THE ASTROPHYSICAL JOURNAL, 459:666–670, 1996 March 10

X-RAY PULSAR TWO-LINE SPECTRA FROM A TWO-COMPONENT ACCRETION COLUMN

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Received 1995 August 16; accepted 1995 September 19

ABSTRACT

Several X-ray pulsars exhibit line structure in their spectra that has been interpreted as originating from cyclotron processes in the accreting plasma. A few of these objects also show evidence of a second spectral feature that, traditionally, has been thought to be the second cyclotron harmonic. Detailed calculations of the emitted flux spectra are presented that incorporate a simple two-component model of the accretion cap. The two components are modeled as slabs separated by a shock wave, where the postshock slab is the thermalized high-density and -temperature plasma that creates the radiation via bremsstrahlung processes and the preshock material is represented by a relatively cool, low-density plasma that is moving near the free-fall velocity. Results show that two spectral features are easily produced, one representing the fundamental cyclotron harmonic of the postshock plasma, and another that is a Doppler-shifted line produced by scattering in the preshock plasma.

Subject headings: accretion, accretion disks — plasmas — pulsars: general — radiation mechanisms: nonthermal — shock waves — X-rays: stars

1. INTRODUCTION

Many observations of accreting X-ray pulsars (AXPs) over the last several years indicate the presence of spectral features that are believed to be caused by cyclotron processes in the accreting plasma (Trümper et al. 1978; Wheaton et al. 1979; Mihara et al. 1989; Makishima et al. 1991). Although not well resolved, two of these observations (Hercules X-1 and X0331 + 53) exhibit evidence of two spectral lines that have traditionally been thought to be the first- and second-harmonic cyclotron lines of electrons bound in a strong magnetic field.

Theoretical models of the emission from AXPs have been constructed to calculate the spectral properties in the continuum and line and also predict pulse shapes. Mészáros & Nagel (1985a, b) employed a static model that incorporated single-photon scattering in the nonrelativistic limit and neglected stimulated effects. Using the discrete-ordinate Feautrier technique to solve the radiative transfer equation, they calculated angle- and polarization-dependent model spectra for slab and cylinder geometries that showed a single cyclotron line created by resonant-photon scattering near the classical cyclotron frequency ω_c. Alexander & Mészáros (1991a) demonstrated that the higher energy line could be calculated as a second-harmonic line at $\sim 2\omega_c$ if the effects of two-photon scattering and emission (Alexander & Mészáros 1991b) were used in conjunction with relativistic cross sections and stimulated effects. This was based on earlier work (Alexander & Mészáros 1990) in which similar effects were used to model the multiple lines seen in the hard X-ray spectra of gamma-ray bursts.

One area in which very little progress has been made is the study of the bulk motion or hydrodynamics of the accretion process and its effects on the emitted spectra, particularly in the region of spectral lines. The self-consistent coupled radiation magnetohydrodynamic problem has been attempted numerically with some success (Burnard, Klein, & Arons 1990); however, these works are limited to the continuum part of the spectrum. As discussed in Mészáros (1992) and references therein, the inherent coupled radiation and hydrodynamic problem remains computationally intractable. However, some authors (e.g., Langer & Rappaport 1982) have concluded that the accretion flow is probably dominated by a shock wave that decelerates the accreting plasma from near free-fall velocity to subsonic speeds, where it settles onto the neutron star's surface. While the details of the geometry of such a flow are very uncertain, Brainerd & Mészáros (1991) report that this scenario can lead to a two-line spectrum in which one line is from the thermalized postshock plasma and another line arises from the preshock, moving plasma. Both lines would be first-harmonic cyclotron lines; however, one would be Doppler-shifted to lower energies, thus creating a two-line spectrum.

In this paper, we present detailed calculations of the emission of AXPs that incorporate a two-component accretion column. Our model, discussed in § 2, is a simple two-component geometry in which the regions are separated by a shock wave that causes a discontinuous change in the plasma parameters. Radiation is produced via thermal processes in the postshock plasma and propagates through the moving preshock region. In § 3, we show that if we correctly account for the angle-dependent Doppler effect and angular aberration, two-line spectra are easily computed that compare reasonably well with observations, as discussed in § 4.

