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Analysis of Gamma Ray Burst Spectra With Cyclotron Lines

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ABSTRACT

Motivated by the recent developments in the cyclotron resonance upscattering of soft photons or CUSP model of Gamma Ray Burst (GRB) continuum spectra, we revisit a select database of GRBs with credible cyclotron absorption features. We measure the break energy of the continuum, the slope below the break and deduce the soft photon energy or the electron beam Lorentz factor cutoff. We study the correlation (or lack of) between various parameters in the context of the CUSP model. One surprise result is that there appears to be marginal correlation between the break energy and the spectral index below the break.

1 INTRODUCTION

Discovery by the GINGA satellite of double cyclotron absorption features in the spectra of cosmic gamma ray bursts (Murikami et al 1988, Fenimore et al 1988) confirms earlier results of the KONUS experiments (Mazets et al 1981, Golenetskii et al 1986) that at least a fraction of these impulsive events may be associated with strongly magnetized (teragauss field) neutron stars. The presence of such strong fields in the GRB emission region, coupled with the lack of x-rays and lack of magnetic pair production absorption out to > 10 MeV from SMM data have motivated a number of authors to invoke the so-called CUSP mechanism in which soft photons emitted near the stellar surface are upscattered with the resonance cross section by outward streaming relativistic electrons and pairs (e.g. Hameury et al 1985, Daugherty and Harding 1986, Dermer 1989, 1990, Vitello and Dermer 1991, Ho et al 1990, Ho and Epstein 1990, Fenimore 1990). While this model still faces many difficulties in explaining the universal features of the GRB continuum, the simplicity and predictive power of this model make it worthy of more careful confrontations with the observed database. In this paper we reexamine a subset of GRB spectra containing cyclotron features in the context of the CUSP model.

An important feature of this model is that it predicts the spectral break at a few hundred keV observed in most GRB spectra (see e.g. Liang 1987, Hurley 1989 for review). This break is associated with the resonance condition that in the electron rest frame the Lorentz boosted photon must have an energy equal to the cyclotron energy. More specifically, if the electrons form a thin target or non-cooling distribution with power law index p, then the upscattered photon spectrum is flat at low energies and breaks into a power law of photon index p+2 above an energy $E_{bk}=2\ E_B^2/E_o$ where E_B is cyclotron energy at rest and E_o is the soft photon energy (Dermer 1989). But, if the electrons form a thick target or cooling distribution then a break occurs above $2E_B$ only if the injected electron spectrum has a low energy cutoff. In this case the break energy is given by $E_{bk} = 2E_B\,\gamma_o$ where γ_o is the cutoff Lorentz factor. The photon index below the break is equal to 1 instead of zero and the index above the break is equal to p instead of p+2 (cf. Dermer 1990, Vitello and Dermer 1991). Hence, the spectrum would have a photon index of either 0 or 1 from roughly from the cyclotron energy to the break energy. Obviously the observed spectra rarely have indices exactly equal to 1 or 0 (e.g. Mazets et al 1981). Such variation in the low energy spectral index can conceivably be due to the superposition of electron energy cutoffs and soft photon energies which vary in space and time. Then the observed break would correspond to the minimum soft photon energy or the maximum electron energy cutoff in the composition. Note, however, that for observed indices flatter than 1 below the break, they can only be synthesized from the superposition of thin target spectra, while indices equal to or steeper than 1 can be due to thin or thick target.

It is important to realize that in CUSP type model, the electrons are nonthermal and relativistic and the spectral break is determined by both the magnetic field strength and the characteristic soft photon energy or electron cutoff Lorentz factor. This is in contrast to thermal models in which the or color temperature (which in most cases is roughly determined by the break energy) is a direct measure of the characteristic emitting electron energy. Thus a spectral break at a few hundred keV would require only mildly relativistic thermal electrons but would require electron beams with Lorentz factor > few in the CUSP model if the field strength is ~ 2 teragauss.

If the CUSP framework is valid to first order, then we expect a study of the correlation or anticorrelation of the various spectral parameters, including the field strength, break energy, spectral indices etc may shed light on the particle energization mechanism and optical depth issues. In this paper we present some preliminary results based on the analysis of a subset of GRB spectra containing credible cyclotron features.

2 METHODOLOGY AND APPROACH

Among all the GRB spectral data in the published literature, we have selected a dozen events for the current study. These include ten events from the KONUS catalogue (Mazets et al 1980, 1982), one from HEAO-1 (Heuter 1988) and one from GINGA (Murikami et al 1988). The criteria for selecting this subset are:

a) We choose only events in which the cyclotron line appears most prominent (say greater than 2- σ).

b) We choose only events in which the continuum has a cleanly defined spectra break above $2E_B$. A separate group of events, which show no spectral break above the cyclotron features out to the detector limit, notably examplified by the HEAO-1 event GB780325 if we identify the observed absorption feature as the second harmonic (Hueter 1987), may be interpreted as due to thick target electrons without a low energy cutoff. They will be treated separately.
c) We choose only events in which the continuum has the best statistics (smallest error bars) and the slope below the break is well defined.
d) We use only spectra published as deconvolved photon spectra. Hence the other GINGA events with cyclotron lines but with only published raw count spectra cannot be used here.

From this database we extract the field strength from the apparent line center (no correction for gravitational redshift, optically depth or field gradient effects), the break energy from the intersection of the low energy power law and high energy power law, and the spectral index below the break from a straight line fit to only those data points lying between the cyclotron feature and the break. In almost all cases this break is defined as the peak power energy at which E^2x photon number spectrum is maximum. However, in GB790622 and 880205, the spectrum has a clean break between two power laws even though the index is flatter than 2 everywhere. We decide to adopt this break for the CUSP interpretation.

The $1-\sigma$ error reported for the spectral index below the break is estimated from minimum chi-square fit procedures. The error for the break energy corresponds to the width of the channels nearest the intersection of the low and high energy power laws, while the error for the cyclotron energy corresponds to the channel width of the apparent line center.

From the break energies we estimate the soft photon energy by the formula: $E_o = 2\,E_B^2/E_{bk}$ and the electron cutoff Lorentz factor: $\gamma_o = 2\,E_{bk}/E_B$ (Dermer 1990). Results for these parameters and studies of their correlations are reported in the next section.

3 RESULTS OF ANALYSES

Table I is a summary of the derived parameters for all twelve GRBs which we judge best satisfy criteria a) - d) of section 2. In the column for the cyclotron energy, the first number is obtained assuming that all observed features above 40 keV are second harmonics (with the first harmonic lying below detector limit), while the second number is obtained assuming that all observed features are first harmonics except for the GINGA event. The two numbers in the other columns correspond to these choices.

In Table II we list three additional bursts which, while satisfying conditions a), c) and d) of section 2, have no spectral break out to detector limit. These could mean that either the break energy lies above the detector limit, or that the electrons are thick target down to Lorentz factor unity without a low energy cutoff. The numbers in the columns correspond to adopting the first assumption.

Table I. Parameters of GRB with both cyclotron feature and break.

GRB*	E_B(keV)	E_{bk}(keV)	γ_0	E_0(keV)	α(Spectral Index)
780608	32/63 ± 8	610	9.7/4.8	3.4/13.4	1.75 ± 0.15
781113	27/53 ± 8	140	2.6/1.3	10/40	1.06 ± 0.21
781117	27 ± 6	350	6.6	4.0	1.23 ± 0.17
790307	25/50 ± 8	400	7.8/3.9	3/12	1.22 ± 0.03
790323	33/66 ± 10	160	2.4/1.2	14/56	1.09 ± 0.32
790329	24/48 ± 8	300	6/3	3.8/15	1.19 ± 0.07
790402b	25/50 ± 10	280	5.6/2.8	4.4/17.8	1.20 ± 0.20
790524	28 ± 6	112	2.0	14	1.12 ± 0.12
790610	21/41 ± 6	120	3.0/1.5	7.3/29	0.9 ± 0.2
790612	23/46 ± 10	150	3.3/1.6	7.1/28	1.23 ± 0.28
790622	25/49 ± 8	220	4.4/2.2	5.7/23	1.02 ± 0.05
880205	20	101	2.5	8	0.85

780608 from HEAO1, 880205 from GINGA, all others from KONUS

TABLE II. Parameters of GRB with cyclotron feature but no break.

