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PHYSICS OF THE SYNCHROTRON MODEL OF COSMIC GAMMA-RAY BURSTS

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ABSTRACT

We review the theoretical arguments leading to the thermal synchrotron model of cosmic gamma-ray bursts. We propose a magnetic flare-resonant absorption mechanism for the production of the hot electrons that can account for most of the unusual properties of the emission layer.

INTRODUCTION

In this article I will try to elaborate on some of the ideas briefly unveiled at the workshop. I will give a more in-depth, yet qualitative discussion of some of the far-fetched but promising approaches to the understanding of the cosmic gamma burst emission mechanisms, under the premise that they originate from the surface of strongly magnetized neutron stars. Analytic and quantitative results will be published elsewhere.

I should emphasize that despite the growing popularity, especially with experimentalists, of fitting burst spectra with the thermal synchrotron (TS) model, the fundamental reasons why we consider it as the most attractive mechanism remain theoretical ones. Let me briefly reiterate them here.

- A. The hardness of the spectrum, especially with new SMM data¹ extending to beyond 10 MeV, excludes single-temperature thermal bremsstrahlung (TB) or inverse Compton (IC) model because of their exponential cutoffs at sufficiently high frequencies (say > 1 MeV). TS spectra are much harder since $I_\nu \propto \mu \exp - (B\nu)^{1/3}$, $\beta^{-1} \propto BT^2$. For sufficiently high temperature T or field strength B it can mimic a power law out to very high energies.
- B. A strong magnetic field ($B > 10^{11}$ G) is independently hinted by (i) confinement of the plasma over long time, (ii) low frequency cyclotron features, (iii) narrow annihilation line suggestive of rapid cooling of the hot electrons, (iv) periodicity in the late-time emissions of the March 5 event. When this is combined with the optical thinness of the spectra [τ_{es} (Thompson depth) < 1] synchrotron emissivity easily exceeds the other emissivities by many orders of magnitude.
- C. The March 5 event, if it is indeed at the distance of LMC, can only produce its enormous luminosity via synchrotron radiation (Ramaty et al.,² Liang³).

Despite these attractive arguments, direct observational confirmations of the TS model are still totally lacking. The exponential continuum shape can obviously be fitted by any number of models and the TS interpretation is far from unique. Low energy harmonic features are only detected in a small fraction of the events. Their

status is controversial and their interpretation is even more uncertain. Major breakthrough in this area must await high quality, undisputable x-ray data covering the frequencies of the anticipated harmonics down to < 1 keV ($B < 10^{11}$ G). In the meantime without a better alternative I suggest that we take the synchrotron model seriously, at least as a baseline framework, and pursue its consequences, difficulties, and observational implications.

THE THERMAL SYNCHROTRON (TS) MODEL REVISITED

Based on the analyses of a large number of gamma burst spectra with the TS model, including those observed by KONUS,⁴ SMM,¹ SIGNE⁵ etc., the following picture of the gamma ray burst emission region has emerged. It consists of a thin, dense, ultrahot (mildly relativistic temperatures) sheet of pair-dominated plasma (at least partially) confined by a strong magnetic field. If the pair annihilation region roughly coincides with the synchrotron radiation source then the well-defined redshift ($z \sim 0.25$) suggests that this sheet must be close to the surface of the neutron star. The synchrotron flux emerging is highly super Eddington ($F_{\text{Edd}} \approx 8 \times 10^{24} (M/M_{\odot}) \text{ erg. cm}^{-2} \text{ s}^{-1}$ for a 10 km neutron star). We will use the following reference values for the typical emission layer parameters: electron temperature $T_e \sim 200\text{--}300$ keV; pair density $n \sim 10^{25} - 10^{26} \text{ cm}^{-3}$; sheet thickness $h \sim 10^{-4} - 10^{-5} \text{ cm}$ ($\Leftrightarrow nh \sim 10^{20} - 10^{22} \text{ cm}^{-2}$); field strength $B < 10^{13}$ G; synchrotron flux $F_{\text{syn}} \sim 10^{29} - 10^{31} \text{ erg. cm}^{-2} \text{ s}^{-1}$. (See Ref. 6 for review. Throughout this paper the generic term "electron" refers to both background electrons and pairs.)

