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FORMATION OF CYCLOTRON LINES IN GAMMA-RAY BURST SPECTRA

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ABSTRACT

We investigate a transmission model of gamma-ray burst sources, using the relativistic QED magnetic resonant opacities including multiple photon scattering, incorporated into a discrete ordinate radiative transport scheme. The physics of the cyclotron line–producing region is discussed in general, and the expected line profiles, relative harmonic strengths, and polarizations are indicated under various conditions. The calculated spectra for these models show good agreement with the spectra reported from *Ginga* for GB 880205 and GB 870303.

Subject headings: gamma rays: bursts — line formation

I. INTRODUCTION

The view that gamma-ray bursters (GRBs) are magnetized neutron stars has recently received strong support by the *Ginga* detections in the bursts GB 870303 and GB 880205 of what appear to be first- and second-harmonic cyclotron lines at 20 and 40 keV, indicating a magnetic field strength of $B \sim 1.7 \times 10^{12}$ G (Murakami *et al.* 1988; Fenimore *et al.* 1988). This is in line with earlier reports (Mazets *et al.* 1982, and references therein) of cyclotron lines in a number of GRBs, and further confirmation of this fact would be of enormous value for understanding the overall physics and the statistical properties of these objects. It is extremely important for this reason to verify the plausibility of the cyclotron interpretation with model calculations, and to understand the gross features of the radiation physics involved (e.g., Harding and Preece 1989; Lamb 1988; Wang *et al.* 1989).

The dominant process in the formation of a line is resonant scattering, which dominates over absorption and emission as well as over collisional excitation and deexcitation rates (Ventura, Nagel, and Mészáros 1979; Mészáros, Nagel, and Ventura 1980; Nagel 1980). However, the presence of a higher harmonic makes the analysis somewhat more complicated, in that one must take into account a number of transitions between Landau levels (Bussard and Lamb 1982). The relativistic QED cross sections for these resonant scatterings between higher Landau levels have been worked out by Bussard, Alexander, and Mészáros (1986) and Daugherty and Harding (1986). Due to the complicated nature of these opacities, the analyses of the *Ginga* events so far have been based either on calculating relative line strengths and shapes from the properties of the QED opacities themselves without performing a transfer calculation (Harding and Preece 1989), or else on Monte Carlo transfer calculations using classical semi-relativistic approximations of the cross sections (Lamb *et al.* 1989; Wang *et al.* 1989). These calculations have provided the first insights into the possible nature of the GRB line formation region, suggesting a configuration where a continuum spectrum propagates through a cold thin sheet of magnetized material. Because of the wide implications of these observations, it is important to perform further detailed radiative transfer calculations of the line and continuum using the exact QED cross sections and including such effects as the polarization and vacuum dependence, which are crucial in determining cyclotron line strengths and shapes. The results described in this *Letter* are restricted to two-streams; however, multistream calculations are feasible and are in progress.

II. SCATTERING PROCESSES AND RADIATIVE TRANSFER

The exact QED cross sections for Compton scattering in a strong magnetic field have been derived in Bussard, Alexander, and Mészáros (1986). In this formalism, transitions between any electron Landau levels and spin flips are included. Of particular interest are resonances for those scatterings that leave the electron in the first or second excited Landau level. When this electron radiatively decays, it produces additional photons which must be included if one is to adequately describe the formation and relative size of cyclotron harmonic lines. The detailed calculations of the opacities for multiple photon emission scattering will be presented elsewhere (Alexander, Mészáros, and Bussard 1989*b*).

Including these scattering processes and their inverses in a radiative transfer scheme presents new difficulties. Several of the terms in the differential equation of transfer depend quadratically on the photon occupation number, or specific intensity, and are thus nonlinear. An iterative procedure has been developed to solve the nonlinear radiative transfer equation that is an extension of the well-known Feautrier technique. The details of the procedure are given in Alexander, Mészáros, and Bussard (1989*a*). Essentially, this method solves for a small perturbation in the radiation field and iterates until convergence. It has proved to be quite stable, and typically converges in less than 20 iterations.