GRB*	E_B(keV)	E_{bk}(keV)	γ_0	E_0(keV)	α
780916	32 ± 7	>500	>8	<4	1.58 ± 0.14
781012b	34 ± 7	>400	>6	<5.8	1.85 ± 0.14
780325	28/56 ± 15	>5000	>90/45	<0.3/1.2	1.75 ± 0.15

*780325 from HEAO1, others from KONUS

In Figures 1-3 we show the spectral shapes of three of the twelve bursts with the best statistics. The solid straight lines correspond to the best power-law fit to the spectrum between the break and the absorption feature. Figures 4-5 are scatter plots of break energy versus cyclotron energy and spectral index for the twelve bursts plus limits for the KONUS bursts of Table II. Figures 6-7 are similar plots of γ_0. Figure 8 is a scatter plot of soft photon energy versus spectral index assuming that all observed features above 40 keV are second harmonics.

We see that there is no obvious correlation with E_B in any of the scattergrams. There is marginal correlation between break energy (and correspondingly γ_0 and E_0) and spectral index: <u>the higher the break energy,</u>

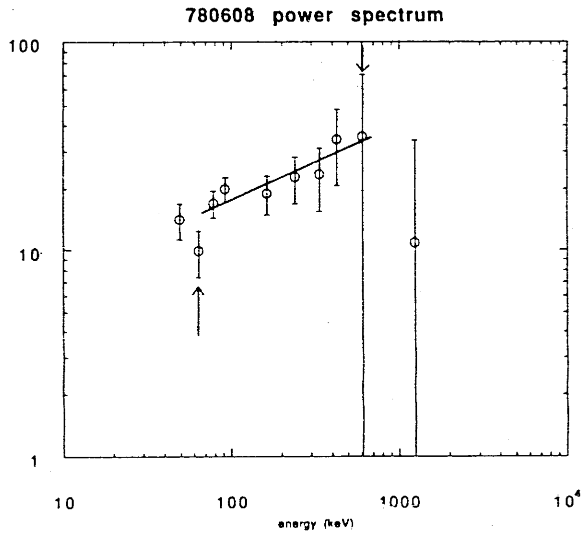

Fig. 1: Power (per decade of energy) spectrum for GB780608. Arrows indicate E_B and E_{bk}. Straight line is best fit to data between E_B and E_{bk}. For channel widths, please refer to Heuter (1988).

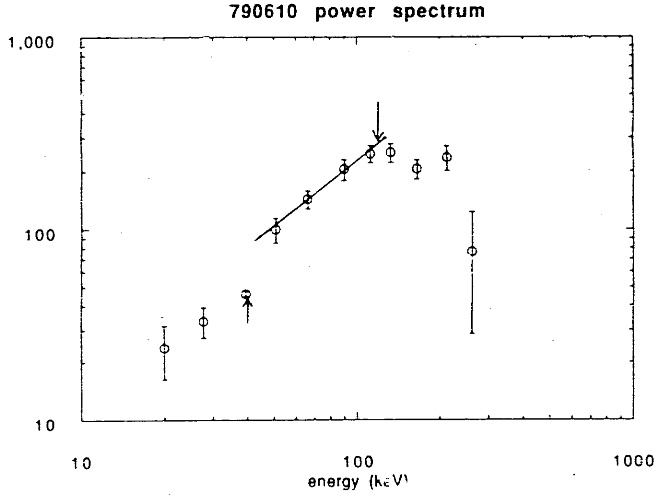

Fig. 3: Same as Fig. 1 for GB790610 (KONUS).

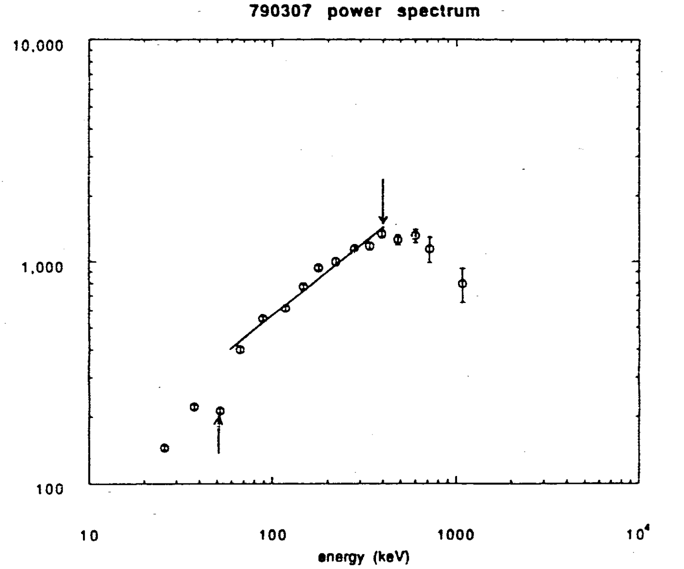

Fig. 2: Same as Fig. 1 for GB790307 (KONUS).

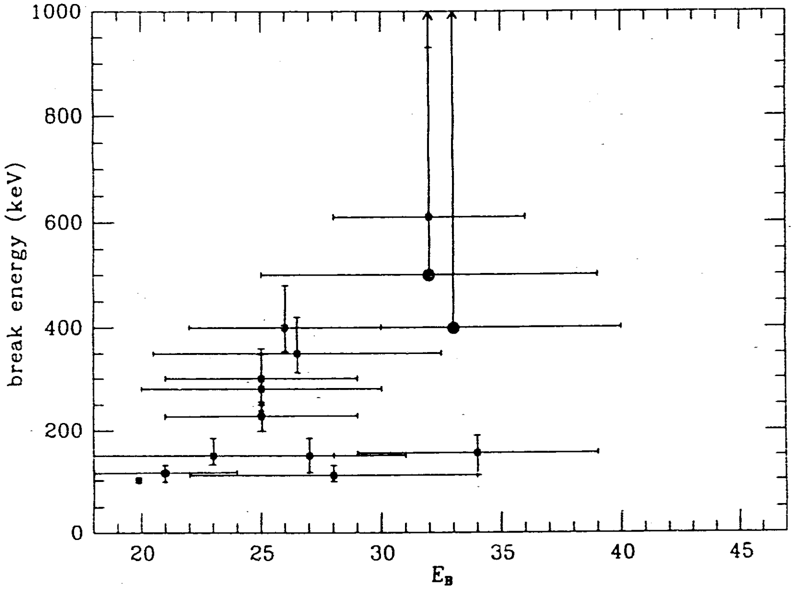

Fig. 4: Plot of E_{bk} versus E_B for bursts of Table I (squares) and II (circles).

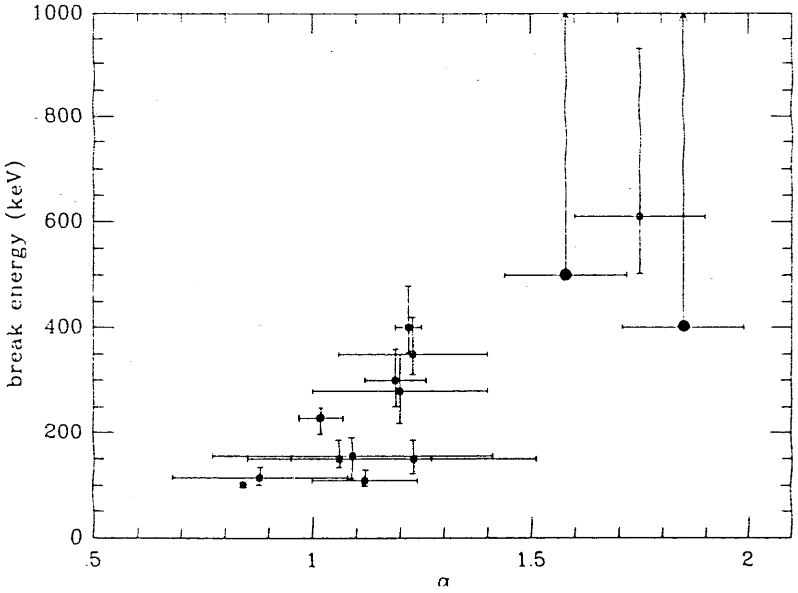

Fig. 5: Plot of E_{bk} versus α, spectral index below the break.

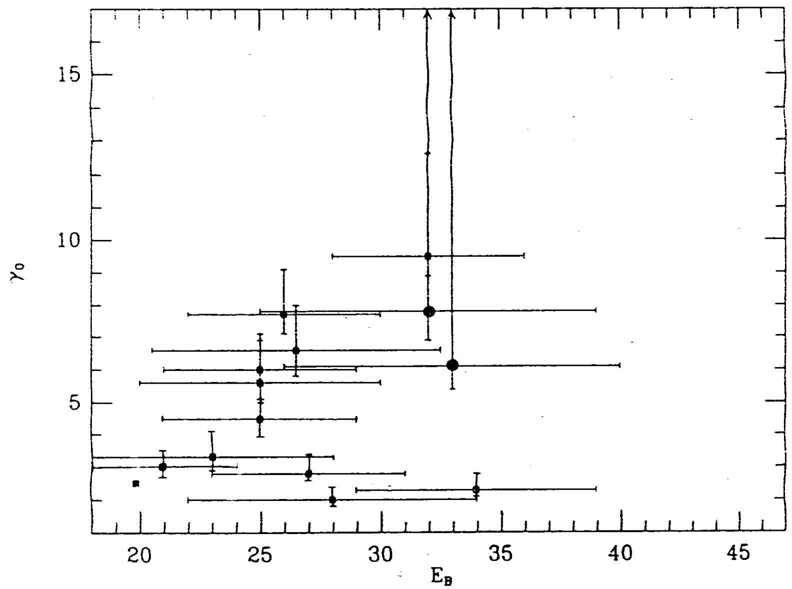

Fig. 6: Plot of γ_0 versus E_B.

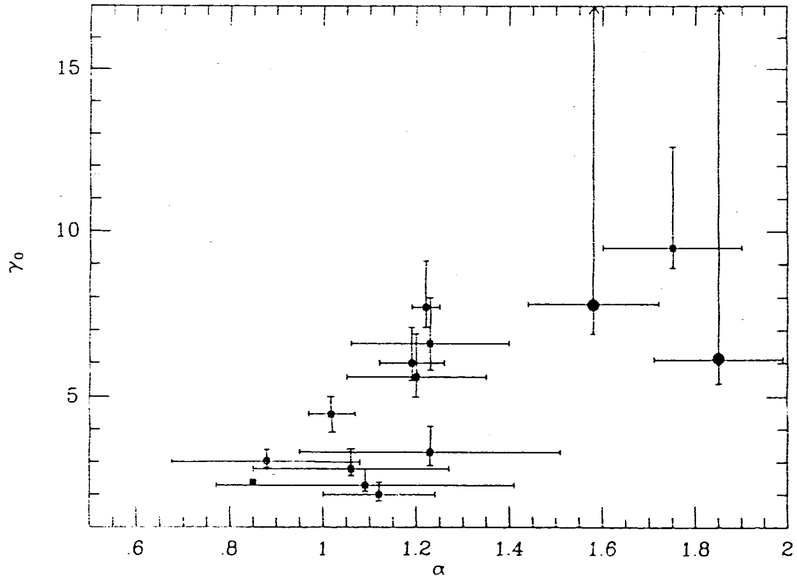

Fig. 7: Plot of γ_0 versus α.