2. THE MODEL

2.1. *The Physical Model*

In Mészáros & Nagel (1985b), the AXP model that gave the best agreement with the observed spectra was for an optically thick slab where the radiation is produced via thermal free-free or bremsstrahlung processes and nonrelativistic one-photon Compton scattering creates the single cyclotron line. The plasma in the slab was assumed to have no bulk motion, and both the temperature and density were held constant, i.e., homogeneous. This accretion model was carried over to Alexander & Mészáros (1991b), where the addition of relativistic scattering cross sections for both one- and two-photon processes were used to study the spectrum at higher cyclotron harmonics.

The details of the accretion flow remain poorly understood; however, the presence of a deceleration shock is a distinct possibility. Therefore, the inhomogeneity of the flow would be dominated by discontinuities in the plasma parameters across the shock wave. We have chosen to model this effect in a rather simple fashion. Figure 1 shows the simplified two-slab model that we employed in our calculations. The emitting region near the magnetic polar cap of the neutron star is modeled as two distinct slabs separated by a shock wave. The plasma in the preshock slab is moving along the magnetic field lines at near the free-fall velocity ($\sim c/2$) and is relatively cool and low-density. After passing through the shock, the plasma is decelerated and thermalized so that the postshock plasma is characterized by its high temperature and density ($kT \sim 10$ keV and $\rho \sim 1$ g cm^{-3}), consistent with the overall observed emission.

In this model, the X-ray emission is created in the optically thick postshock slab by thermal free-free emission, and resonant cyclotron scattering creates a single spectral line near ω_c, the classical cyclotron frequency. The radiation propagates upward through the shock into the preshock slab, where it interacts with the accreting electrons. While the postshock slab is optically thick to emission, the preshock slab is optically thin and, therefore, is not an effective emitter; however, it may still be optically thick to scattering. Thus, the photons produced in the postshock slab can scatter from the moving electrons in the preshock slab.

The spectral line created when the photons scatter from the moving preshock plasma will necessarily be Doppler-shifted to lower energies, thereby creating a second spectral line. This process can be easily understood by considering two sets of photons created in the postshock slab, with energies $\omega_a \sim \omega_c$ and $\omega_b < \omega_c$. In the postshock slab, photons ω_a are resonant and will scatter, creating a spectral line near ω_c, whereas photons ω_b are nonresonant and will scatter very little. As these photons pass into the preshock slab, the infalling electrons "see" them as being blueshifted; therefore, in the electrons' frame, photons ω_a are no longer resonant and pass freely through the preshock slab. On the other hand, photons ω_b may be resonant in the electron frame and will thus scatter from the electrons, creating another spectral line in the lab frame at energies less than ω_c. In this scenario, it is the higher energy line that is the fundamental or ground cyclotron harmonic (Brainerd & Mészáros 1991). For example, for Her X-1, the spectral feature seen at ~ 38 keV is the Doppler-shifted line, and the line between 70 and 80 keV is the ground cyclotron harmonic. This would of course mean that the magnitude of the neutron-star magnetic fields for X-ray pulsars may be too low by an approximate factor of 2.

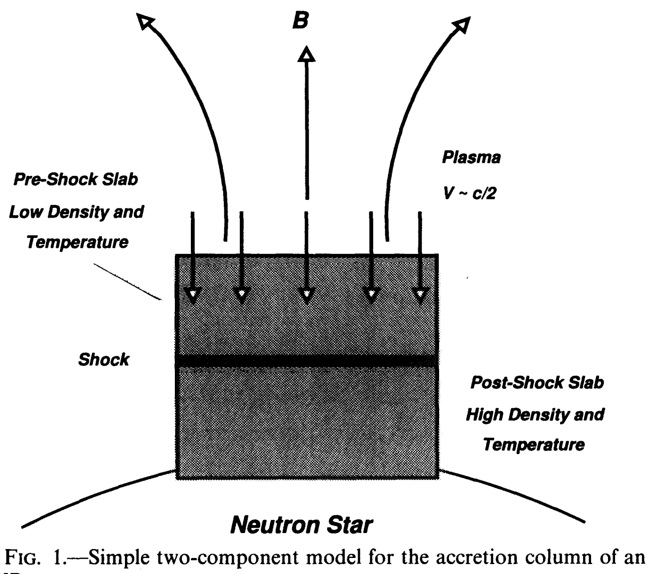

FIG. 1.—Simple two-component model for the accretion column of an AXP.

