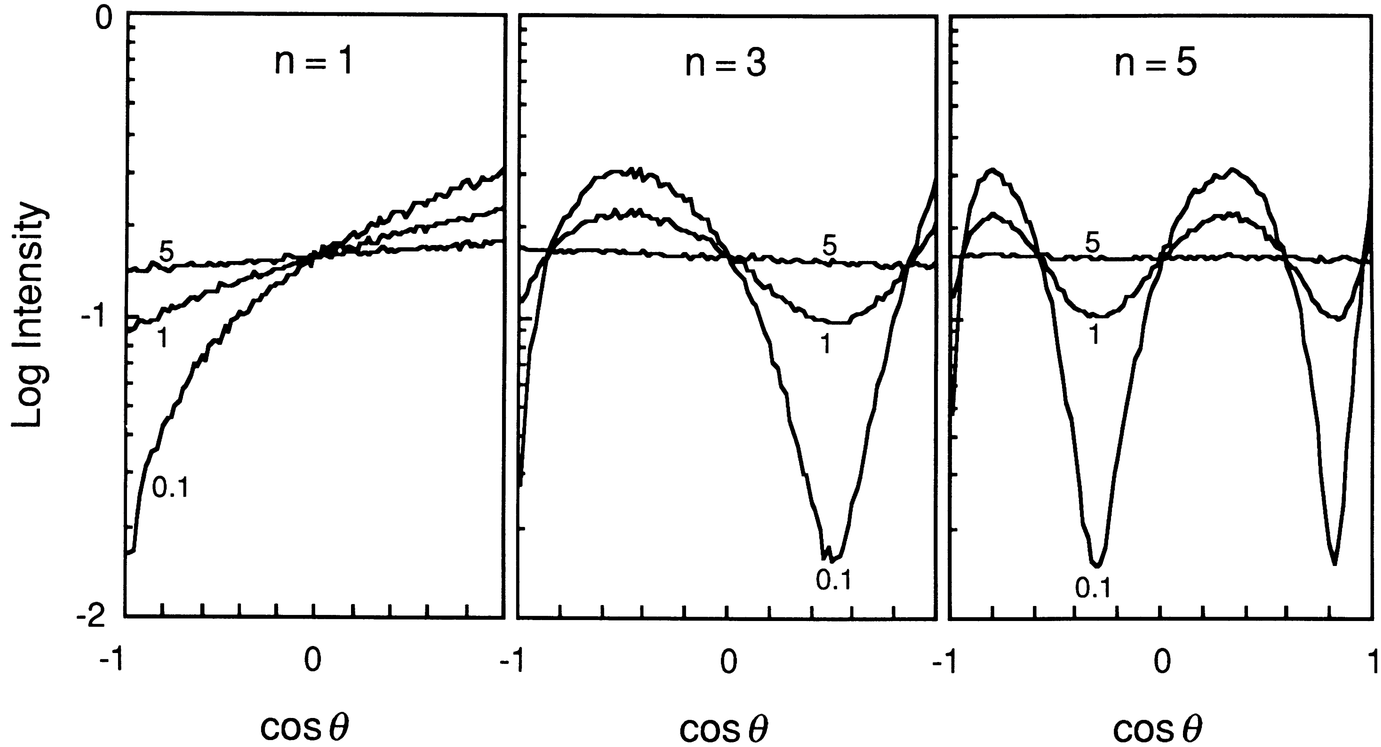

FIG. 3.—Monte Carlo results for the intensity distribution at infinity $I(\theta, \phi, \tau_c)$ as a function of $\cos\theta$ for source beam patterns of the form $I_0(\theta) \propto 1 + \cos n\theta$ with $n = 1$, 3, and 5 and clouds of optical depth $\tau_c = 0.1$, 1, and 5. The intensity is normalized to unity when integrated over 4π sr. Note the nearly linear dependence on $\cos\theta$ for $\tau_c = 5$.

The intensity distributions (3) and (4) may be used to calculate the light curve seen by a distant observer when the source is rotating about an arbitrary axis by summing a series of these distributions that have been rotated and weighted appropriately over the time required for photons to escape from the cloud. However, the finite escape time has a negligible effect on the light curve if it is short compared to the time required for the source radiation pattern to rotate through an appreciable angle, i.e., if $r_c\tau_c/c \ll 1/f_{\rm rot}$, where $f_{\rm rot}$ is the rotation frequency of the pattern. Written as a constraint on $f_{\rm rot}$ and choosing cloud parameters like those inferred for Cyg X-2, this condition becomes

$$f_{\rm rot} \ll 300\left(\frac{10^7 \text{ cm}}{r_c}\right)\left(\frac{10}{\tau_c}\right) \text{ Hz}. \quad (5)$$

In the FLOs, QPO frequencies are ~ 5–50 Hz while neutron star rotation frequencies are expected to be ~ 100 Hz. For frequencies of this order and cloud parameters like the nominal parameters displayed in inequality (5), the effect of the finite escape time on the light curve may be neglected. If the rotation frequency of source is so large that inequality (5) is *not* satisfied, the amplitude of the oscillation in the X-ray intensity seen at infinity will be further reduced, and the amplitudes quoted below will be upper bounds.

