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CONSEQUENCES OF NARROW CYCLOTRON EMISSION FROM HERCULES X-1

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ABSTRACT

The implications of the recent observations of a narrow cyclotron line in the hard X-ray spectrum of Hercules X-1 are studied. A Monte Carlo code is used to simulate the X-ray transfer of an intrinsically narrow feature at $\approx$ 56 keV through an opaque, cold magnetospheric shell. The results of this study indicate that if a narrow line can be emitted by the source region, then only about 10% of the photons remain in a narrow feature after scattering through the shell. The remaining photons are scattered into a broad feature (FWHM $\simeq$ 30 keV) that peaks near 20 keV. Thus, these calculations indicate that the intrinsic source luminosity of the cyclotron line is at least an order of magnitude greater than the observed luminosity.

KEY WORDS: X-ray sources- Hercules X-1; Cyclotron emission; Compton Scattering.

Consequences of Narrow Cyclotron Emission from Hercules X-1

A line feature has been observed [1,2,3,4] in the hard X-ray ($E \approx 58$ keV) spectrum of the compact X-ray source Hercules X-1. If this feature is interpreted as cyclotron line emission from a strong magnetic field ($B \gtrsim 10^{12}$ G), these observations can be used to place strict limits on the total source luminosity in the cyclotron line.

The salient feature of the observed line emission is that the FWHM is less than 12 keV[1], with a total observed luminosity in the line of approximately 1% of the total X-ray luminosity. The line seems to be pulsed in phase with the 1.24^s hard X-ray pulse[2]. If we understand, even vaguely, the physical conditions at the pole of an accreting neutron star, as in Hercules X-1, one would expect copious amounts of cyclotron emission. For a temperature of $kT_e \approx 20$ keV, as inferred from the X-ray spectral data[5], and a strong magnetic field ($B \approx 5 \times 10^{12}$ G), as inferred by flux conservation, it is easy to excite the electrons, either by collisions or by blue-shifted photo-excitation. Note that for a neutron star with such a magnetic field and a gravitational red-shift of 0.1, the fundamental harmonic of the cyclotron radiation appears at approximately 58 keV. In Trümper and his colleagues' data, there is some evidence for the second harmonic, tending to give credence to the reality of the interpretation. If the line emission is real and the hard X-ray pulse is due to the occultation of a more isotropic hard X-ray emission by a shell of gas at the neutron star magnetosphere[6,7], the calculations presented here indicate that the total source luminosity of the cyclotron line is more than an order of magnitude greater than the observed amount.

McCray and Lamb[6] and Basko and Sunyaev[7] have proposed that Her X-1 has a magnetospheric shell of variable opacity in magnetic latitude, to account for the soft X-ray luminosity[8,9,10]. They predicted[6] a certain pulse phase relationship between the hard and soft X-rays, which was later confirmed by observations.[10] McCray and Lamb estimate that the scattering depth of this shell is $\tau_{es} \approx 3 - 5$. In the cyclotron line source region at the magnetic poles of the neutron star, the electrons are confined to travel nearly parallel to the B-field lines. Thus, a narrow cyclotron line is only emitted at angles that are nearly perpendicular to the field lines. Even if $kT_e = 15$ keV, the line photons must be emitted at angles greater than $\alpha \geqslant 40°$ to the field lines, in order not to be broader than the observations.[11] For higher temperatures, the narrow radiation is beamed even more directly at the magnetic equator of the shell.

Since the narrowest line is directed toward the thickest part of the shell, it is easy to show that most of the line photons will be removed from the narrow core of the line by incoherent Compton scattering[12]. In fact, averaging over angles at $T_e = 0$ (a good approximation for the conditions in the shell), one finds that the average loss in energy per Compton collision (using the Thomson cross section) is $< \Delta E > = - E^2/m_e c^2$, where E is the initial energy of the photon. Superimposed on this steady energy loss is a dispersion of the line distribution due to the fact that not all photons scatter through the same angles. This gives rise to an important source of broadening[13], even for a zero temperature gas: $\sigma^2(E) \approx E^2 \cdot \frac{2}{5}\left[\frac{E}{m_e c^2}\right]^2$. Thus, the broadening is of the same order as the energy shift. For $\tau_{es} = 4$, one expects that an average photon will scatter about 16 times; thus, even a delta function at 58 keV will be scattered into broad peak centered near 20 keV and having a width of $2\sigma \approx 30$ keV!