In this paper, we do not attempt to justify this model with any hydrodynamic calculations. Our intent is rather to demonstrate that if this two-component shock-dominated accretion column is present in AXPs, it provides a simple way to generate a two-line spectrum. In accordance with these assumptions, we have selected the simplest computational model possible that can demonstrate this effect.

2.2. *The Computational Model*

Computations to determine the emitted spectrum from the two-component accretion column were performed by solving the radiative transport equation using the Feautrier method, as in Mészáros & Nagel (1985a, b). Radiation is produced by thermal free-free emission in the postshock slab only. The postshock region is modeled as a slab that is homogeneous in temperature and density with constant magnetic field. The radiation field is calculated in this slab at discrete depth points for two polarization modes and either a set of 128 frequencies and one angle of propagation or a set of 32 frequencies and four angles. In essence, this part of the calculation duplicates that of Mészáros & Nagel (1985a, b) and yields similar results. In order to simplify the calculations, we employed nonrelativistic one-photon Compton scattering cross sections for frequency, polarization, and angle redistribution. Use of the relativistic cross sections would have greatly increased our computation times, and the purpose of this work is to demonstrate the production of a two-line spectrum from the correct treatment of the scattering in the preshock plasma.

The preshock region is also modeled as slab with uniform temperature and density, but lower than that in the postshock slab. The radiation that is emitted from the top of the postshock slab is incident on the lower boundary of the preshock slab and is treated as a boundary condition. However, before the Feautrier calculation is performed for the preshock slab, the incident radiation field is transformed to the rest frame of the electrons. In addition, the angles of propagation for the radiation change in the electron frame because of the effect of angular aberration. For a photon with frequency ω and angle of propagation θ measured from the magnetic field, the corresponding frequency and angle in the electron frame, ω' and θ', are

$$\omega' = \omega\gamma(1 + \beta \cos \theta) , \tag{1}$$

$$\tan \theta' = \frac{\sin \theta}{\gamma(\cos \theta + \beta)} , \tag{2}$$

where $\beta = v/c$, v is the bulk speed of the electrons, and $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor. The Feautrier calculation for the preshock slab can now be carried out in the rest frame of the accreting electrons. When the radiation spectrum that is emitted from the preshock slab is calculated, it is transformed back to the rest frame of the neutron star to compare with observations.

As will be shown in § 3, the characteristics of the lower energy spectral line are easily changed with slight modifications of the plasma parameters in the preshock slab. On the other hand, the postshock plasma parameters are essentially fixed to yield luminosity and thermal turnover that agree with observations.

3. RESULTS

Calculations were made to model the spectrum of Her X-1 and then compare the characteristics of the line structure to observations. For the observed luminosity and thermal turnover of Her X-1, Mészáros & Nagel (1985a, b) indicated that the postshock-slab parameters are density $\rho = 0.5$ g cm^{-3} and temperature $kT = 8$ keV. Using a slab thickness of $R = 1000$ cm gives a Thomson optical depth $\sigma_T \sim 200$, which essentially represents an optically thick semi-infinite slab. All of the calculations for Her X-1 use these parameters for the postshock slab, where the radiation is produced. In all previous works, the cyclotron energy ω_c was assumed to be near 38 keV; however, here we use a much greater cyclotron energy, near 76 keV, since the lower energy line will be created as a Doppler-shifted line from the preshock slab.

Figure 2 shows a total flux (i.e., summed over polarization) spectrum for Her X-1 calculated using only one angle, 60° with respect to the magnetic field axis. The conditions for the preshock slab are $kT = 3$ keV and $\rho = 5 \times 10^{-5}$ g cm^{-3}, which give a Thomson optical depth $\sigma_T \sim 0.004$. For this and subsequent calculations for Her X-1, we assumed a bulk electron speed in the preshock slab of $\sim 0.7c$ since this would yield a Doppler-shifted line at ~ 38 keV. Because of our uncertainty regarding the accretion hydrodynamics, this choice is arbitrary, but the electron velocity can be adjusted to position the line where it is observed. The polarization effects are taken into account in this calculation; however, since they are identical to those in Mészáros & Nagel (1985a, b), we do not include them in these plots or in any others in this paper. All the results presented here show the total flux.

