Cyclotron Line Formation in a Relativistic Outflow

Michael Isenberg\textsuperscript{1}, D. Q. Lamb\textsuperscript{1}, and John C.L. Wang\textsuperscript{2}

\textsuperscript{1}Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637
\textsuperscript{2}Department of Astronomy, University of Maryland, College Park, MD 20742-2421

There is mounting evidence that, if gamma-ray bursters are Galactic in origin, they are located in a Galactic corona at distances greater than 100 kpc. This has created a need to explore new models of cyclotron line formation. In most previous calculations the line-forming region was modeled as a static slab of plasma, optically thin to continuum scattering, and threaded by a magnetic field of the order $10^{12}$ gauss oriented normal to the slab. Such a model is appropriate, for example, for the magnetic polar cap of a neutron star with a dipole field. However, if bursters lie at distances farther than several hundred parsecs, the burst luminosity exceeds the magnetic Eddington luminosity, and the plasma in a line-forming region at the magnetic polar cap would be ejected relativistically along the field lines. Mitrofanov and Tsygan have modeled the dynamics of such an outflow, and Miller et al. have calculated the properties of the cyclotron second and third harmonics, approximating them as due to cyclotron absorption. Here we describe Monte Carlo calculations of cyclotron resonant scattering at the first three harmonics in a relativistic outflow from the magnetic polar cap, and show that such scattering can produce narrow lines like those observed by Ginga.

INTRODUCTION

One of the most compelling pieces of evidence that gamma-ray bursts are Galactic in origin is the observation of absorption-like features in the spectra of some bursts and the interpretation of these features as cyclotron lines \cite{1}. In particular, the Ginga observations of three gamma-ray bursts with harmonically spaced lines \cite{2} strongly supports this interpretation. Recent reports of several highly significant line candidates by the BATSE \cite{3} and Konus \cite{4} groups have further heightened interest in cyclotron line formation.

Most theoretical models of line formation in gamma-ray bursts assume physical conditions that are appropriate for burst sources in the Galactic disk. For example, in the model of Wang et al. \cite{5}, the line-forming region is a static slab of plasma, optically thin to continuum scattering, and threaded by a uniform magnetic field $\sim 10^{12}$ gauss oriented along the slab normal. Such a
model is suitable, for example, for the magnetic polar cap of a neutron star with a dipole field. Lamb, Wang, and Wasserman [LWW, (6)] pointed out that if the line-forming region is indeed at the polar cap, the static model is valid only if the bursters lie at distances less than several hundred parsecs. Otherwise, the burst luminosity is sufficient to create a relativistic plasma outflow along the field lines.

However, the BATSE burst brightness and sky distributions (7,8) suggest that if the bursters are Galactic, they lie in a Galactic corona at distances of 100-400 kpc. In light of the BATSE results, it is important to explore line formation models that are appropriate for sources at these distances. One possibility is line formation in a static slab located at the magnetic equator of a neutron star, where the plasma is magnetically confined near the surface (9,10). In the present work, however, we explore another possibility: that the lines are formed in a relativistic outflow.

In an outflow, the variation of the magnetic field and plasma velocity with altitude tends to broaden the lines. Miller et al. (11,12) calculated the properties of the second and third harmonics, approximating them as due to cyclotron absorption. They showed that narrow lines can be formed at these harmonics. Chernenko and Mitrofanov (13) calculated the properties of the first harmonic line, also approximating it as due to absorption, and found that the formation of a narrow line is possible. However, such an approximation is not valid for the first harmonic. Thus the question of whether narrow first harmonic scattering lines can be formed in an outflow has remained open. In the present work we use a Monte Carlo radiative transfer code to calculate the properties of the first three harmonic lines and address this question.

**PHYSICS OF THE LINE-FORMING REGION**

In our model, photons are injected into the line forming region at a circular hot spot, with radius $r_{\text{hot}}$, located on the surface of a neutron star and centered on the magnetic pole. The photons are distributed uniformly over the hot spot and their directions are distributed isotropically. We choose an injected photon number spectrum that varies inversely with photon energy ($dN_{\gamma}/dE \propto E^{-1}$). The field strength decreases with altitude, $z$, as a dipole:

$$B(z) = B_0 \left(1 + \frac{z}{R}\right)^{-3},$$  \hspace{1cm} (1)

where $B_0$ is the field strength at the stellar surface, $R$ is the stellar radius, and $z$ is the altitude above the surface. Although the lines of force in a dipole field flare outwards as the altitude increases, we assume for simplicity that the field lines remain perpendicular to the surface. This is a good approximation for $z \ll R$ and $r_{\text{hot}} \ll R$. Since our Monte Carlo simulations for $r_{\text{hot}} = 0.1R$ show that $> 90\%$ of scatters occur at $z < 0.1R$, we do not expect this assumption to have a significant effect on the emerging spectrum.
The radiation force accelerates an electron-proton plasma to a flow velocity, $\beta_f$, which varies with altitude. Mitrofanov and Tsygan (14) derived the radiation force due to resonant scattering of an electron located above the center of the hot spot. At any given altitude, there is an equilibrium velocity at which the radiation force on the electron, averaged over the energies and directions of the photons, is equal to zero. The equilibrium velocity is:

$$\beta_e(z) \approx \frac{1}{2} \left( 1 + \frac{z}{\sqrt{z^2 + r_{\text{hot}}^2}} \right).$$  \hspace{2cm} (2)$$

An electron injected at the surface with an initial velocity of zero accelerates quickly. From the magnitude of the radiation force, we can estimate the distance the electron travels before reaching $\beta_e$. For a magnetic field strength $B_0 = 1.7 \times 10^{12}$ gauss and an x-ray luminosity between 1 keV and 1 MeV equal to $10^{40}$ ergs s$^{-1}$ (i.e., 1% of the total burst luminosity) the distance to $\beta_e$ is $\sim 10^{-7}$ of the stellar radius. Once the electron reaches $\beta_e$, its velocity continues to increase according to eq.(2) until it reaches an altitude where the radiation becomes too diffuse to provide sufficient energy for acceleration to continue at the rate required by the equation. At this point, the electron’s velocity starts to lag behind the equilibrium velocity. We estimate that this happens at an altitude $\sim$ a few stellar radii. Since most scatterings take place far below this point, we take $\beta_f = \beta_e$ throughout the line-forming region.

We emphasize that we calculate $\beta_e$ using the unscattered radiation spectrum. We have not attempted in the present work to account for the effect on $\beta_e$ of the reduction in photon flux at the cyclotron energy due to scattering.

We assume that in the frame of reference co-moving with the flow the distribution of electron velocities is Maxwellian. LWW showed that the heating and cooling of the electrons by scattering with the radiation balances at the Compton equilibrium temperature, $T_c$. Applying the single-scattering model of LWW to the angular distribution of radiation in the co-moving frame, we find that $kT_c \approx \bar{h}\omega_B/4$, where $\bar{h}\omega_B$ is the cyclotron energy.

For burster distances $\sim 100$ kpc, the time scales for energy and momentum exchange between the electrons and the radiation field are much shorter than the time scale for establishing a Maxwellian electron velocity distribution by particle collisions. The actual electron distribution is therefore likely to be much narrower than a Maxwellian, which would narrow the cyclotron lines in the emerging spectrum. Thus our assumption of a Maxwellian electron velocity distribution in the present calculation is conservative.

Following Miller et al. (11,12), we calculate the density of the plasma as a function of altitude from the continuity equations for conservation of mass and magnetic flux:

$$n_e(z) = n_{e,o} \frac{B(z)}{B(0)} \frac{\beta_f(0)}{\beta_f(z)}$$ \hspace{2cm} (3)$$

where $n_{e,o}$ is the plasma density at the stellar surface.
FIG. 1. Theoretical photon number spectra for \( B_0 = 1.7 \times 10^{12} \) gauss and electron column depth \( n_{e, o} r_{\text{hot}} = 10^{22} \text{cm}^{-2} \). Resonant scattering (solid line) and pure absorption (dashed line) spectra are shown for two viewing angles, \( \theta \) with respect to the magnetic field. Top panels: hot spot radius, \( r_{\text{hot}} = 0.05 R \), where \( R \) is the stellar radius; bottom panels: \( r_{\text{hot}} = 0.1 R \). Narrow absorption-like lines occur for most viewing angles, while broad absorption-like or emission-like features occur when the viewing angle lies along the field.

