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AUTHOR(S): E. E. Fenimore, R. W. Klebesadel, and J. G. Laros

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

INVERSE COMPTONIZATION VS. THERMAL SYNCHROTRON

E. E. Fenimore, R. W. Klebesadel, and J. G. Laros
University of California, Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

There are currently two radiation mechanisms being considered for gamma-ray bursts: thermal synchrotron and inverse Comptonization. They are mutually exclusive since thermal synchrotron requires a magnetic field of $\sim 10^{12}$ Gauss whereas inverse Comptonization cannot produce a monotonic spectrum if the field is larger than 10^{11} and is too inefficient relative to thermal synchrotron unless the field is less than 10^9 Gauss. Neither mechanism can explain completely the observed characteristics of gamma-ray bursts. However, we conclude that thermal synchrotron is more consistent with the observations if the sources are ~ 40 kpc away whereas inverse Comptonization is more consistent if they are ~ 300 pc away. Unfortunately, the source distance is still not known and, thus, the radiation mechanism is still uncertain.

INTRODUCTION

Although gamma-ray bursts were the first class of high energy transients to be discovered,¹ no model has satisfactorily explained their nature. Recently, there have been a growing consensus that they are a surface effect on a strongly magnetized neutron star (Mazets et al.²), but there is no consensus on either the macroscopic mechanism which releases the energy or the microscopic process that emits the gamma rays. Some of the macroscopic mechanisms that have been proposed are thermonuclear flashes³ and asteroid collisions⁴. There has been three suggested microscopic emission processes: optically thin thermal bremsstrahlung^{2,5}, thermal synchrotron⁶⁻⁸, and inverse Comptonization⁹. Of these, optically thin thermal bremsstrahlung appears to be implausible because even under extreme conditions, the sources would have to be less than 10 pc away¹⁰.

There are several arguments in favor of thermal synchrotron. First, it is widely assumed that a strong magnetic field is required to confine the very hot plasma and if the field is stronger than 10^{11} Gauss, synchrotron emission is clearly the most efficient method of producing photons, eliminating inverse Comptonization as a radiation mechanism. Second, the KONUS spectra have absorption features which have been interpreted as cyclotron lines due to a 5×10^{12} Gauss magnetic field². Third, many of the KONUS continuum spectra² have shapes which are consistent with thermal synchrotron⁷. The fits to thermal synchrotron use the parameter $\nu_c = \nu_L (kT/mc^2)^2$ where ν_L is the energy of the synchrotron fundamental and T is the temperature of the plasma. Most gamma-ray bursts are fit by ν_c in the range 1.0 to 10.0 keV, implying a magnetic field of $\sim 10^{12}$ Gauss for temperatures of several hundred keV.

There are also arguments in favor of inverse Comptonization. First, the most compelling evidence is the occasional occurrence of unusual spectra. Two-component spectra and spectra similar to a 200 keV Wien peak have been observed,^{2,11} and appear to be very difficult to explain as thermal synchrotron but are naturally explained as, respectively, low-density and high-density examples of inverse

comptonization⁹. Second, the inverse comptonization timescale (10^{-6} sec) seems a more reasonable timescale on which the electrons must be heated. This is in contrast to the 10^{-16} sec timescale for thermal synchrotron where unspecified plasma processes have to be invoked. Third, some gamma-ray burst spectra have been fit in detail to an inverse comptonization model consisting of an underlying blackbody source of x-rays and an overlying, hotter region⁹. However, this cannot be considered strong evidence that inverse comptonization is, indeed, operating since the spectral analysis technique is naturally "obliging", that is, the observations will move to agree with a wide range of spectral shapes^{12,13}.

This paper compares inverse comptonization and thermal synchrotron. We discuss the confinement of the plasma, the presence of absorption features, the shape of the continuum, and other characteristics. We conclude that inverse comptonization is the more likely mechanism if the bursts are about 300 pc away and thermal synchrotron is more likely if the bursts are of the order of 40 kpc away.

MAGNETIC FIELD CONFINEMENT

If a magnetic field is required to confine the plasma, then the radiation mechanism can not be inverse comptonization since inverse comptonization will not work in a strong field⁹. If the field is greater than 10^9 Gauss, then comptonization will not occur since thermal synchrotron would remove all of the energy of the plasma on a timescale much shorter than the comptonization timescale. In addition, monotonic comptonization spectra are not possible if the field strength is larger than 10^{11} Gauss due to the effect of the field on the scattering crosssection. An estimate of the magnetic field required to confine a plasma has been obtained by equating the radiation pressure with the magnetic field pressure^{4,6}. That is,

$$\frac{\sigma T^4}{3c} \lesssim \frac{B^2}{8\pi} \quad (1)$$

where c is the speed of light and σ is the Stefan-Boltzmann constant. Using a typical temperature associated with gamma-ray bursts (i.e. ~ 170 keV) yields a field of $\sim 10^{12}$ Gauss in rough agreement with the interpretation of the KONUS absorption features as being due to $\sim 10^{12}$ Gauss field. However this analysis assumes that the source is emitting as a blackbody, that is, its luminosity per cm^2 is σT^4 . Using an estimate for the emitting area and the observed flux at the earth one can obtain an estimate of the distance to the bursters. Even using a rather small area ($1 \text{ km}^2 \approx 0.001$ the surface area of a neutron star) gives a distance on the order of ~ 40 kpc. However, to be consistent with distances less than 1 kpc and a luminosity commensurate with σT^4 , the source size would have to be of the order of a square meter. Since a meter seems too small for the lateral size of a gamma ray burst, we conclude that either the bursters are close by and the gamma ray producing plasma does not produce photons commensurate with σT^4 or the bursters must be about 40 kpc away. (Of course, the spectral shape is also not consistent with a blackbody.)

Rather than using a radiation pressure based upon blackbody radiation, σT^4 , we suggest that the confining magnetic field can be estimated from the observed flux. That is, we will replace Eq. 1 with

$$\frac{L/A}{3c} < \frac{B^2}{8\pi}$$

where L , the luminosity, is $4\pi D^2 S$, S is the observed flux, and D is the distance to the source. Using a typical observed flux of $S \approx 10^{-5}$ ergs sec $^{-1}$ cm $^{-2}$, the magnetic field required to confine the plasma is

$$B > 5.6 \times 10^8 (D/100 \text{ pc})(A/\text{km}^2)^{-1/2} \text{ Gauss.} \quad (3)$$

Thus, the observed flux implies that a field strength of 5×10^9 Gauss can adequately confine the plasma if the source is of the order of 300 pc away. However, if the sources are in fact 40 kpc away, then a field of the order of 10^{12} Gauss is required.

SPECTRAL FEATURES

If spectral features near 50 keV are, indeed, cyclotron absorption features, then the emission mechanism is certainly not inverse comptonization. However, the features are not without controversy. In the past, we have pointed out the difficulty of analyzing gamma-ray burst spectra in the vicinity of 50 keV. We wish to emphasize here that, despite those problems, we have always recommended only open-mindedness, not disbelief¹⁰⁻¹³. There are good reasons to believe the presence of absorption features. From private communication with Mazets, we have learned much about his analysis technique and it is a fairly reasonable method. The UCSD absorption feature (see Heuter¹⁴) appears to be statistically very significant and their analysis technique is as good as is possible.

The origins of our skepticism are twofold. First, many of the lines are broad features extending from the lowest energy bin of KONUS to about 60 keV. These are identified as absorption features only because the observed counts disagree from those expected from optically thin thermal bremsstrahlung. Thus, they are "lines" only if the continuum has a shape like optically thin thermal bremsstrahlung. A harder continuum can fit the so-called deviation without assuming absorption. Thus, we believe that the broad absorption features could be, in fact, a continuum which is simply harder than optically thin thermal bremsstrahlung. (Inverse comptonization can produce such a spectrum.) The second reason for our skepticism is that, if you discount the broad lines, the balance of the absorption features are narrow and mostly occur at energies for which it is extremely difficult to deconvolve the instrumental response function due to the nearby K edge of Iodine. These

difficulties have been described elsewhere¹⁰⁻¹³. Since it is not yet possible to evaluate these difficulties quantitatively, we believe it is prudent to remain open-minded when the narrow lines occur only at the energies which can be affected by the K edge.

Even if the spectra, indeed, contain narrow absorption features near 50 keV, the features reported so far do not have the shape expected from a thermal synchrotron model. One has to position a cold plasma with a 5×10^{12} Gauss field above the region which is producing a rather smooth continuum by thermal synchrotron, an unlikely arrangement. Thus, even ignoring the open-mindedness that we recommend, the features do not seem consistent with thermal synchrotron.

CONTINUUM

In many cases, it appears that thermal synchrotron and inverse comptonization can both produce continuum shapes similar to those observed. Thermal synchrotron seems better able to explain the energy range 30 keV to several MeV but might have to depend on some other mechanism to explain the x-ray observations^{5,15}. Inverse comptonization seems better able to explain the range 3 keV to 1 MeV but might have to depend on some other process to explain the observed flux above 1 MeV¹⁶. A key feature of the continuum to be explained is the occurrence of low energy (20 to 60 keV) turnovers. Thermal synchrotron assumes they are due to a Rayleigh-Jeans limit, resulting in distance estimates of the order of 40 kpc. Inverse comptonization would try to explain such turnovers in terms of saturated comptonization, but not so saturated as to be a blackbody. There is one case (GB781119) of a turnover that did not peak until 400 keV¹⁵. This is difficult for thermal synchrotron to explain, but is naturally explained as a Wien peak due to saturated comptonization. A second key feature to be explained is the occurrence of two-component spectra which appear to be made up of a softer x-ray spectrum plus a normal gamma-ray burst spectrum. Such spectra (e.g., GB790329 and GB790524) are expected in an inverse comptonization scenario when the density of the overlying, hotter region is low. It is not clear how thermal synchrotron would be adapted to explain such spectra.

DISCUSSION

It appears that the key discriminator between radiation mechanisms is the distance to the sources. Short distances favor inverse comptonization and large distances favor thermal synchrotron. Unfortunately, our state of knowledge concerning the distances is inadequate since they are presently determined from log N-log S curves (see Klebesadel et al.¹⁷). Until recently it appeared as if nearby distances (300 pc) were consistent with the log N-log S curve¹⁸. Presently, the isotopic distribution of source positions combined with a log N-log S curve that deviates from a $-3/2$ power law implies a distance of the order of 40 kpc¹⁹. Of course this, like most other gamma-ray burst observations, is not without controversy. It is possible that the deviation is due to instrumental threshold effects. We note, for example, that the log N-log P curve (P = instantaneous flux) follows the $-3/2$ power law more closely than does the log N-log S curve. If the log N-log P curve does not deviate from a $-3/2$ power law down to the flux levels of the bursts for which

positions have been found, then distances of the order of 300 pc would be acceptable.

If the distance is 40 kpc, then thermal synchrotron is clearly favored since a magnetic field could possibly confine the plasma as well as providing a radiation mechanism efficient enough to produce the requisite flux that is 10^4 times the Eddington limit. The source size would be a comfortable one square kilometer. The two-component spectra would have to be explained by some other process. The narrow absorption dips are not easily explained by thermal synchrotron but they seem more likely to be consistent with thermal synchrotron than inverse comptonization. The major problems with thermal synchrotron at 40 kpc are: defining a mechanism which can heat the electrons on a 10^{-16} sec timescale, confining the 10^4 Eddington limit flux with the magnetic field, and determining why gamma-ray bursts are the only observed way that the extended galactic halo emits.

If the distance is 300 pc, then inverse comptonization is favored since the low energy turnovers would imply a lateral source size of only a square meter if thermal synchrotron is assumed. Inverse comptonization can give a source size of a square kilometer without violating the Eddington limit. In fact the number of photons we observe in a gamma-ray burst is equivalent to the number of photons produced by a square kilometer x-ray source, with just the energies having been shifted to the gamma-ray region. Inverse comptonization can easily explain the two-component spectra. The major problems would be to explain the photons above 1 MeV and the narrow absorption features.

Given the uncertainty in distance originating in the log N-log S curves, it is not yet clear if the most probably radiation mechanism is thermal synchrotron in a high magnetic field at 40 kpc or inverse comptonization in a low field at 300 pc.

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