The thin curve in Figure 2 is the flux spectrum emitted by the postshock slab that is injected into the preshock slab. This injected spectrum is identical to that calculated by Mészáros & Nagel (1985a, b) except that here the cyclotron line is at ~ 76 keV. As this spectrum passes through the optically thin preshock plasma, photons near 76 keV are not scattered since they are blueshifted away from resonance. On the other hand, photons near 40 keV are blueshifted to resonance and thus scatter from the electrons in the preshock slab. The thick curve in Figure 2 is the flux spectrum that is transmitted through the preshock slab, and its two-line structure is what is observed.

To demonstrate how the depth of the low-energy, or Doppler-shifted, line depends on the optical thickness, we performed calculations similar to those illustrated in Figure 2 but with different plasma densities in the preshock slab. The results of these calculations are presented in Figure 3, which shows the transmitted flux spectra for three preshock slab densities: $\rho = 1 \times 10^{-6}$, 1×10^{-5}, and 3×10^{-5} g cm^{-3}, which give Thomson optical depths $\sigma_T = 8 \times 10^{-5}$, 8×10^{-4}, and 2.4×10^{-3}, respectively. Again we see that the true cyclotron line at ~ 76 keV passes right through the preshock plasma with no scattering; however, we also see that the depth of the Doppler-shifted line is very sensitive to the optical thickness of the preshock slab. This feature allows us to vary the depth of this line to better agree with observations.

The location of the low-energy line depends on the postshock slab's emission angle through the Doppler formula (eq. [1]), and the scattering angle in the preshock plasma is determined by the angular aberration (eq. [2]). The dependence of the transmitted flux spectrum on angle is shown in Figure 4, which gives the results for four single-angle calculations for preshock-slab conditions $\rho = 5 \times 10^{-5}$ g cm^{-3} and $kT = 3$ keV and a slab thickness of $R = 200$ cm. The four angles of photon propagation in the postshock frame are $\theta = 18°, 40°, 61°, 78°$ measured from the magnetic field axis. These become $\theta' = 7°, 17°, 26°, 36°$, respectively, in the preshock frame. We see here, quite explicitly, the angular dependence of the Doppler formula since each angle has a different resonance in the preshock frame.

Figure 4 also shows that when a multiple-angle calculation is made, some of the Doppler-shifted line will fill in since each angle has its own resonant energy. We found this to be the case, so the multiple-angle calculation utilized a preshock slab density of $\rho = 2.5 \times 10^{-4}$ g cm^{-3}, which corresponds to a Thomson optical depth of $\sigma_T = 0.004$ and is

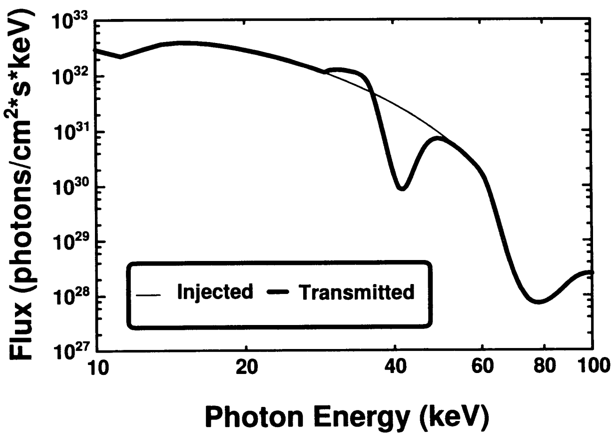

FIG. 2.—Calculated Her X-1 flux spectrum for one angle

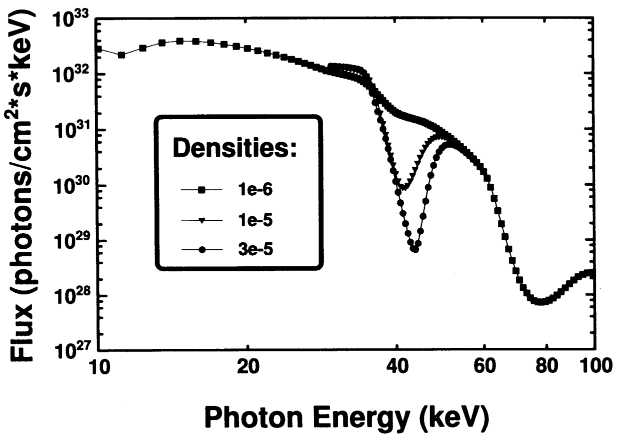

FIG. 3.—Calculated Her X-1 flux spectra for one angle and three different preshock slab densities: $\rho = 1 \times 10^{-6}$, 1×10^{-5}, and 3×10^{-5} g cm^{-3}.

