# Cyclotron Resonant Scattering in the Spectra of $\gamma$-Ray Bursts

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Fits of theoretical spectra from Monte Carlo radiation-transfer calculations to dips at $\approx 20$ and 40 keV in a spectrum of the "classical" $\gamma$-ray burst GB 880205 give best-fit values and 68%-confidence intervals $B=(1.71\pm 0.07)\times 10^{12}$ G, $N_e=(1.2\pm 0.6)\times 10^{21}$ electrons/cm$^2$, and $\mu=\cos\theta=0.31\pm 0.05$, where $\theta$ is the viewing angle relative to the field. Physical self-consistency fixes the temperature and $T_C=5.3^{+0.3}_{-0.2}$ keV. These results suggest that this $\gamma$-ray burst and many others which exhibit a low-energy dip originate from strongly magnetic neutron stars and are galactic in origin.

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$\gamma$-ray bursts were discovered over twenty years ago,[1] yet their nature and origin have remained a profound mystery.[2] Mazets *et al.*[3] reported single low-energy ($E\approx 50$ keV) dips in the spectra of more than 20% of the bursts observed with the Konus experiment on Venera 11-14. Hueter[4] reported single low-energy dips in several bursts observed with the A4 experiment on HEAO-1. These features have been interpreted as due to absorption at the cyclotron first harmonic (fundamental), $\hbar\omega_B\approx 11.6B_{12}$ keV, where $B_{12}$ is the magnetic field strength in units of $10^{12}$ G. They constitute the strongest evidence in favor of a magnetic-neutron-star origin for $\gamma$-ray bursts.[2]

The statistical significance of these low-energy dips is low. Moreover, low-energy dips can be an artifact of the spectral deconvolution and their properties depend sensitively on the assumed form of the continuum spectrum.[5] Consequently, the existence and interpretation of these dips, and therefore the magnetic-neutron-star model of $\gamma$-ray bursts, have remained controversial.

Low-energy dips have recently been seen during certain time intervals in the spectra of two of the $\gamma$-ray bursts detected with the burst detector on the Ginga satellite.[6] These dips are better resolved than previously: They span six or eight detector energy channels, not just one, as in the Konus data.[3] Furthermore, the spectra of both bursts show two dips—not just one, as in the Konus (Ref. 3) and A4 (Ref. 4) data—and the dips are nearly harmonically spaced at $\approx 20$ and 40 keV, as is expected for cyclotron features. Ginga could confidently identify line features with energies as low as 15 keV,[6] lower than in previous $\gamma$-ray observations, making it ideal for detecting first-harmonic cyclotron lines for $B\approx 10^{12}$ G. The single features at 40–60 keV reported by Konus (sensitive to $E\gtrsim 30$ keV) could be *second-harmonic lines,* analogous to the lines at $\approx 40$ keV seen in GB 870303 and GB 880205. Finally, the continuum spectra of both bursts are characteristic of "classical" $\gamma$-ray bursts. In the case of GB 880205, PVO data show that there is substantial emission above 1 MeV,[7] as is typical of classical bursts.

Two aspects of the dips might seem puzzling. First, the dips are narrow, indicating that the scattering medium is much cooler than the typical photon energy $E_\gamma\gtrsim 1$ MeV in the continuum spectrum. Second, the strengths of the dips at the first and second harmonics are similar, despite the fact that the cyclotron resonant scattering cross section decreases rapidly with increasing harmonic number when $B\ll B_c\approx 4.4\times 10^{13}$ G.

Fenimore *et al.*[8] have fit a variety of analytic models to the spectrum for the 5-s interval of GB 880205 labeled (b) in Fig. 2 of Ref. 6. This allows them to assess the statistical significance of the two dips and to provide quantitative estimates of the physical parameters in the scattering region. Using an $F$ test, they found that the (corrected) probability that the six additional parameters needed to describe the dips as Gaussian-line features are unnecessary is $9\times 10^{-6}$ (cf. Ref. 8). Further, they obtained an excellent fit to the spectrum by (1) approximating cyclotron *resonant scattering* as cyclotron *absorption,* which is not appropriate for the first harmonic but is valid for higher harmonics; (2) allowing different column densities for each harmonic; and (3) assuming nonrelativistic kinematics. Their analysis strengthens the cyclotron interpretation of the dips. They find best-fit values and 68%-confidence intervals $B_{12}=1.69\pm 0.04$, $T\mu^2=6.6\pm 2.4$ keV, and (correcting for a factor of $2\pi$) $N_e^{\rm los}(1-\mu^4)\approx 2.4\times 10^{21}$ electrons/cm$^2$, where $N_e^{\rm los}$ is the column density along the line of sight. The quantity $\mu$, which is the cosine of the viewing angle $\theta$ relative to the magnetic field, is effectively not determined by the fit and $T$ and $N_e^{\rm los}$ are therefore poorly constrained.

In this Letter, we calculate the GB 880205 line features from first principles in a particular physical model for the line-forming region. Instead of adopting convenient analytic forms for the line shapes, we compute them using a Monte Carlo radiative-transfer scheme. We then perform direct fits of the theoretical model spectra to the data. Our model offers possible solutions to *both* of the puzzles raised by the properties of the lines (see below).

We model the x-ray spectrum as power-law emission which is altered by cyclotron resonant scattering in a cool isothermal medium of modest optical depth threaded by a superstrong magnetic field. We assume that the x rays must pass through the slab on their way to the observer.[9] We do not address here the appearance and disappearance of the lines. We treat cyclotron resonant line transfer using an expanded Monte Carlo code originally developed to study x-ray emission from accreting magnetic neutron stars.[10] The code uses resonant cross sections derived quantum mechanically in the weak-field limit. It includes relativistic kinematics, finite natural linewidth, the first three harmonics, and photon spawning (see below). It averages over photon polarization, which is a good approximation as long as $[n_e/(10^{22}\ \text{electrons/cm}^3)]B_{12}^{-4} \lesssim 1$.[10] Both the code and the resulting spectra are described fully elsewhere.[11]

In our calculations, the temperature of the line-forming region is determined self-consistently by the requirement that there is no net energy input from the incident photon flux (or any other source) to the slab. Lamb, Wang, and Wasserman[12] argue that the line-forming layer is moderately optically thick to cyclotron resonant scattering but optically thin in the continuum. The thermal balance of such a layer is dominated by heating and cooling primarily due to cyclotron resonant scattering. The layer will reach an equilibrium temperature $T_C$ on the short time scale $t_C \lesssim 10^{-8}$ s for typical burst-source parameters such as those for GB 880205. Since it is the relatively low-energy photons near the cyclotron first harmonic (not the more plentiful high-energy continuum photons) that dominate the heating and cooling, typically $kT_C \lesssim \hbar\omega_B$ in the line-forming region. Resonant cyclotron scattering in this thin, comparatively cool region produces narrow dips.

We interpret the dips observed at $\approx 20$ keV in the spectra of GB 870303 and GB 880205 as cyclotron *resonant scattering,* in which electrons undergo radiative $0 \rightarrow 1 \rightarrow 0$ Landau transitions initiated by photons near the first harmonic $\hbar\omega_B$.[8,10] No simple description can be used to explain the appearance of this line which depends critically on the outcome of the multiple resonant scatters which individual photons undergo before escaping,[10,13] as well as on the introduction of new photons which are "spawned" at energies near $\hbar\omega_B$ by Raman scattering at higher harmonics,[13] as described below.

We attribute the dips at $\approx 40$ keV to *Raman scattering,* in which electrons undergo $0 \rightarrow 2 \rightarrow 1 \rightarrow 0$ radiative transitions initiated by photons with energies near that of the second harmonic $(2\hbar\omega_B)$.[8,11] Resonant scattering of second-harmonic photons, in which electrons undergo ra-

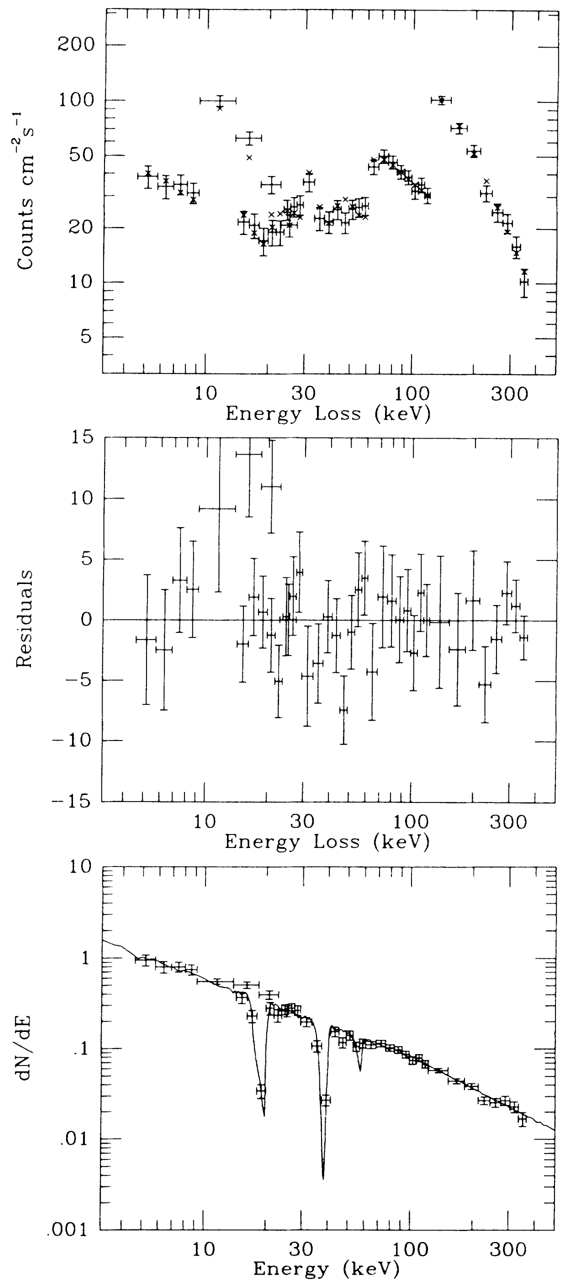


FIG. 1. Top: observed count-rate spectrum (crosses) and best-fit theoretical count-rate spectrum (crosses) for the 5.0-s interval of GB 880205 labeled (b) in Fig. 2 of Ref. 6, for the proportional counter and scintillation counter on Ginga. Middle: residuals. Bottom: best-fit theoretical photon-number spectrum (solid curve) and inferred Ginga photon-number spectrum (crosses) (Ref. 23).

diative $0 \rightarrow 2 \rightarrow 0$ Landau transitions, is rare since $B/B_c \ll 1$;[14] when it does occur, we treat it using the same formalism we use for the first harmonic. Because most of the photons which undergo scattering at the second harmonic are destroyed, the resulting line feature is approximately that for absorption.[8] This is a general property of higher-harmonic cyclotron lines when the magnetic field strength $B \ll B_c$. There is no observable dip at $\approx 60$ keV in GB 880205 because the third harmonic is optically thin.

We compare the spectrum expected from cyclotron resonant scattering to the spectrum observed in interval (b)[6,8] of GB 880205 as follows. We first fit the x-ray continuum outside the first- and second-harmonic line features using an analytical broken power-law form, $N(E) = A(E/E_b)^{-\alpha}$, for the photon-number spectrum. We take the detector response function to be that for an angle of 37° between the direction of the burst source and the normal to the detectors, the same as assumed in Fenimore *et al.*[8] We find best-fit parameter values $A = 0.08$ cm$^{-2}$s$^{-1}$keV$^{-1}$, $E_b = 101.3$ keV, and $\alpha = 0.846$ ($1 \leq E \leq 101.3$ keV) and 1.174 ($101.3 \leq E \leq 1000$ keV), with $\chi^2 = 14.2$ for 23 degrees of freedom. We then inject photons with this spectrum isotropically into a slab with constant $B$, $T_C$, and $N_e$ ($= \mu N_e^{\rm los}$), with the slab normal parallel to **B**. We follow the resulting cyclotron resonant line transfer with the Monte Carlo code.

Using more than 100 Monte Carlo spectra, each with $(1\text{-}3) \times 10^6$ photons, and folding these spectra through the Ginga detector response functions, we do $\chi^2$ fits to the observed photon count-rate spectrum. We find best-fit values and 68%-confidence intervals $B = (1.71 \pm 0.07) \times 10^{12}$ G, $N_e = (1.2 \pm 0.6) \times 10^{21}$ electrons/cm$^2$, and $\mu = 0.31 \pm 0.05$, with $\chi^2 = 43.9$ for 36 degrees of freedom $[P(>\chi^2) = 0.17]$.[15] This value of $\chi^2$ is uncertain by $\pm 1.5$ due to the finite number of photons in the Monte Carlo spectra. The resonant cyclotron Compton temperature is *not* a free parameter, but is fixed by the model to be $T_C = 5.3^{+0.3}_{-0.2}$ keV. Figure 1 shows the predicted and observed photon count-rate spectra, the residuals, and the incident photon-number spectrum for the best-fit parameters. Figure 2 shows the 68.3%-, 95.4%-, and 99.7%-confidence regions in $(B, N_e, \mu)$ space.[16]

Within its model assumptions (isothermal plane parallel slab with constant **B**), this work provides a physically self-consistent model for the formation of the narrow cyclotron scattering features seen in $\gamma$-ray burst spectra. It demonstrates that cyclotron resonant and Raman scattering can account for the positions and shapes of *both* dips in the spectrum of GB 880205, including their narrow widths and comparable strengths. It provides stronger evidence that a superstrong magnetic field ($B \approx 2 \times 10^{12}$ G) exists in the source of this burst.[6,8] Taken together with the Konus data,[3] which show low-energy dips in more than 20% of all classical $\gamma$-ray bursts, this work suggests that superstrong magnetic fields exist in many $\gamma$-ray-burst sources. If this suggestion is indeed correct, it is powerful evidence that these $\gamma$-ray bursts originate from strongly magnetic neutron stars. These neutron stars must belong to the Galaxy, resolving a long-standing controversy about the distance to $\gamma$-ray-burst sources.