So, even if an extremely narrow line can be emitted by the source region, the question is: how can such a narrow line survive after scattering through the magnetospheric shell. Within the framework of the shell model, there are two possible ways a photon can leave the system. Either it escapes through the holes in the shell over the magnetic poles where the hard X-ray pulse originates, or it escapes through the shell itself. Photons in the narrow line that escape through the holes must have backscattered at least once since they were originally beamed toward the magnetic equator of the shell. For photons that escape the system through the shell, the only way a narrow line can be maintained is if the broad peak of scattered line photons is sufficiently removed in energy from the position of the original narrow core that the residual peak of unscattered, or primarily forward scattered photons can be seen above the "continuum". I have studied both of these escape routes by using a Monte Carlo radiation transfer code. The results of this study indicate that a narrow line can escape the system via either route, if the initial energy of the line is greater than approximately 20 keV.

As the simplest possible model of the shell geometry, and following Langer, Ross and McCray[14], I have used a uniformly thick $(\tau_{es} = 3)$ and cold spherical shell surrounding a point source of X-rays, with symmetrically placed holes over the magnetic poles. The holes remove 25% of the surface area of the shell. The line emission is approximated by injecting monoenergetic photons into the shell at 90° from the center of the holes. Absorption of the X-rays is neglected. Using this model, one may see qualitatively whether narrow features can escape the system; however, quantitative results concerning, for example, the exact source strength of the line, depend critically on the angular distribution of the line emission, which is extremely uncertain at present owing to the unknown geometry and physical conditions in the source region. The main feature we know about the source region is that if a narrow line is emitted, it is emitted perpendicularly to the field lines. This is the only source parameter specified in this model.

The results of this study are shown in Figure 1 and 2. Figure 1 shows the spectrum of the total radiation that escapes through the shell. In particular, there is a residual line feature which is much stronger than the tail of the scattered radiation at that energy. The initial energy of the line here is $E_o = 56$ keV. If the total number of emitted line photons were plotted on this figure using the bin width at the line energy, its photon spectral strength would be 4.8×10^3 photons keV^{-1}. Figure 2 shows the spectrum of the total radiation that escapes through the holes. Again there is a narrow feature in the spectrum. The energy of this narrow ($\Delta E \approx 3$ keV) feature is exactly the energy of a once backscattered line photon $E' = E_o/(1 + 2E_o/m_e c^2) = 46$ keV. In both cases the total luminosity in the narrow feature is only a small fraction of the total luminosity emitted in the line. Only 5% of the total initial luminosity escapes in the narrow feature through the holes, while 11% escapes in the narrow feature through the shell. In any case where there is a scattering medium surrounding the source, the total number of photons that escape the system in the cyclotron line feature is only a small fraction of the total number that were emitted in the line.

A narrow line can escape this idealized model of the Her X-1 geometry. However, if the scattering depth from points on the shell through the "hole" over the magnetic poles is sufficiently large, photons that would have escaped in the narrow core would Compton scatter again. In this case, one would not see a narrow line core. This scenario may occur, for example, if the opaque accretion column (due to the converging magnetic field lines) over the poles can intercept a large fraction of the photons that would have escaped. Thus, the question of whether a narrow line can, in reality, escape the Her X-1 system, depends on the (presently unknown) exact accretion flow structure near the magnetopause.

The results of this study indicate that if a narrow line can escape the system, then some fraction greater than ≈10% of the available gravitational energy in the accretion is being transformed into the cyclotron line. Note that in this model (even if a narrow line is not seen), a significant amount of the 20 - 50 keV continuum is merely scattered cyclotron radiation. Since the observed line seems to be pulsed in phase with the hard X-rays[2], it seems reasonable that the observed emission is cyclotron line radiation that has backscattered and escaped through the holes in the magnetospheric shell. More detailed models using model dependent angular emission distributions need to be developed in order to make better quantitative predictions as to the source luminosity of the cyclotron line.