The physical model for the formation of cyclotron features in gamma-ray burst GB 880205 suggested by Fenimore *et al.* (1988) and Wang *et al.* (1989) consists of an optically thin relatively cool electron plasma which is threaded by a strong magnetic field perpendicular to the surface. When photons from the burst event pass through it, they scatter from the electrons and produce the cyclotron lines. Our calculation model consists of a plasma slab of uniform density and temperature that is illuminated from below by a specified incident spectrum that is taken to be a patched power law. The incident power law has an index of $\frac{2}{3}$ for 10.0 keV $< \hbar\omega <$ 18.4 keV, and an index of 1.0 for $\hbar\omega >$ 18.4 keV. Normal ground-state to ground-state Compton scattering is included, as is scattering with multiple photon emission and free-free processes. For both of the scattering effects, the calculations extend up to and include the third cyclotron harmonic. Sums over intermediate states extend up to the fourth harmonic. Since the optical depths that are considered are all quite small ($\tau_T \ll 1$), stimulated scattering effects can be neglected. The emergent flux from the slab is calculated for scattering through several choices of the angle θ in the two-stream formalism, i.e., scattering occurs from θ into $\pi - \theta$ and vice versa. The opacities are averaged over relativistic one-dimensional Maxwellians, using the two normal polarization modes calculated for a fully relativistic hot magnetized plasma including vacuum effects (see Bussard, Alexander, and Mészáros 1986).

III. RESULTS

We calculated the emergent flux for a range of scattering angles relative to the magnetic field and a range of slab thicknesses. For the calculations described below, we used a plasma with uniform temperature, $kT = 5.2$ keV, uniform density, $\rho = 6.0 \times 10^{-4}$ g cm^{-3}, and cyclotron frequency, $\hbar\omega_c = 20$ keV. We also calculated results for $kT = 7$ keV and other densities, but such small variations in the temperature have only a predictable, small effect on the line widths, while variations in the density would affect only the location of the first vacuum frequency which is well below the lowest frequency grid point for the densities of interest. The specific values were chosen so as to afford a comparison with the values of Fenimore *et al.* (1988), Lamb *et al.* (1989), and Wang *et al.* (1989). The most important features of the observed spectrum are the apparent cyclotron lines of roughly equal depth from the continuum at $\sim$20 keV, $\sim$40 keV, and the possibility of a very shallow line at $\sim$60 keV. If indeed these are to be interpreted as cyclotron harmonics, then one must explain why the line at $\sim$40 keV appears to be of similar depth or deeper than that at $\sim$20 keV. It is well known that the cyclotron opacity decreases for increasing harmonic, so that naively one might expect that the deeper line would be $\sim$20 keV. This indicates the importance of scattering with an excited state final electron (see also Harding and Preece 1989 and Wang *et al.* 1989). To show this, several runs were made that included only ground-state to ground-state Compton scattering. None of these runs were able to produce a second harmonic line that was as deep, or deeper, than that at the first. In all cases, it is essential to include Compton scattering with multiple photon emission to achieve the line structure that is observed for gamma-ray burst GB 880205 as shown in Fenimore *et al.* (1988).

The calculated emergent total flux (i.e., summed over polarization modes) for three angles relative to the field direction and a fixed slab thickness, is shown in Figure 1. At all three angles we see, to varying degrees, the general cyclotron line structure that is evident in the observations: deep lines at the first and second harmonic with a much shallower line at the third. For all cases, the line depths are roughly a factor of 2 greater than that observed. The line widths at the first harmonic, FWHM $\sim$ 6 keV, 4 keV, and 2.5 keV for $\theta = 45°$, 60°, and 75°, respectively, agree quite well with the value of 4.1 ± 2.2 keV that is quoted in Fenimore *et al.* (1988). On the other hand, the second harmonic widths, FWHM $\sim$ 8 keV, 6.5 keV, and 3.5 keV for $\theta = 45°$, 60°, and 75°, respectively, are smaller than the reported value of 16.0 ± 4.6 keV. However, the reported observational widths and depths are highly dependent on the choice of function that is used to fit the raw data (as emphasized by Fenimore *et al.* 1988; Lamb *et al.* 1989; and Loredo and Epstein 1989). Short of fitting directly to the raw data, which is not available to us, our fits remain qualitative in nature, but the physical conclusions that can be derived are independent of this fact.

