LA-UR -83-2586

CONF-8307104--4

LA-UR--83-2586

DE84 001355

TITLE: GAMMA-BURST EMISSION FROM NEUTRON-STAR ACCRETION

AUTHOR(S): Stirling A. Colgate,
Albert G. Petschek,
Robert Sarracino, NASA

SUBMITTED TO: For publication in the Proceedings of the Summer Workshop in Astronomy and Astrophysics, Santa Cruz, CA, July 10-22, 1983

August 30, 1983

GAMMA-BURST EMISSION FROM NEUTRON-STAR ACCRETION

Stirling A. Colgate[a,b]
Albert G. Petschek[a,b]
Robert Sarracino[b,c]

[a] Los Alamos National Laboratory, Los Alamos, New Mexico 87545
[b] New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801
[c] Present address: NASA, Goddard Space Flight Center, Greenbelt, Maryland 20771 USA

ABSTRACT

A model for emission of the hard photons of gamma bursts is presented. The model assumes accretion at nearly the Eddington limited rate onto a neutron star without magnetic a field. Initially soft photons are heated as they are compressed between the accreting matter and the star. A large electric field due to relatively small charge separation is required to drag electrons into the star with the nuclei against the flux of photons leaking out through the accreting matter. The photon number is not increased substantially by bremsstrahlung or any other process. Instability in an accretion disc might provide the infalling matter required.

INTRODUCTION

The hard spectra of commom gamma bursts (as opposed to the singular March 5 event) have been interpreted as (1) optically thin bremsstrahlung,[1-3] (2) thin electron synchrotron radiation,[4-6] and (3) a comptonized soft black body spectrum.[7] Here we propose a fourth radiation mechanism namely photon compression and diffusion. One may rightfully wonder why, with so many possible mechanisms to choose from, another may be of importance. If one assumes that hot electrons are available, then there are obviously many ways for such electrons to emit hard photons. In the case of bremsstrahlung, the emission mechanism is weak, of order α compared to Compton scattering, and the source must be highly extended ~ 10^{16} cm to avoid self absorption.[8] Hence the rapid fluctuations observed in almost all gamma bursts[9] would be impossible. In the case of synchrotron radiation and Compton scattering the problem is creating and maintaining the necessary hot electrons. Liang[10] has pointed out that electron radiation in a strong magnetic field is so effective that, a radiating layer more than 10^{3} Compton mean free paths thick would be optically thick and lead to a black body spectrum, contrary to observations. Pair formation and annihilation further restricts the physical thickness of such a radiating layer to 10^{-3} to 10^{-4} cm. The problem is then finding any process to keep such a layer hot. For example, if the heating is to be done by Alfvén waves, as proposed by Liang at this meeting, then these Alfvén waves must originate in and propagate through regions which do not radiate photons notwithstanding the high energy densities that must be involved. For Alfvén waves to propagate along curved field lines, the minimum rest mass density becomes $\rho \gtrsim B_{12}^2/(4\pi c^2) \cong 40$ g cm^{-3}, a value that violates the assumption of a vacuum magnetic field. Similarly if one postulates a high temperature region free of magnetic field as would be required by Fenimore et al[7] to Compton heat a soft photon flux, one has the problem of how to keep these electrons hot using a source of energy that does not introduce more electrons than is allowed by the "thin" approximation.

For these reasons we have spent some time attempting to find an emission mechanism for gamma bursts that converts a reasonable source of energy into the hard photon spectrum observed. We believe we have found such a mechanism as the normal consequence of moderately thin ($\tau = 1$ to 4) accretion onto a field free neutron star. The model is that photons of nearly constant number are sequentially compressed, heated, diffused, further compressed, heated, diffused and ultimately escape in a hard spectrum at an average flux near the Eddington limit, but with wide fluctuations.

The physics of such accretion is complex. To begin with:

1. The mass flux corresponding to steady state Eddington limit accretion corresponds to a thickness of $\tau \cong 2$. The accreting matter cannot be much thicker, else the energy flux of radiation will be less than the kinetic energy flux of infalling matter.
2. In a transient state when the initial instantaneous photon flux corresponds to a value much less than the Eddington limit flux, ϕ_{Edd}, the free fall time is very much less than the time necessary to multiply the photon number by bremsstrahlung. Therefore, accretion with $\tau = 2$ to 4 occurs without increase in the photon number.