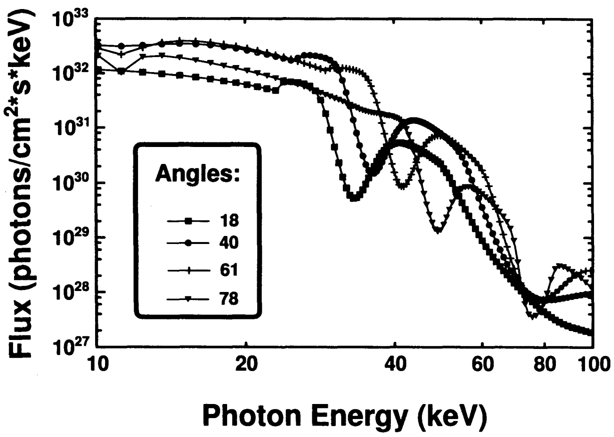

FIG. 4.—Calculated Her X-1 flux spectra for four different angles of propagation: $\theta = 18°, 40°, 61°, 78°$.

thus still optically thin. Figure 5 shows the multiple-angle results for Her X-1 in the form of an angle-averaged photon flux spectrum for a set of four angles and 32 frequencies. Again, the injected spectrum is the radiation emitted from the postshock plasma that is incident on the lower boundary of the preshock slab, and the transmitted curve is the spectrum that ultimately comes out of the preshock plasma. We see here two distinct lines, the fundamental cyclotron line at $\sim$76 keV that is produced in the thermalized postshock plasma and the Doppler-shifted line that is created by scattering from the moving electrons in the preshock plasma. The irregularities seen in the Doppler-shifted line are caused by the discrete number of angles used in the calculation; the use of more angles would give a smoother profile to the line. Comparing Figure 5 to observations of Her X-1 (Trümper et al. 1978; Mihara et al. 1990), we see here the same general line structure within the error of the observations. Both exhibit two absorption features, one between 70 and 80 keV and the other between 30 and 40 keV. The relative depths of the lines are also in good agreement. The spectrum in Figure 5 also compares quite well with that in Alexander & Mészáros (1991b); however, in that work the lines were calculated as cyclotron harmonics.

More recently, Makishima et al. (1991) reported two lines in the spectrum of the accreting X-ray pulsar X0331+53 at photon energies of $\sim$28 and $\sim$53 keV. We attempted to model the spectrum of this AXP in a similar manner as Her X-1. Because of the lower luminosity of X0331+53, we chose the following conditions for the postshock plasma: $\omega_c = 53$ keV, $kT = 3$ keV, $\rho = 0.05$ g cm^{-3}, and $R = 1000$ cm, which corresponds to a Thomson optical depth of $\sigma_T = 20$. We found that, using the two-slab model developed here, we could compute a spectrum that is in reasonable agreement if the preshock plasma is characterized by $v = 0.79c$, $kT = 1.5$ keV, $\rho = 2.5 \times 10^{-4}$ g cm^{-3}, and $R = 100$ cm, which corresponds to $\sigma_T = 0.01$. The results for this multiangle calculation are illustrated in Figure 6, which shows two spectral lines near those observed and roughly the same relative depth. As with the calculations for Her X-1, the irregularities in the low-energy line are caused by the use of a discrete set of photon angles.