A useful measure of the amplitude of oscillations produced by a rotating radiation pattern is the fractional rms intensity variation $\gamma_{\rm osc} \equiv \langle(\Delta I)^2\rangle^{1/2}/\langle I\rangle$. Here $\Delta I \equiv I - \langle I\rangle$ and the angle brackets indicate averaging with respect to the rotation phase φ. The power at the rotation frequency that would appear in the power density spectrum of the intensity time series seen by a distant, fixed observer is proportional to $\gamma_{\rm osc}^2$. For an axisymmetric beam, $\gamma_{\rm osc}$ is maximal for rotation about the axis perpendicular to the plane defined by the beam direction and the sightline to the observer. Since we seek an upper bound on $\gamma_{\rm osc}$, we shall assume this geometry. Equation (4) then gives

$$\gamma_{\rm osc} = 2^{1/2}\left|\frac{1}{4 - n^2}\right|\left(\frac{1}{1 + \tau_c}\right), \quad (6)$$

for n odd and $\gamma_{\rm osc} = 0$ for n even. We expect this result to be accurate for $\tau_c \gtrsim 5$.

III. DISCUSSION AND CONCLUSIONS

As discussed in § I, the lag of the QPOs at higher X-ray energies observed in Cyg X-2 and GX 5-1 indicates that the QPOs in these sources are produced well inside a central scattering cloud of optical depth ~ 3–10 and radius ~ 200 km. This argues against models in which the QPO frequency reflects the orbital frequency of self-luminous, obscuring, or scattering matter in the accretion disk, since the required radius is ~ 200 km for a QPO frequency of 20 Hz, as observed in Cyg X-2 and GX 5-1, and ~ 600 km for a QPO frequency of 5 Hz, as observed in Sco X-1 (Brainerd, Lamb, and Shibazaki 1987).

The results reported here show that scattering in a central corona of optical depth τ_c reduces the amplitude of oscillations produced by a narrow, rotating pencil beam to $\sim 1/(1 + \tau_c)$ of the original amplitude or less. For asymmetric beams with n lobes, the amplitude of the oscillations outside a central corona of optical depth $\gtrsim 5$ is reduced by an additional factor $\sim 1/n^2$. For symmetric beams, the amplitude of oscillations outside such a corona is likely to be negligible.

These results, when combined with the evidence that the QPOs are produced well inside a central coronae of optical depth ~ 3–10, indicate that beaming models in which the QPOs are caused by a vertically oscillating or orbiting pattern of luminous, obscuring, or scattering matter may have difficulty accounting for the relatively large observed amplitudes of the oscillations, which are typically $\sim 5\%$–10% but sometimes reach 20% of the total flux (van der Klis 1987*b*).

The presence of a moderately dense central corona is *not* a difficulty for models—such as the beat-frequency modulated accretion model—in which the QPOs reflect oscillations in the luminosity of the star. In such models, the amplitude of the oscillations is unaffected by scattering as long as the time for photons to escape is small compared to the oscillation period (Chang and Kylafis 1983). For central coronae with the properties discussed here, this is the case.

These recent observational and theoretical results also suggest why periodic oscillations at the rotation frequency of the neutron star have proved to be so weak in the FLOs. (Current upper limits on the rms amplitudes of periodic oscillations range from 10% to 30% in many low-mass X-ray binaries [see Leahy *et al.* 1983; Mereghetti and Grindlay 1987] to 0.3% to 0.8% in GX 5-1 [van der Klis *et al.* 1985], Sco X-1 [Middleditch and Priedhorsky 1986], and Cyg X-2 [Norris and Wood 1987].) For the luminosities observed and the field strengths $\sim 10^9$ G expected in these neutron stars, the magnetosphere is small, the radiation pressure is very large, and channeling of the accretion flow by the stellar magnetic field is likely to be only partially effective (Lamb *et al.* 1985; Lamb 1986). As a result of weak channeling and scattering of photons by the relatively dense plasma within the magnetosphere, the X-radiation emerges from the magnetosphere much more isotropically in these stars then in canonical accretion-powered pulsars. Also, the thick plasma torus expected around the small magnetosphere restricts the path for unimpeded propagation of X-rays to directions near the rotation axis, where modulation of the intensity by beaming and rotation is inherently weak. The expected peak in the power spectrum at the rotation frequency of the star may also be substantially broadened by amplitude and phase modulation caused by the intermittent and fluctuating accretion flow expected within the magnetospheres of these sources, making it more difficult to detect. Detection of periodic pulsations is also made difficult by the substantial orbital Doppler shifts expected and the fact that the orbital period, the semi-major axis of the orbit, and the orbital phase of the neutron star are frequently unknown (see Norris and Wood 1987; Mereghetti and Grindlay 1987). If, as expected, the amplitude of the rotational modulation just outside the magnetosphere is no more than $\sim 30\%$ and the beams have multiple lobes, scattering in a central corona of optical depth ~ 5–10 will reduce the amplitude of the oscillations seen by a distant observer to a few tenths of 1%. If the time required for photons to escape from the corona is not small compared to the rotation period or the star produces an axisymmetric beam but is not an orthogonal rotator, the observed amplitude will be still smaller.

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