CALCULATIONS

We have modeled this phenomenon with a one-dimensional (radial) multi-energy group numerical calculation with mass layers and photon diffusion in both energy and radius. Both radiation stress and gravity accelerate the accreting matter. The neutron star surface is assumed to have an albedo of unity, mass layers are merged with the surface when they get within ΔR of it and each layer is treated as a semi-transparent diffuse scattering layer with zero heat capacity and therefore no defined temperature. A photon number density corresponding to a small temperature initially seeds the problem. A typical resulting spectrum is shown in the figure where the initial seed temperature was 0.355 keV, $\tau_{init} = 2.2$ (integrated to infinity) and the initial velocity distribution corresponded to free fall. The curve drawn through the points is that corresponding to a thin bremsstrahlung distribution with $kT_e = 139$ keV.

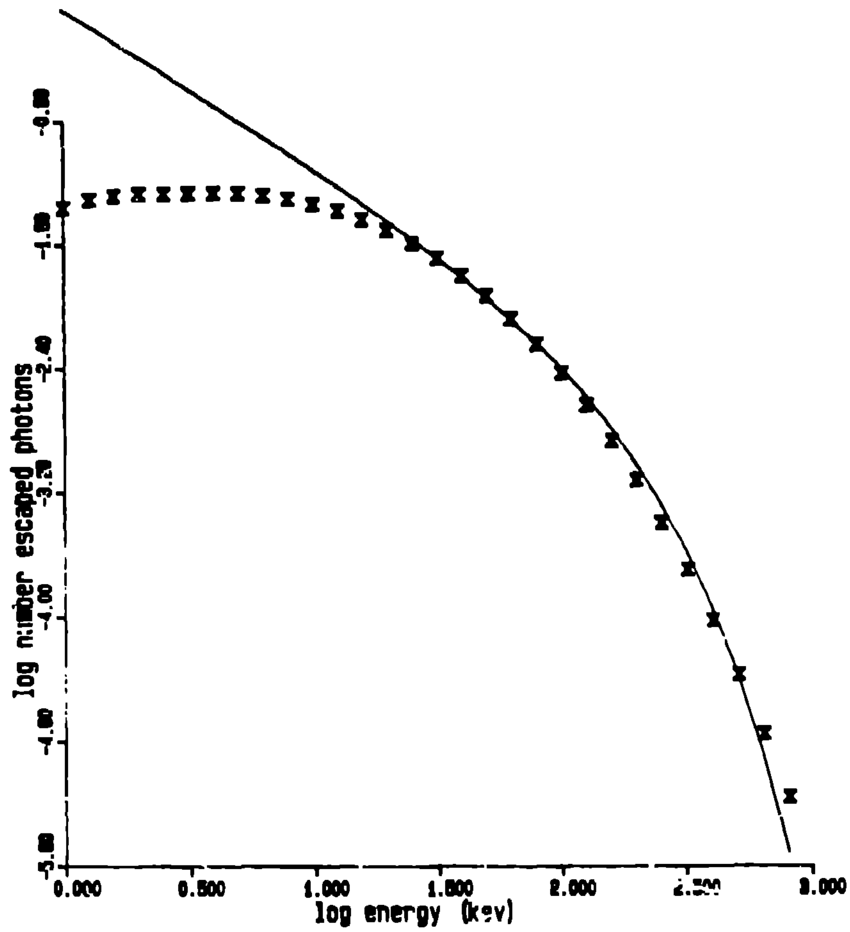

Fig. A γ-burst spectrum from field free matter accreting onto a neutron star. The curve is a bremsstrahlung fit with kT_e = 139 keV.

The justification for the set of assumptions leading to the calculations are:

1. In steady state Eddington flux limited accretion the gravitational field of the neutron star acting on the ions drags the electrons by a charge separation electric field $E \lesssim g\mu m_p/e$ where $g = M_{NS}G/R_{NS}^2$, μ is the molecular weight per electron, and m_p the mass of the proton. This electric field, $E \sim 100$ v/cm is small enough that charge neutrality almost prevails, $\Delta n_e/n_e \simeq 3 \times 10^{-17}$. This ensures that the electrons are dragged by the ions against the photon stress even for stopping distances that are infinitesimal compared to the neutron star radius.
2. The seed photon number density, generally characterized by a black body temperature $kT \lesssim 1$ keV is small compared to the Eddington limit value of $kT_{limit} \simeq 2$ keV for a neutron star of mass 1 $M_\odot$. This ensures initial free fall of the plasma.