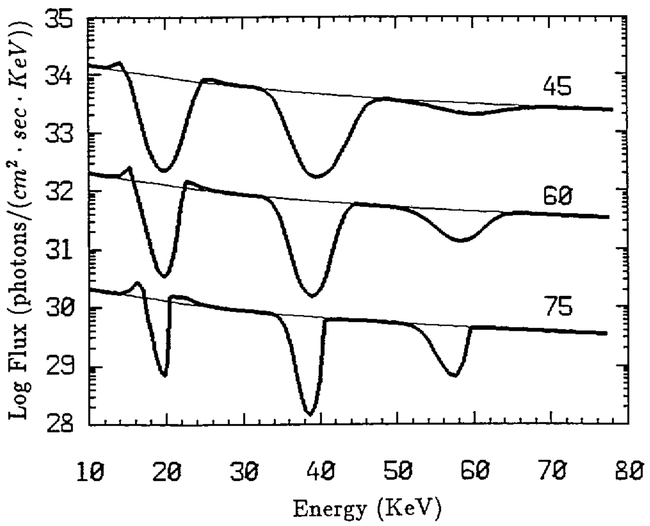

FIG. 1.—Total flux spectra for three angles and slab thickness of 100 cm ($\tau_T \sim 0.024$). For each, the light line is the incident power law spectrum. For clarity, the curve for 45° is shifted up by a factor of 50, while the curve for 75° is shifted down by a factor of 50.

Also in Figure 1, we see the effect of the nonharmonicity of the cyclotron absorption frequencies for relativistic Compton scattering. Including relativistic effects causes the resonant frequency to be slightly less that the integral multiples of ω_c. The relativistic resonances are given by $\hbar\omega = [-m_e c^2 + (m_e^2 c^4 + 2m_e c^2 \hbar\omega_c n \sin^2\theta)^{1/2}]/\sin^2\theta$, where n is the Landau principal quantum number. The location of these resonances is evident in all of the plots in Figure 1. Another relativistic effect, discussed by Wasserman and Salpeter (1980) is seen near the lines at the first harmonic. This is the preferential scattering from the line core to the red wing over the blue wing and causes the slight increase in flux in the red wing of the line.

The width of the line depends on the angle of observation with respect to the magnetic field, θ, and in our code photons are scattered from an angle $\pi - \theta$ to θ and vice versa (notice that this scattering angle is not equivalent to that used by Wang *et al.* 1989, who scatter from isotropic to θ). Our 75° case gives line widths that are too narrow, and there is too much structure at the third harmonic. Howeverer, both the 45° and the 60° cases show adequate agreement with the observed spectrum. The one feature of the 60° spectrum that is not present in the 45° is that the line at $\sim$40 keV, attributed to the second harmonic, is deeper in absolute flux than the first harmonic line. This feature is also apparent in the published fits of the observations. Figure 2 shows the calculated flux for the 60° case for three values of the slab thickness. If the relative depths of the lines as given in Fenimore *et al.* (1988) are a guideline, then the middle curve in Figure 2 for an optical depth, $\tau_T \sim 0.024$, represents a best fit. At lower optical depths, the upper curve indicates that the second harmonic line is not as deep as the observations, while the lower curve shows that at higher optical depths, the third harmonic line is much larger than that observed.

Additional information is contained in the behavior of the individual normal polarization modes. Figure 3 shows the flux spectrum for the best-fit model, 60° and $\tau_T \sim 0.024$, with the