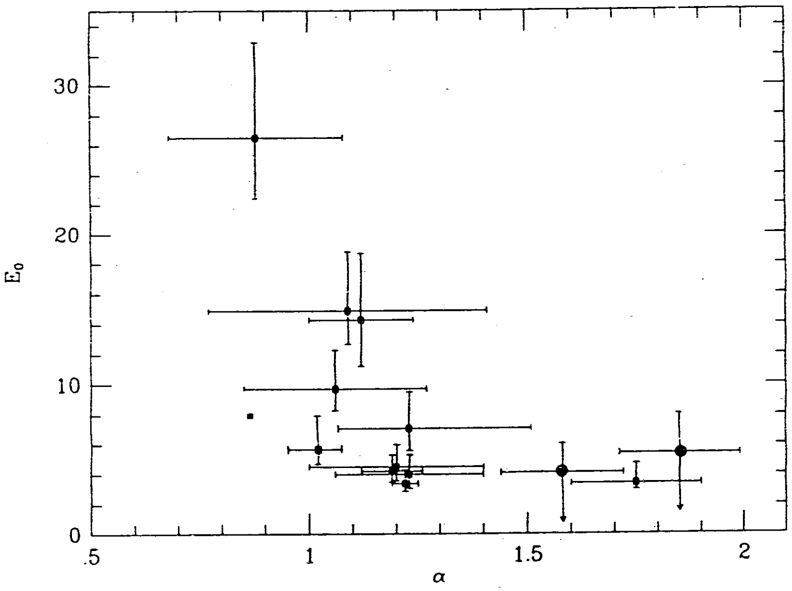

Fig. 8: Plot of E_O versus α.

correspondingly γ_0 and E_0) and spectral index: the higher the break energy, the steeper the slope below the break. This correlation is strengthened if we include the bursts of Table II, using the detector limit as the lower limit to the break energy. This is a somewhat surprising and intriguing result. If confirmed it might have important implications for the emission and energization mechanisms of the electrons that contribute to the spectrum below the break. If the continuum spectra were optically thin thermal bremsstralung, thermal synchrotron or nonmagnetic inverse Compton, we would expect that the hotter the color temperature (hence the higher break energy), the flatter the slope below the break, opposite to Fig. 5. It remains to be seen what this implies for the CUSP type model.

We note that the typical derived soft photon energy is rather high (> 1 keV) and the electron Lorentz factor cutoff correspondingly low. This means that a) the soft photon source should be within observable range of GINGA and especially HETE; and b) the ultrarelativistic, forward scattering assumption of current CUSP models may need to be amended to include effects of nonzero pitch angle scattering and excitation to higher Landau levels (Daugherty and Harding 1986) and related synchrotron emission. In fact, such emissions may be relevant to the formation of the low energy continuum.

4 SUMMARY AND CONCLUSION

We report the result of analyzing a dozen GRB spectra with both cyclotron absorption features and spectral breaks in the hundreds of keV range. We find that there may be marginal correlation between the break energy and spectral index below the break, but no correlation between break energy and field strength, or spectral index and field strength. The correlation between break energy and spectral index, if confirmed by future observations, is intriguing and may shed light on the emission and energization mechanims of the electrons.

We note that the estimated soft photon energies are typically in the few keV range, consistent with the finding by GINGA that there may be a blackbody x-ray component of ~couple keV temperature (Murikami 1990) which persists long after the gamma ray emission. All of the derived electron Lorentz factor cutoffs are less than 10 (less than 5 if we assume the observed feature is the first harmonic), suggesting that the ultrarelativitic assumption in most conventional CUSP models may need to include higher order corrections.

If the ~few keV blackbody observed by GINGA is indeed present throughout the entire burst, the fact that its intensity does not seem to be standing above the extrapolated gamma ray continuum suggests that the photon flux in the blackbody and in the upscattered component are comparable, pointing to a scattering medium of scattering depth ≥ unity. This is in contrast to the current CUSP model assumption that the scatterers are optically thin and multiple scattering is unimportant. If the scattering is would be needed before the CUSP models can be confronted with observed spectra.

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