3. The photon number density always greatly exceeds the electron number density since n_e is of order $10^{24}\ \tau/R_{NS}$ or $10^{18}\ cm^{-3}$ while at 1 keV, $n_{h\nu} = 2.5 \times 10^{22}\ cm^{-3}$. Therefore the electron specific heat is negligible compared to that of the photons.

4. Provided the electrons do not run away in the charge separation electric field, the electron temperature will be an average of the local photon energy. Hence electron recoil and comptonization where the thermal energy content of the hot or cold electrons heats or cools the photons can be neglected. In fact, runaway will not occur because an electron undergoes many photon collisions in a distance equal to its energy multiplication distance $\lambda = kT_e/Ee$, $Ee \leq n_{h\nu} < h\nu > \sigma_c/3\tau$, $t = 2\lambda/(2\ kT_e/m_e)^{\frac{1}{2}}$, and hence the number of collisions in λ becomes $n_{h\nu}\ \sigma_c\ ct \sim (c/v_e)$ sufficient to ensure against runaway. This assumes that $kT_e = \langle h\nu\rangle/3$ consistent with the large number of collisions.

5. Since for matter freely falling at a constant rate, $\int_R^\infty \rho dR \propto R^{-3/2}$, the thickness $\rho R \propto R^{-\frac{1}{2}}$ and so photons will scatter and be heated within several radii of the neutron star. From this distance the free fall time is roughly equal to the diffusion time. This ensures that some photons are trapped and raised in energy by compression, yet also ensures that leakage allows the large photon heating without exceeding the Eddington limit. Since the gravitational potential is roughly $c^2/5$, the limiting free fall velocity is $\cong c/2$. The diffusion "velocity" is roughly $(c/3\tau)$ so that $\tau = 1$ to 2 meets the criterion.

6. The neutron star surface has an albedo of the order of unity. Since bremsstrahlung is small compared to Compton scattering, the "surface" is where there first exists an additional scattering mean free path. Therefore a photon reaching the "surface" from larger radius has a high probability of being scattered back out, rather than being absorbed and reemitted as is necessary to establish a black body spectrum.

7. The photons added to the accreting matter during free fall due to the neutron star surface emission are not large compared to the assumed in situ number density. Since the free fall time is comparable to the escape time, the net addition of photons after the start of free fall is not greater than several fold.

8. Photons that remain local, i.e., trapped, are compressed by a factor no greater than the local matter compression ratio, η, so that photons that remain trapped within a given layer of matter are increased in energy by the factor $\eta^{1/3}$. This is a constraint in the numerical calculation. If the problem consists of n layers and a minimum $R/\Delta R = \eta_{max}$, the maximum increase in energy of a given photon becomes of the order $(R/\Delta R)^{n/3}$.

9. The Eddington limit flux just balances radiation pressure against the gravitational force, which is GM_{NS}/R^2 per unit mass. To decelerate freely falling matter in a distance ΔR

requires an impulse per unit mass of the momentum v to be supplied in a time $2\Delta R/v$ and therefore requires a force $v^2/2\Delta R$. The ratio of the flux required to decelerate the matter to the Eddington flux is therefore $v^2R^2/2GM_{NS}\Delta R$ which is $R/\Delta R$ taking account of $v^2 = 2GM_{NS}/R$. The bremsstrahlung rate is proportional to n_e^2 or ΔR^{-2} and the time of deceleration is proportional to ΔR so that the total number of photons produced by bremsstrahlung is proportional to $1/\Delta R$ the same as the deceleration flux. Therefore, for all ΔR and the previous conditions, the photon heating rate by the free fall matter will exceed the photon multiplication rate by bremsstrahlung.

10. Double compton scattering will increase the photon number at a rate compared to Compton scattering:

$$\sigma_{double\ c} = (1/137)\ \sigma_c (\frac{h\nu}{mc^2})^2 \quad .$$

The highest energy photons have on the average undergone the most scatterings and so are the most likely to have made a second photon along the way. The number of scatterings per doubling is roughly 3, so the number of scatterings going from $(3\ keV \rightarrow mc^2) \simeq 3 \log_2(160) = 22$. Then

$$\frac{22\ \sigma_{double\ c}}{\sigma_c} \simeq 1/6 \ \langle (\frac{h\nu}{mc^2})^2 \rangle$$

which is < 1 so that double Compton does not limit photon energy significantly until $h\nu > mc^2$.

The free falling matter is decelerated only when the photon energy exceeds the matter energy. