Cyclotron Lines in γ-Ray Burst Spectra: Absorption in a Radiation-Driven Wind

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Previous models of cyclotron-line features in the spectra of cosmic γ-ray bursts have assumed that the lines form in a thin, static atmosphere. Here we show that the observed absorption lines may in fact form in a radiation-driven plasma wind expelled at relativistic velocities from the surface of a neutron star.

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Discoveries of cyclotron-line features in the spectra of several cosmic γ-ray bursts[1-4] provide strong evidence that the bursts are associated with neutron stars which have surface magnetic fields $B_s \sim 10^{12}$ G. Previous investigators assumed that the cyclotron lines form in a static magnetized plasma atmosphere.[4-7] Their computed line profiles were consistent with the data for restricted values of B_s, angle of observation, and electron column density. However, for static models to be plausible the outward radiation force on the absorbing plasma must be less than the gravitational force,[8] limiting the possible burst luminosity L: If the plasma is ionized hydrogen, then $L \lesssim 10^{36}$ erg s^{-1}, or if it is largely composed of electron-positron pairs, $L \lesssim 10^{32}$ erg s^{-1}. The former limit requires that the observed γ-ray bursters be closer to the Earth than ~ 100 pc, and the latter limit places them too close to be consistent with a stellar origin.

We show here that acceptably narrow absorption lines can form in a relativistic, radiation-driven wind. Although one might expect that lines formed in such a wind would be considerably broadened, it is the velocity dispersion and magnetic-field variation in the line-forming region which broaden the line, not the wind velocity itself.

We consider a planar model in which the field strength B, plasma temperature T, and flow velocity $v_f \equiv \beta_f c$ vary only with height z above the γ-ray-emitting region, which is assumed to be near the stellar surface. This planar approximation is consistent if (as we find to be the case) most of the absorption occurs in a distance $\ll R$, where R is the stellar radius. Although the model is planar and the magnetic field points only in the z direction, we take the field strength to have a dipolar dependence on height: $B(z) = B_s(1+z/R)^{-3}$. Similarly, the electron and/or positron density is taken to vary as $n_e(z) \propto B(z)/v_f(z)$. It is assumed that new plasma constantly enters the flow from the γ-ray-producing region at $z=0$ and that pair annihilation is negligible. More realistic and complex calculations (e.g., including general relativistic effects) are not warranted at this stage because the actual geometry of a γ-ray burst source is so uncertain.

An electron with no momentum along the z axis has quantized energy levels $E_n = mc^2(1+2nb)^{1/2}$, where $b \equiv \hbar|eB|/m^2c^3 = 0.0227B/(10^{12}\text{ G})$ is the electron cyclotron energy E_{cyc} in units of the electron rest energy mc^2, e is the electron charge, and n is a non-negative inte- ger. Since the radiative lifetimes of excited states ($\sim 10^{-15}[(10^{12}\text{ G})/B]$ s) are short compared to the expected excitation time scales, the electrons lie mainly in their ground state, $n=0$. Furthermore, excitations are typically followed by radiative deexcitations in which n drops by 1, so that photons which excite an electron from the ground state to $n \geq 2$ (*second or higher harmonic* photons) are not replenished by deexcitation; these photons may be regarded as destroyed. By contrast, photons which excite $0 \to 1$ transitions scatter resonantly. (Reference 4 used similar approximations to describe the formation of $n \geq 2$ lines in *static* atmospheres.) Here we treat only $n \geq 2$ lines, reserving line formation by resonant scattering for a separate paper.

The absorption-line profile calculation has two parts. First, the wind-velocity profile is derived by considering the radiation force on the wind plasma in a prescribed radiation field. Second, given the velocity profile and an assumed wind-temperature profile, the probability that a photon of a given momentum escapes the wind is computed.

We assume that radiation force on the plasma greatly exceeds the gravitational force, so that the condition that the net radiation force on the scatterers vanishes in an inertial frame moving with the flow determines the flow velocity.[9] Photons overtaking the plasma lose momentum to the flow, but photons moving at sufficiently large angles to the flow direction are overtaken by the flow and extract momentum from it. If the photons driving the wind travel in a range of angles $\theta \leq \theta_0$ to the z axis, photon speeds parallel to the z axis are all $\geq c\cos\theta_0$ and the wind velocity satisfies $\beta_f \geq \cos\theta_0$.