The magnetic fields of many neutron stars have been

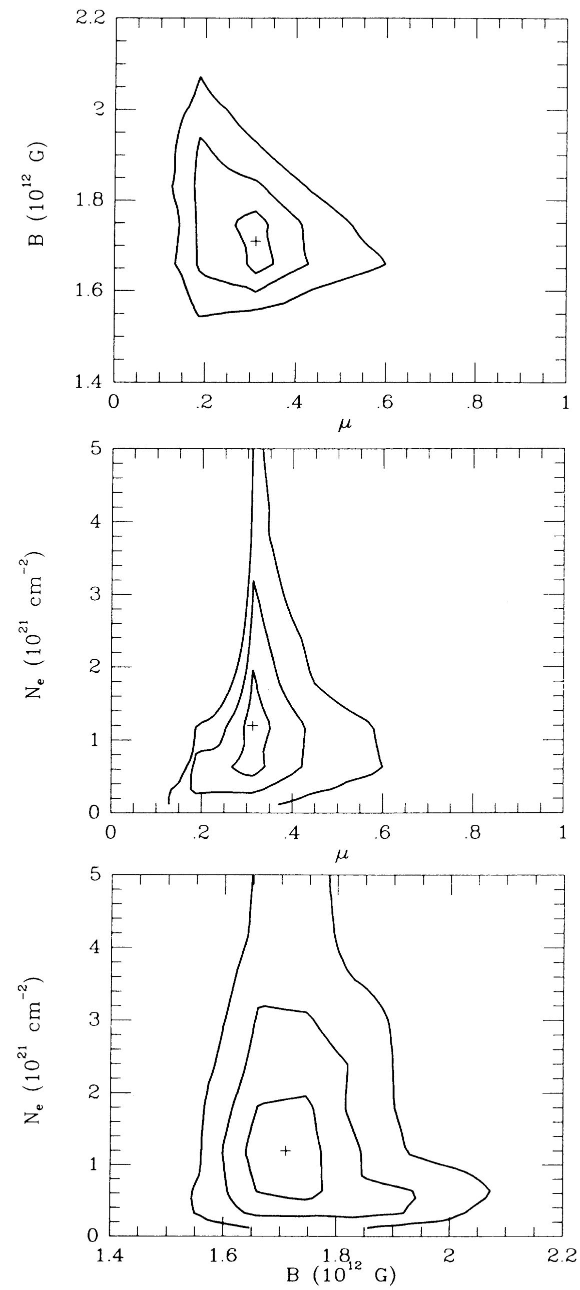


FIG. 2. The 68.3%-, 95.4%-, and 99.7%-confidence regions for $B$, $N_e$, and $\mu$ determined from fits to the middle 5.0-s interval of GB 880205. Top: projected in the $(\mu, B)$ plane. Middle: projected in the $(\mu, N_e)$ plane. Bottom: projected in the $(B, N_e)$ plane.

measured indirectly, e.g., through the spin-down rate of rotation-powered pulsars[17] and through the spin behavior of accretion-powered pulsars.[18] However, the magnetic field strengths of only three neutron stars have been measured directly previously: those of the accretion-powered pulsars Her X-1, 4U0115+63, and 4U1538 −52, which all show cyclotron-scattering features in their x-ray spectra.[19] Plausibly, x-ray observations of $\gamma$-ray bursts may provide direct, and therefore accurate, measurements of the magnetic fields of many more neutron stars than has any other method.

If $\gamma$-ray bursts originate from magnetic neutron stars which lie at distances of $\lesssim 300$ pc, as several physical arguments suggest,[12,20] some of these neutron stars must be much older than $2\times 10^7$ years. This follows from comparing the number of distinct $\gamma$-ray sources now known and the birth rate of neutron stars.[21] Such a conclusion would contradict the conventional wisdom that the surface magnetic fields of neutron stars decay on a time scale $\tau_{decay} \lesssim 2\times 10^7$ years.[22]

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[15]The value of $B$ is not corrected for gravitational red shift. Comparison between the theoretical and observed spectra can, in principle, determine the gravitational red shift (or blue shift) of the line-forming region. However, the resolution of the current data is insufficient to give meaningful constraints.

[16]These confidence regions do not preclude significant variations in **B** through the scattering region, nor significant variations in $\mu$ (e.g., due to rotation). The widths of the cyclotron-scattering features could be larger than appear in Fig. 1 (bottom) as a result of such variations (cf. Ref. 8). We are exploring the constraints on such variations imposed by our model and the data.

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[23]In Fig. 1 (top), the horizontal error bars of the data points indicate the energy-loss range of the photons which contribute to that channel. The marked discontinuities in the count-rate spectra arise from changes in the size of the energy-loss range. In Fig. 1 (bottom), the vertical positions and error bars of the data points correspond to the theoretical spectrum multiplied by the ratio of the observed and theoretical count-rate spectrum at that energy, and are therefore model dependent. The horizontal positions of the data points correspond to the detector-energy-channel centers and the horizontal error bars show the amount of photon energy loss corresponding to that channel, and do not measure the spectral resolution of the detector; the actual spectral resolution of the detector is significantly worse.