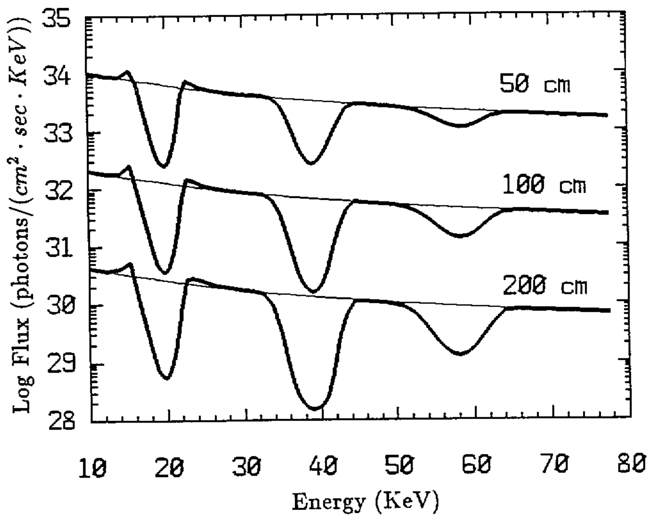

FIG. 2.—Total flux spectra for 60° for three slab thicknesses or Thomson optical depths, $\tau_T \sim 0.012$, 0.024, and 0.048. For each, the light line is the incident power-law spectrum. For clarity, the curve for $R = 50$ cm is shifted up by a factor of 50, while the curve for $R = 200$ cm is shifted down by a factor of 50.

fluxes for the normal modes designated here as mode 1 (extraordinary) and mode 2 (ordinary). The incident spectrum was assumed to be injected as an equal mixture of polarizations, and thus the continuum flux remains unpolarized. However, the flux scattered in the lines becomes significantly polarized. In fact, a calculation for the degree of linear polarization in Figure 3 gives ~30%, ~50%, and ~75% for the lines at ~20 keV, ~40 keV, and ~60 keV, respectively. Since no polarization information is currently available from the observations, this feature remains unchecked; however, we see here a prediction of our model for cyclotron line formation in gamma-ray bursts that could be verified with the proper observations (see Mészáros *et al.* 1988).

IV. DISCUSSION

We have solved the nonlinear differential equation of transfer, using the exact relativistic QED magnetic opacities including polarization of the plasma and the vacuum, spin flip, recoil, thermal effects, stimulated scattering, and resonant multiple photon scattering which occurs when scattering leaves the electron in an excited state. Thus, all of the physics which is currently thought to be relevant is explicitly included. In the present *Letter* we concentrate on what can be learned about the physics of the line formation mechanism, and about the transmission models discussed by Harding and Preece (1989), Lamb *et al.* (1989), and Wang *et al.* (1989). In general terms, our power-law transmission models confirm many of the conclusions reached by these authors on the basis of either a simpler transfer model or simpler cross sections. At the same time, the inclusion of the complete microphysics and a detailed transfer calculation allows us to indicate qualitatively new aspects and some accurate quantitative model predictions concerning the line widths, shape asymmetries and the expected polarization.

The physical mechanism by which the line at the second harmonic may be as deep as or deeper than that at the first is found in the process of Compton scattering with multiple photon emission, as argued by Harding and Preece (1989), Bussard and Lamb (1982), and Fenimore *et al.* (1988). The opacity for scattering from the ground state to the first excited state has a large resonance for $\omega \sim 2\omega_c$ that significantly exceeds the ground-state to ground-state opacity. In addition, the ground to ground process essentially scatters within the line core and for few scatters does not redistribute photons far from $\omega \sim 2\omega_c$. On the other hand, in the multiple emission case, each scattering removes a photon with $\omega \sim 2\omega_c$ and gives two photons with $\omega \sim \omega_c$. Thus, photons at $\sim 2\omega_c$ are depleted, while those at $\sim \omega_c$ are replenished, and the line at the second harmonic becomes deeper, while that at the first becomes shallower. This is why in Figure 2 the depth of the lines at the second and third harmonic appears to depend more sensitively on the optical depth than the ground harmonic. The sheet temperature and optical depth that we require for a good transmission fit are $kt \simeq 5.2$ keV, $\tau_T \simeq 0.024$. The optical depth depends on the angle prescription that is used, and ours is different than that of Wang *et al.* (1989) who get a somewhat different optical depth. They relate the temperature to the characteristic electron inverse Compton temperature in the presence of ~20 keV cyclotron photons. This indicates the validity of their approximate opacities under the present physical conditions of low temperature and low optical depth.

The full benefits of our relativistic polarization-dependent QED opacities and of the Feautrier transfer scheme would arise in circumstances involving higher magnetic field strengths, higher temperatures, and higher optical depths than discussed here. However, a number of finer points concerning even such "moderate" bursts as GB 880205 can be made using the more exact formalism. The line profiles obtained here have the characteristic relativistic asymmetry with a sharper drop in the blue than in the red wing (cf. Mészáros, Bussard, and Nagel 1984; Bussard, Alexander, and Mészáros 1986). The transmitted spectra given in Figures 1–3 show that the blue wing of the ground harmonic accumulates photons which have been scattered out of the lines. This is not apparent at the higher harmonics because of the larger Doppler width and the fact that photons taken from the higher harmonics (which are not exactly "harmonic" because of the relativistic mass shift) reappear preferentially near and slightly below the ground energy. The width of the harmonics increases with harmonic number, which contributes to a progressive decrease in the profile asymmetry. However, this asymmetry can be important also at

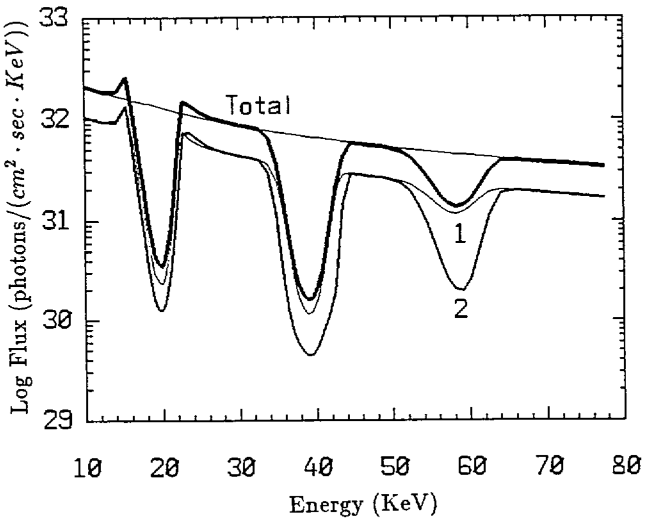

FIG. 3.—Flux spectra with normal polarization modes 1 and 2 for an angle of 60° and slab thickness, $R = 100$ cm ($\tau_T \sim 0.024$). The light line is the incident power law spectrum.

the high harmonic numbers for large photon angles with respect to the magnetic field direction, an effect not apparent in the calculations of Wang *et al.* (1989), which did not include fully relativistic cross sections. For transmission of a power-law continuum which results in first and second harmonics of comparable depth, we expect a third harmonic which is less deep and significantly broader, but nonetheless detectable. The optical depth can be gauged very accurately from the relative depth of the ground and second harmonics. The width of the ground harmonic and the ratio of the ground- to second-harmonic widths can pin down the temperature of the transmitting material and the angle of observation with respect to the magnetic field.

Much remains unclear about the geometry of the emission and absorption region, and about the origin of the radiation. Our present calculations confirm the physical plausibility of a transmission model for the cyclotron interpretation of the GRB events observed by *Ginga*, although they do not prove the astrophysical necessity of this model. The continuum may arise in a hotter region different from that responsible for the cyclotron scattering, although this hot region need not necessarily be distant from the stellar surface, as shown by Mészáros, Bagoly, and Riffert (1989). However, if the continuum does arise farther from the surface, then a thin sheet near the magnetized surface is not the only model possible. Another possibility is one where a continuum arising higher up is reflected by the neutron star surface. Such a high optical depth reflecting surface could also produce cyclotron absorption features. Such a model could be tested by requiring consistency with the X-ray paucity constraint (Imamura and Epstein 1987), and an additional powerful test is provided by the different line polarizations expected from a transmission and a reflection spectrum. Indeed, as seen in our Figure 3, the line polarization is a strong function of the optical depth, and such measurements are currently feasible (Mészáros *et al.* 1988). As discussed in § III, linear polarizations of 30%–75% are expected. In fact, since the polarization degree is also a strong function of the optical depth, angle of observation, and harmonic number, this provides an extremely sensitive test of any model of the cyclotron line region. In conclusion, a transmission model of GB 880205 appears plausible, but clearly much work remains to be done on similar and alternative models before a clear picture of GRBs is achieved.

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