These parameters point towards very exotic physical conditions. Conventional wisdom immediately raise a number of intuitive difficulties:

- The ultrashort synchrotron cooling time means that we must populate the high-lying Landau levels (i.e., pitch-angle scatter rate) faster than $\sim 10^{16} \text{ s}^{-1}$ to mimic a hot Maxwellian electron distribution. Coulomb collision is orders of magnitude too slow and leads to much softer exponential spectra (Petrosian⁶). This forces us to invoke collisionless plasma processes which can operate on the electron plasma frequency time scale $\nu_{pe} \approx 10^{17} (n/10^{26})^{1/2} \text{ s}^{-1}$.
- Even with 10^{12} G magnetic fields the hot emitting plasma would still expand along the field lines on light travel time scales. Hence we must find additional means to suppress this expansion and keep the emitting layer dense and thin over macroscopic time scales.
- The emerging gamma rays above the pair production threshold (511 keV) should be strongly attenuated, both by $\gamma\gamma$ and γB pair production processes. Yet the SMM data show no break in the spectrum at 0.5 or 1 MeV.¹
- Synchrotron radiation should not extend to much below the Larmor frequency. Yet in most spectra exhibiting the narrow absorption "dip" (between 40–70 keV, interpreted as first harmonic absorption) the intensity continues to rise monotonically below the

"dip" frequency without cutoff.⁴ This suggests that the cold absorption region may have a higher field strength than the hot emission layer, an unintuitive picture. However, we caution that the theory of the low frequency part of the spectra is in a very primitive state.⁸ Since the optical depth and photon occupation number there may not be small, scattering,⁹ absorption and induced processes may be important. Until we have reliable full-fledged radiative transfer calculations we should treat with caution critical parameters derived from the low frequency features.

- e. Unless the emission area is much smaller than the conventional 1 km^2 polar cap region, the high synchrotron emissivity implies that the sources are far away (distance $> \text{kpc}$) with some luminous events likely extragalactic ($10\text{--}100 \text{ kpc}$). This, however, may be consistent with the recent $\log N\text{--}\log S$ and isotropy results which suggest that gamma ray bursts may form an extended halo population (radius $\sim 100 \text{ kpc}$).¹⁰ In that case the sources must be associated with very old, population III-type stellar remnants. The large distance of a few events may also pose a problem for the energetics since a 10 km , 10^{12} G -field neutron star magnetosphere contains only about $\sim 10^{41}$ ergs of total energy.

Before we bravely march forward and attempt to resolve all these real or imagined difficulties of the synchrotron model it is good to fall back and ask: Are there really no serious alternatives? It is clear that any alternative such as bremsstrahlung or Comptonization, must do away with a strong B-field ($\ll 10^{10} \text{ G}$). Even if we can live with anomalous aspect ratios of the emission region, bremsstrahlung is so inefficient that we must bring all burst sources to within a small local neighborhood,^{11,20} which is already inconsistent with current statistics.¹⁰

Comptonization can certainly account for the gross spectral shape and be adjusted to fit any distance requirement. All one has to do is to put in more or less soft photons. But where do these soft photons come from? The x-ray observations by Laros et al.¹³ giving an L_x/L_γ ratio of $1/50$ to $1/100$ for several events may pose difficulties for this picture since the spectral shape suggests that the Kompaneet parameter $y \lesssim 1$.¹¹ In addition, narrowness of the spectral lines may be a problem if $\tau_{\text{es}} \sim 1$ and $T_e \sim mc^2$. On the other hand, some small amount of Comptonization must be present in all emission models, including the TS model.³

An expanding fireball model in which we are mainly seeing the blueshifted and scattered pair annihilation radiation as the fireball becomes transparent¹⁴ is interesting, as it bypasses the difficulty with the pair-creation attenuation. But no detailed radiative transfer has been done so we know nothing about the predicted spectrum. There will be obvious difficulties with the absorption and annihilation features in this model.

To summarize, a consistent, viable and testable alternative to the synchrotron model, even if we can give up the strong magnetic field, is lacking at present. In principle (but probably very difficult for Γ -rays), synchrotron radiation can be distinguished

from other emissions by its unique angular distributions and polarizations.

ORIGIN OF THE "HOT" ELECTRONS

Any scheme for heating and maintaining the thin synchrotron emitting layer must satisfy the following conditions:

1. Energy for the hot electrons cannot be stored in-situ since the volume is too tiny. It must be stored in a much larger volume (e.g., the magnetosphere or stellar interior) and supplied to the radiating electrons via a very large energy flux ($\geq 10^{30}$ erg cm⁻² s⁻¹).
 2. The above energy flux must be consistent with the confinement of the sheet, especially along the field lines.
 3. The electrons must be heated on a time scale $< 10^{-16}$ s.
 4. The electrons retain a Maxwellian distribution except may be for the highest energy tail with $E > 10$ kT_e where it may cut off or turn into a power law.
 5. Space above the sheet must remain "empty" to allow gamma rays to emerge with little absorption or scattering ($\tau_{\text{syn}} < 1$, $\tau_{\text{es}} < 1$).
 6. Besides the above hot electrons, the appearance of narrow line features, if confirmed, strongly suggests the simultaneous presence of a cold component with floor temperature T_f < 10 keV as deduced from the line widths.
- In addition, if the latest discovery by Golenetskii et al.¹⁵ is confirmed, we also have the interesting requirement:
7. The synchrotron luminosity must scale with emission temperature approximately as $L \propto T^3$.

The above stringent requirements, taken together, eliminate most schemes and drive us toward the following "magnetic reconnection-resonant absorption" picture. At present this picture is still in a very primitive conceptual phase. But it does hold some promises of satisfying the above requirements and makes additional predictions that can be checked observationally. It combines two familiar concepts which have often been applied to solar flares and laser-target interactions separately.

Condition 2 suggests that an external energy flux impinging onto the stellar surface is preferable to an internal energy flux emerging from the stellar interior (e.g., Refs. 28 and 29) since the momentum flux associated with the former automatically helps to "pin down" the plasma sheet. Condition 5 demands that this external flux be non-particulate, otherwise the impinging particle column density would be so high as to obliterate the optically thin spectrum. Thus we are left with only low frequency waves of an electromagnetic nature propagating downward through a "corona" of very low density, say $n < 10^{18}$ cm⁻³. To carry a flux of $\geq 10^{30}$ erg cm⁻² s⁻¹ the wave perturbation δE or δB must be $>$ a few percent of the ambient field $B_* \sim 10^{-2}$ G. How can this intense nonlinear EM flux couple to and heat the stellar surface? Conditions 3, 4, 6, and 7, taken together, strongly suggest that we are dealing with resonant absorption or similar collisionless processes, in which the

electric field of the incident and reflected waves drives nonlinear plasma oscillations, which, upon propagating down the steep density gradient, breaks directly into "hot" electrons. Such phenomenon is observed in a variety of terrestrial and laboratory situations such as ionospheric wave absorption¹⁶ and laser-target interactions.¹⁷ The "hot" electrons are indeed accelerated collisionlessly on an electron plasma oscillation time scale and possess roughly Maxwellian distributions out to $> 10 kT_{\text{hot}}$. More importantly T_{hot} is known to scale with the incident wave flux F_w roughly as $T_{\text{hot}} \propto (F_w \lambda_w)^{.3-.4}$ where λ_w is the incident wavelength.^{17,18} This is consistent with condition 7 provided the emission area stays constant. The details of resonant absorption is still being studied but a typical derivation of the hot electron temperature using the Debye wavelength to determine the self-consistently steepened density profile scale would give a result like¹⁹

$$T_{\text{hot}} \approx 14 \text{ keV } T_f^{1/3} [(F_w/10^{23}) (\lambda_w/10^{-4})^2]^{1/3}. \quad (1)$$

where T_f is the floor temperature of the unheated electrons in keV. As we will discuss below, there are reasons to believe that universal values for $T_f \sim$ a few keV and $\lambda_w \sim 10^{-6}$ cm for our case. Substituting into Eq. (1) we obtain a typical hot electron temperature of a few hundred keV for $F_w = 10^{30}$, consistent with observations.

We emphasize, however, that resonant absorption is not the only nonlinear collisionless process that can produce hot electrons when intense EM waves interact with a sharp density gradient. A host of other plasma processes, such as Raman scattering, parametric decay, etc., could also do it. But they would have different scaling laws.¹⁷

Based on the resonant absorption picture, we obtain, from first principles, the following parameters of the emission layer. The hot electron density is set by balance between hot electron energy flux and absorbed wave flux:

$$\alpha_{\text{ab}} F_w \sim n_h m_e (T_h/m_e)^{3/2}, \quad \alpha_{\text{ab}} \sim 0(1). \quad (2)$$

which gives, for $F_w \sim 10^{30}$, $n_h \sim \alpha_{\text{ab}} 10^{26} \text{ cm}^{-3}$. These hot electrons would then traverse a distance (along field lines) of approximately $(T_h/m_e)^{1/2} \cdot t_{\text{syn}}$ before cooling off, where t_{syn} is the synchrotron cooling time ($\sim 3 \times 10^{-16}$ s for $T_{\text{hot}} \sim m_e c^2$). Hence the hot synchrotron emitting layer would have a thickness of $h \sim 10^{-5}$ cm and a column depth $n_h h \sim 10^{21} \text{ cm}^{-2}$. The electrons obviously could not cool to arbitrarily low temperatures as it will be heated by Compton scattering with hard photons and Coulomb scattering with other hot charged particles. A floor temperature T_f for the cooled electrons can be found by setting the synchrotron cooling rate equal to Coulomb and Compton heating rates. We find typically $T_f \sim$ few keV. This low temperature is consistent with the narrow widths of the absorption and annihilation line features.

MAGNETIC FLARE

As everyone would have guessed by now, the origin of our intense EM wave flux must be something of the nature of a magnetic flare in the neutron star corona (see Katz²⁰, Liang and Antiochos²¹ for earlier ideas). Let us ask the fundamental question: What happens when a stressed 10^{12} G field reconnects in a rarefied neutron star atmosphere? The answer is far from trivial since we cannot simply scale laboratory or solar models to such exotic regimes, with $B^2/8\pi \gg \rho c^2$, $v_A \sim c$, etc., and even laboratory or solar reconnections are far from being understood. Despite all the unknowns we believe there must be certain generic properties dependent only on dimensional arguments.

- Since the highly rarefied coronal plasma cannot carry the bulk of reconnection energy ($B^2/8\pi \sim 10^{22}$ erg/cc $\approx 10^7$ erg/particle for $n_c = 10^{15}$ cm⁻³; this density is a plausible number as then $n_c L < 10^{21}$ for loopsize $L < 10^6$ cm yet it is enough to provide sufficient current to produce a stressed field of 10^{12} G.) most of this energy must be dumped into waves of an electromagnetic nature (e.g., relativistic Alfvén waves).
- The low plasma density means that for any wave perturbation of the magnetic field, $\delta E \sim \delta B (> \sqrt{\rho c^2})$ and these are transverse waves ($\delta E \perp B_*$).
- If the reconnection proceeds via a neutral sheet as in Petschek's mechanism,²² the shortest wavelength perturbation would be approximately the ion cyclotron radius (Alfvén shock thickness):

$$r_{ic} \sim 10^{-6} \text{ cm } \left(\frac{v_{ion}}{c} \right) B_{12}^{-1}$$

In fact we expect most of the power will reside in waves near this wavelength. As $v_A = c$,

$$v_w = \frac{c}{r_{ic}} \sim 10^{16} \text{ s}^{-1} \left(\frac{c}{v_{ion}} \right) B_{12}.$$

Since this lies in the EUV to soft x-ray regime, we are tempted to speculate that cosmic gamma ray burst may be accompanied by bursts in the EUV and soft x-rays ($\lesssim 100$ eV) of comparable luminosity, which, unfortunately are very difficult to observe. Whether or not the optical bursts discovered by Schaefer²³ could be the low-frequency tails of these EUV bursts remain to be investigated.

As noted before, waves of the above frequency resonate with plasma oscillations of $n \sim 10^{26}$ cm⁻³ and give the correct hot electron temperature. So we have at least an overall self-consistent picture.

As many authors have pointed out, the various time scales of the gamma bursts must reflect the history of the energy release mechanism. In the context of the magnetic flare picture, we must understand these in terms of the various reconnection time scales.

According to conventional wisdom, there are at least two distinct time scales (a) the nonlinear (Petschek-type) growth time²² ~ 10 Alfvén crossing time τ_A ; (b) the resistive-tearing growth time²⁴ $\sim (\tau_A \tau_{\text{Diff}})^{1/2}$, where τ_{Diff} is magnetic diffusion time. In the present case since $v_A \sim c$ so for a loop of size $L \sim 10$ km, $\tau_A \sim 10^{-4}$ sec and $(\tau_A \tau_{\text{Diff}})^{1/2} \sim 10$ sec if we use collective plasma process for the diffusion coefficient and $n_c \sim 10^{15} \text{ cm}^{-3}$. These roughly coincide with the shortest and longest time scales of observed gamma bursts. The remaining time scale, namely the duration of individual spikes (~ 10 -100 ms) may be associated with the resistive-tearing growth time of subregions going through reconnection (e.g. filaments).

ORIGIN OF THE SHEARED FIELD ENERGY

As it has been pointed out (e.g., Katz²⁰), the two most popular energy sources associated with neutron stars (i.e., transient accretion^{2,26} and surface flash²⁷) both face severe difficulty with the optical thinness and lack of soft x-ray emission since the energy must be released in extremely large optical depths. A magnetic flare driven by either of the above energy sources will have a hard time reconciling with all the observational constraints. On the other hand, internal sources, such as vibrations set off by phase changes^{28,29} or field regeneration by internal dynamos or thermoelectric effects³⁰ are highly speculative at this point. What is clear, however, is that we are likely dealing with a new class of neutron star phenomena associated with very dim old-population objects, distinct from known galactic pulsars (radio or x-ray).

Throughout the development of the ideas presented here I have benefitted greatly from endless conversation with many colleagues. I would like to express my thanks to all who have listened patiently.

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