We calculate the radiation force by introducing an inertial frame called the "c frame" which moves along the z axis at speed $c\beta_c$. In the c frame, the total momentum along the z axis of an electron and the photon with which it collides is zero. The polarization-averaged cross section in the c frame for an electron in the ground state

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to be excited to the nth Landau level is

$$\sigma_{n,c}(E_c,\mu_c)=s_n(1+\mu_c^2)(1-\mu_c^2)^{n-1}b^{n-1}\delta(E_{t,c}-E_n) \quad (1)$$

in the nonrelativistic approximation (appropriate when $b \ll 1$), where $\mu=\cos\theta$, E is the photon's energy, μ_c and E_c are the corresponding quantities in the c frame, $E_{t,c}=E_c+(\mu_c^2E_c^2+m^2c^4)^{1/2}$ is the total c-frame energy of the electron and photon, and

$$s_n=2\pi^2\frac{\hbar e^2}{mc}\frac{(n^2/2)^{n-1}}{(n-1)!} \quad (2)$$

depends only on n. The c-frame cross section is related to the stationary-frame cross section by

$$\sigma_n(E,\mu)=(1-\mu\beta_c)\sigma_{n,c}(E_c,\mu_c)\,. \quad (3)$$

For $b \ll 1$, the $n=1$ cross section is much larger than for second harmonic and higher excitations; we thus adopt the simplifying assumption that $0 \rightarrow 1$ collisions predominantly determine the radiation force on the wind. The wind velocity is then determined by finding the average momentum transferred to an electron of velocity v in collisions with photons of energy E and direction cosine μ, multiplying by the stationary-frame cross section and photon distribution function, and integrating over E and μ to get the average radiation force on the electron as a function of its velocity. The root of this function is the flow velocity v_f.

We approximate the photon distribution function f by treating the γ-ray source as an isotropically emitting luminous disk of radius D at the stellar surface and ignoring the effects of photon scattering in the wind; the number flux of photons is nonzero only for direction cosines greater than $\mu_0(z)=z(D^2+z^2)^{-1/2}$. We assume the incident photon spectrum to be a power law in photons per energy interval. The distribution function is thus

$$f(E,\mu;z)\propto E^{-\alpha}\Theta(\mu-\mu_0)\,. \quad (4)$$

We find that the resulting flow velocities are insensitive to α; when $\alpha \sim 1$, the flow velocity $c\beta_f$ is approximately equal to the mean photon velocity parallel to the z axis, $c(1+\mu_0)/2$. We estimate that the corrections to β_f due to multiple photon scattering are of order of the ratio of the mean free path of the repeatedly scattered photons to the characteristic acceleration length scale: $v_{\text{thermal}}/c\tau_1 \sim 0.1$ for the case of interest here; τ_1 is the optical depth of the fundamental [see Eq. (7) below].

Now consider the photon spectrum at energies above the fundamental line. Since these photons are destroyed by their interactions with the wind, the spectrum seen by an observer who looks down onto the source at an angle θ to the vertical is

$$S_{\text{obs}}(E,\mu)=f(E,\mu;0)\exp[-\tau(E,\mu)]\,, \quad (5)$$

where $\tau(E,\mu)$ is the wind's optical depth. The energy of the photons absorbed at any height z in the wind depends on the local magnetic-field strength and distribution of electron velocities. To absorb photons of energy E and direction cosine μ, electrons at height z must have one of the two velocities $c\beta_\pm(z)$ given by the roots of

$$E^2\frac{1-\mu^2}{2}+Emc^2\frac{1-\mu\beta}{(1-\beta^2)^{1/2}}-m^2c^4nb(z)=0\,. \quad (6)$$

A warm wind with a wide distribution of electron velocities absorbs photons from a range of energies at each height. The electron velocities $v'\equiv c\beta'$ in the frame comoving with the wind are in a one-dimensional Maxwellian thermal distribution $F_{\text{th}}(\beta';z)$ characterized by temperature $T(z)$. The competition between heating and cooling by resonant photon scattering determines the electron temperature $T(z)$, so that[8] $k_BT(z)/mc^2 \approx b(z)/4$. The velocity distribution $F_v(\beta;z)$ in the stationary frame is $F_v(\beta;z)=F_{\text{th}}(\beta';z)\partial\beta'/\partial\beta$.

With the preceding definitions the contribution to the optical depth of the wind by $0 \rightarrow n \geq 2$ absorptions is

$$\tau_n(E,\mu)=\int_{-1}^{1}d\beta\int_0^\infty\frac{dz}{\mu}n_e(z)F_v(\beta;z)\sigma_n(E,\mu;z,\beta)\,. \quad (7)$$

We numerically evaluate this to produce line profiles. Figure 1 shows calculated second-harmonic ($n=2$) line profiles, with the energy given in units of the cyclotron energy at the stellar surface. The underlying continuum spectrum is taken to be a power law [Eq. (4)] with $\alpha=1$. The electron density $n_e(0)$ has been adjusted so that each line has unit optical depth at its deepest point.

Several characteristics of wind-formed lines may be understood without recourse to the full line profiles described by Eq. (7). The mean energy of the photons absorbed at height z is

$$E_a(\mu,z)\approx\frac{[1-\beta_f^2(z)]^{1/2}}{1-\mu\beta_f(z)}nb(z)mc^2\,. \quad (8)$$

Since the probability that a photon is absorbed decreases with decreasing electron density and magnetic-field strength, both of which diminish with increasing height

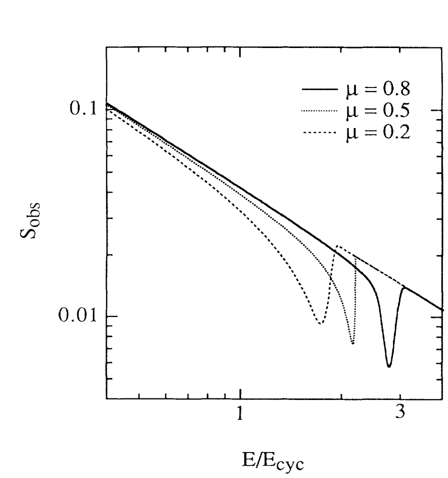

FIG. 1. Second-harmonic ($n=2$) line profiles calculated with Eq. (7), as seen from a variety of viewing angles.

in the wind, the deepest part of the line forms near the base of the flow. Higher regions in the wind absorb photons of lower energy, and an asymmetric line is produced with a comparatively deep and sharp high-energy edge. Given a velocity profile $\beta_f \sim (1+\mu_0)/2$, the line is deepest at an energy

$$E_d \approx E_a(\mu,0) \approx (10\,\text{keV}) \left[\frac{B}{10^{12}\,\text{G}}\right] \frac{n}{1-0.5\mu} . \quad (9)$$

Both the thermal dispersion of electron velocities at a given height in the wind and the variation of the mean absorbed energy $E_a(\mu,z)$ with height contribute to the linewidth. The variation of E_a with height has its smallest effect on the linewidth when $\partial E_a(\mu,z)/\partial z$ vanishes at the base of the flow ($\mu \approx 0.8$ with the assumed velocity profile and $D=0.1R$). At this viewing angle the linewidth is dominated by the thermal width and the asymmetry of the line is least pronounced. The thermal broadening of the line is minimized when $\partial E_a(\mu,0)/\partial\beta_f(0) \approx 0$, which occurs at $\mu = \beta_f(0) \approx 0.5$. At this viewing angle the photons seen move perpendicular to the field in the frame comoving with the plasma at the base of the wind.

Observers looking down along the field see a line with a full width at half maximum $\Delta_{\text{FWHM}}/E_d \approx 0.2$ due mainly to thermal broadening and *narrower* than the values $\Delta_{\text{FWHM}}/E_d \approx 0.4$ Fenimore *et al.* report.[4] It is important that the lines produced by our idealized model may be narrower than those observed, since in a more realistic model the wind might emanate from a significant fraction of the stellar surface and the line profile would be broadened by variations in the magnetic-field strength and the viewing angle. Figure 1 demonstrates how the line center energy varies with viewing angle; the line energy is greatest at small angles and decreases at angles farther from the vertical in accordance with Eq. (9).

Using Eq. (7), we have fitted the Ginga spectral data for GB880205 previously fitted[4,7] with static atmosphere models. Data points influenced significantly by the fundamental line were not utilized (the seven bins between 16 and 24 keV), since we only model the higher harmonics. The fit to the continuum is taken from Ref. 4. For a fixed μ, the parameters B_s and $n_e(0)$ were allowed to vary to minimize χ^2. Acceptable χ^2 were obtained for all values of μ in the range $\sim$0.02–0.95. Figure 2 shows fits for four representative values of μ: 0.05, 0.3, 0.6, and 0.9; the fits have $\chi^2 = 27.6$, 27.9, 28.3, and 28.6, respectively, for 29 degrees of freedom. Without a calculation for the fundamental, μ is not effectively constrained. The resulting magnetic-field strengths $B_{12} = B_s/(10^{12}\text{ G})$ and electron column densities along the line of sight $y_{20} = \mu^{-1}\int n_e\,dz/(10^{20}\text{ cm}^{-2})$ are indicated. Our model allows $1.0 \le B_{12} \le 2.4$. Typical values of y are close to those found by workers using static models.[4,7]

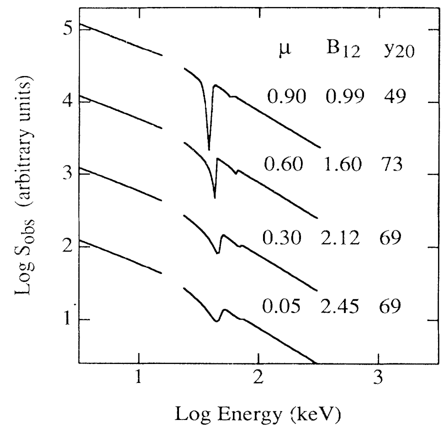

FIG. 2. Fit of the wind model to observations by the Ginga satellite of cyclotron lines in the γ-ray burst GB880205. All of the displayed profiles are statistically acceptable fits to the data. Note the presence of a weak third-harmonic line.

In summary, lines which form in a radiation-driven wind are sufficiently narrow to be consistent with current observations. Wind models are an attractive alternative to models utilizing static atmospheres, since they avoid the strong constraint that radiation forces not expel the atmosphere. Since the line shapes and energies depend on the wind-velocity profile and the angle from which the wind is viewed, it may be possible to deduce these quantities with future high-resolution observations of γ-ray burst spectra.

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