RESULTS AND DISCUSSION

We calculate the emerging radiation spectrum using a Monte Carlo radiative transfer code similar to the one described by Wang et al. [1]. The code is valid for line forming regions where the cyclotron first harmonic is optically thick in the line core but optically thin in the wings. The cross sections are summed over final and averaged over initial polarizations. We use exact relativistic kinematics and zero natural line width. We include scattering at the first three harmonics and photon spawning.

The emerging spectrum of radiation is shown at two viewing angles in Figure 1. \( r_{\text{hot}} = 0.05 R \) in the top panels and \( 0.1 R \) in the bottom panels. In each case \( B_0 = 1.7 \times 10^{12} \) gauss and the electron column depth \( n_{e, o} r_{\text{hot}} = 10^{22} \text{cm}^{-2} \).

The behavior of the spectra is explained by the high velocity of the plasma, which causes scattered photons to be beamed along the field. Consequently, when the spectra are viewed perpendicular to the field (left panels) the scattered spectra are almost identical to pure absorption spectra. Although we
expect this in the second and third harmonics, it is also the case for the first harmonic. In both spectra, the equivalent widths in the first and second harmonics are $W_{E1} \approx 4.7$ and $W_{E2} \approx 6.2$ keV. By comparison, in GB880205, observed by Ginga, $W_{E1} = 3.7$ and $W_{E2} = 9.1$ keV. The narrowness of the lines is due to the finite radius of the hot spot. Photons redward of the line are normally capable of scattering at high altitudes where the cyclotron energy is smaller, thus broadening the line. However, a photon moving at a large angle to the field escapes through the sides of the cylinder of outflowing plasma before reaching the altitude where it would scatter.

The beaming of scattered photons also accounts for the properties of the lines when viewed along the field (right panels). In Figure 1b, the first harmonic scattering line has been almost entirely filled in, compared with the first harmonic absorption line. Only a shallow line remains. When the hot spot radius is larger (Figure 1d), photons scatter at higher altitudes where the magnetic field strength is smaller. Consequently, scattered photons emerge at lower energies and fill in the absorption line entirely, forming a broad emission-like feature.

Our calculations suggest that a relativistic outflow is able to form cyclotron scattering lines with properties similar to the lines observed by Ginga, provided the hot spot is a small fraction of the stellar surface. In the future we propose to confirm this suggestion by more detailed calculations and a fit of the model spectra to the Ginga observations. If confirmed, our results would imply that the interpretation of the observed features as cyclotron lines does not rule out burst sources in a Galactic corona.

REFERENCES

1. E. P. Mazets et al. 1981, Nature 290, 378.
2. T. Murakami et al. 1988, Nature, 335, 234.
3. M. S. Briggs, 1996, these proceedings.
4. E. P. Mazets et al. 1996, these proceedings.
5. J. C. L. Wang et al. Phys. Rev. Lett. 63, 1550 (1989).
6. D. Q. Lamb, J. C. L. Wang, and I. M. Wasserman, Ap. J. 363, 670 (1990).
7. C. A. Meegan et al. Nature 355, 143 (1992).
8. M. S. Briggs et al. Ap. J., in press (1996).
9. M. Isenberg, J. C. L. Wang, and D. Q. Lamb, submitted to Ap. J. (1996).
10. P. Freeman, submitted to Ap. J. (1996).
11. G. S. Miller et al. Phys. Rev. Lett. 66, 1395 (1991).
12. G. S. Miller et al. Gamma-Ray Bursts: Observations, Analyses, and Theories, Cheng Ho, R. I. Epstein, and E. E. Fenimore, eds., (Cambridge: Cambridge University Press), p. 423 (1992).
13. A. Chernenko and I. Mitrofanov, Isolated Pulsars, K. A. Van Riper, R. Epstein, and C. Ho, eds., (Cambridge: Cambridge University Press), p. 215 (1993).
14. I. G. Mitrofanov and A. I. Tsygan, Astrophys. Sp. Sci., 84, 35 (1982).
15. E. E. Fenimore et al. Ap. J. Lett. 335, L71 (1988).