4. DISCUSSION

We have shown that it is possible to generate a two-line spectrum for an AXP using a two-component accretion column. We have proposed a model in which the accreting plasma is decelerated by a shock wave so that there are two distinct regions with different plasma properties. Radiation is produced in the thermalized postshock plasma via thermal bremsstrahlung emission, and a single spectral line at the ground cyclotron harmonic is created by one-photon Compton scattering. The preshock region is characterized by a plasma that has lower density and temperature than the postshock plasma. This creates a situation in which the postshock region is optically thick and, hence, a good emitter; however, the preshock plasma is optically thin to emission but remains a good scatterer. Thus, the photons escaping from the postshock plasma scatter from the moving electrons in the preshock region and, correctly accounting for the Doppler shift to the electrons' frame, yield two spectral lines.

For the purposes of solving the radiative transport equation via the Feautrier technique, we have modeled the two-component accretion column as two distinct slabs where the radiation emitted from the postshock slab is injected into the preshock slab as a condition on its lower boundary. The resulting spectrum contains two spectral features: one at the ground cyclotron harmonic and the Doppler-shifted one at lower photon energy. We have presented the results for single-angle and multiple-angle runs to compare with the observations of the AXPs Her X-1 and X0331+53. In both cases the calculated multiangle spectra are in good qualitative agreement with the time-averaged observations.

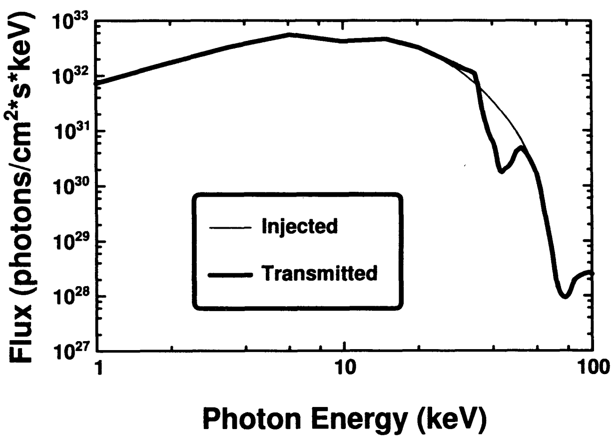

FIG. 5.—Calculated Her X-1 flux spectrum for multiangle calculation

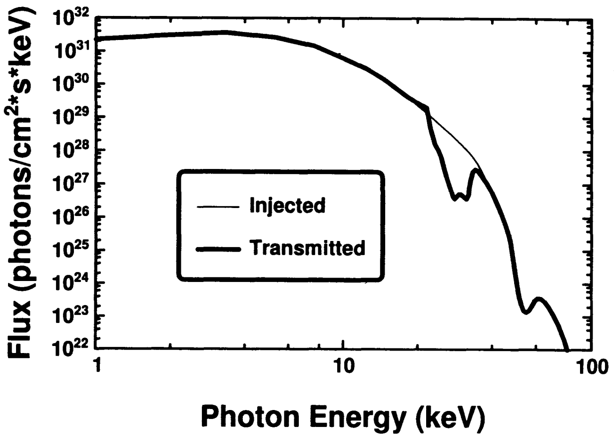

FIG. 6.—Calculated X0331+53 flux spectrum for multiangle calculation.

Is this the true source of the two-line structure seen in some AXPs, or is the cyclotron-harmonic explanation correct? To date, the few observations of a second spectral line are very uncertain, and the poor resolution at the higher energy results in large error in the actual location of that line. For the two AXPs considered here, the lines appear to be approximately in a 2:1 ratio in photon energy. This fact would indicate that the cyclotron-harmonic explanation is correct; however, it should be pointed out that the models used to fit the observations assumed this 2:1 ratio. In the simple two-component accretion column model, rather large speeds are required in the preshock plasma to achieve a 2:1 ratio in the lines. Lower accretion speeds would result for a ratio in line location less than 2:1 and could easily be implemented into the two-component model. Thus, an observation of an AXP with two spectral lines with ratio significantly less than 2:1 would indicate that the two-component source of the lines is correct.

One observation that would be extremely relevant is the corresponding lines from ion scattering, which should be in the extreme-ultraviolet part of the spectrum. While this region of the spectrum is not very accessible because of absorption by the interstellar medium, the potentially better resolution might resolve the question of Doppler versus harmonic models of X-ray pulsar spectra.

The authors would like to thank Prof. Peter I. Mészáros of the Department of Astronomy and Astrophysics of Pennsylvania State University for his advice on this work and the use of his computers in the preliminary stages.

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