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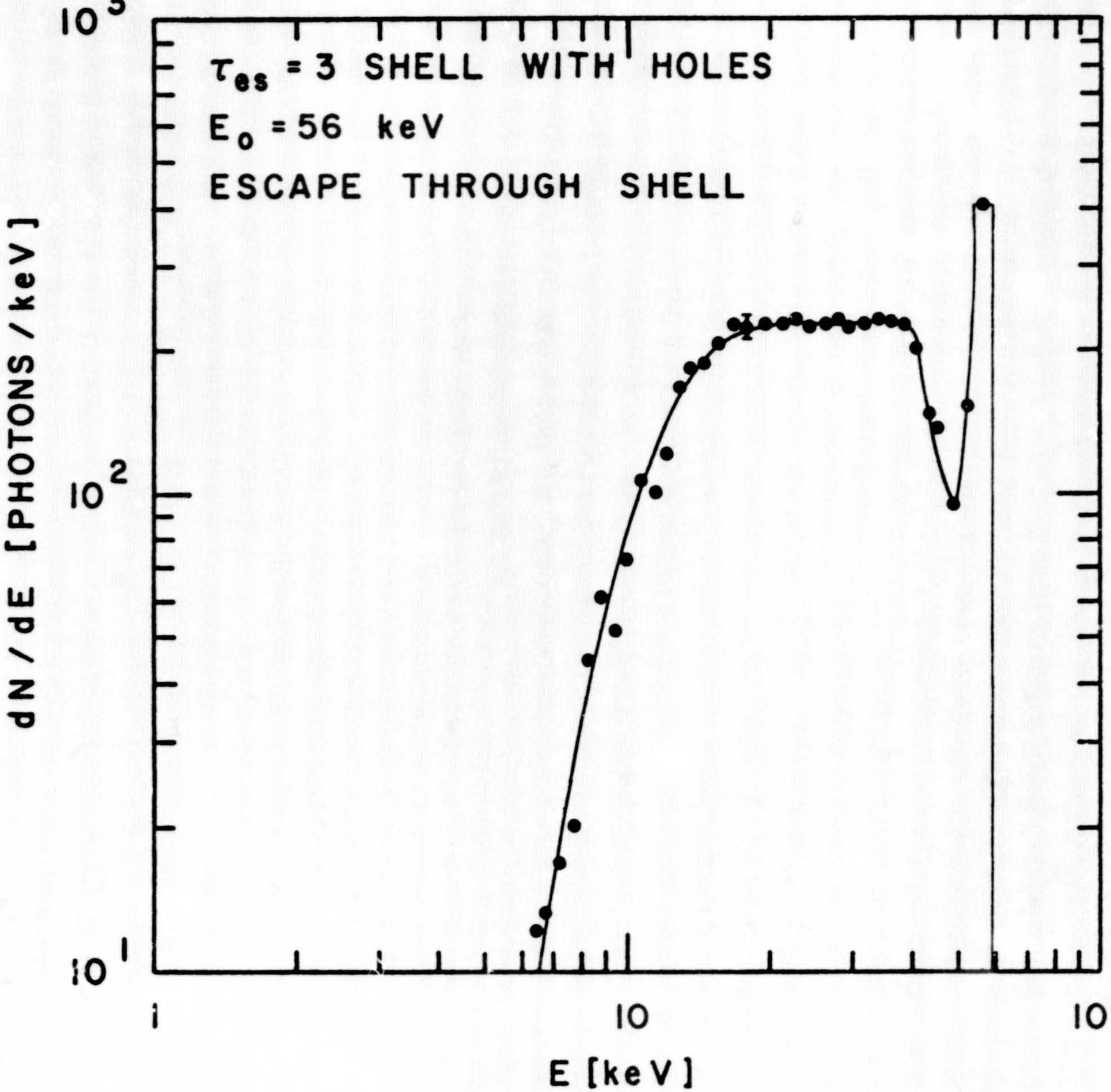
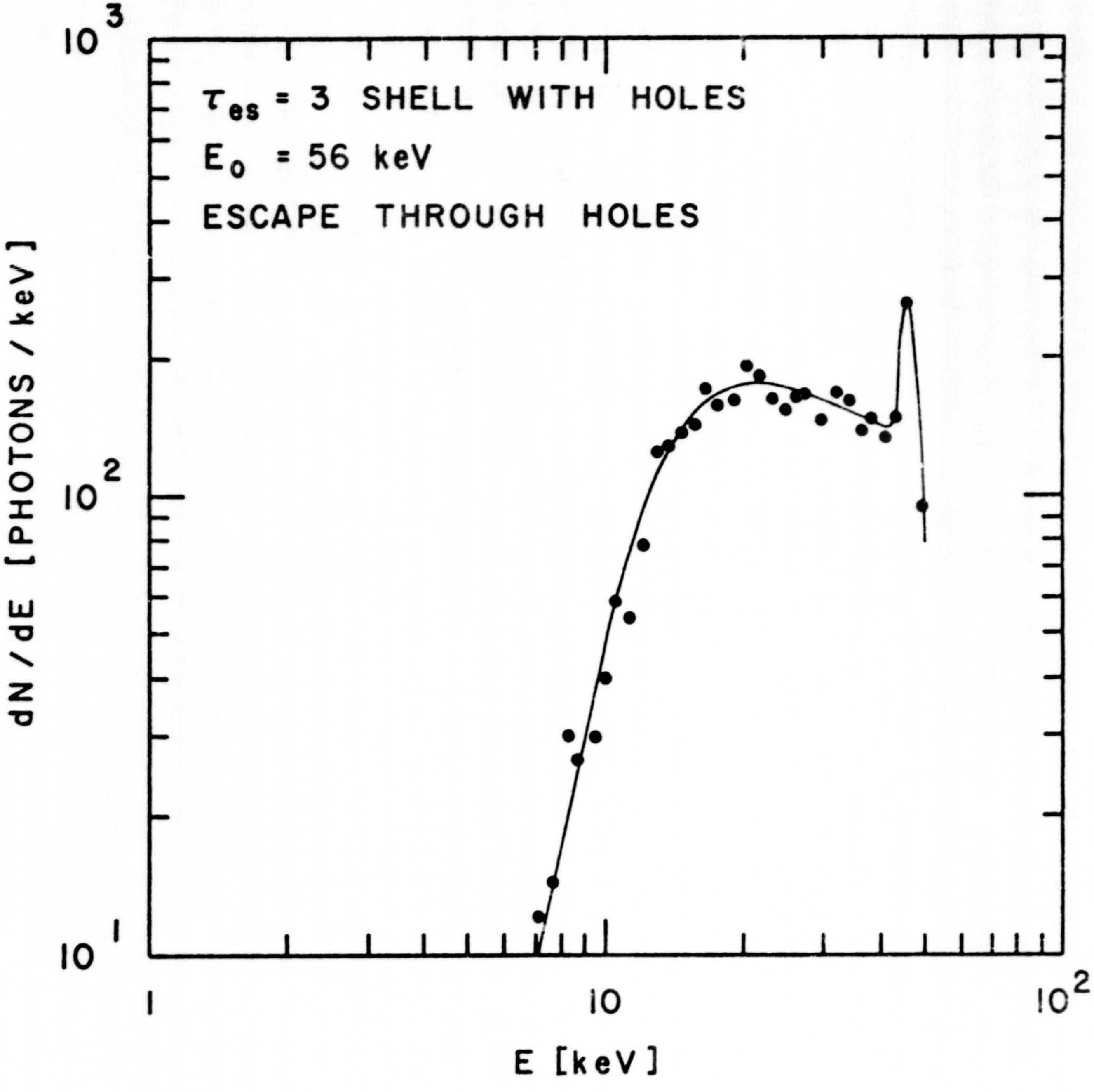
Figure Captions

Figure 1. The spectrum of the radiation that escapes through the shell. The line is drawn through the Monte Carlo points merely to guide the eye.

Figure 2. Same as Figure 1 for the radiation that escapes through the holes in the shell. The holes remove 25 % of the total surface area of the shell-- see the text.



τ_{es} = 3 SHELL WITH HOLES
E_0 = 56 keV
ESCAPE THROUGH SHELL
10^3
10^2
10^1
dN / dE [PHOTONS / keV]
1
10
10^2
E [keV]


τ_{es} = 3 SHELL WITH HOLES
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dN / dE [PHOTONS / keV]
E [keV]
10^3
10^2
10^1
1
10
10^2

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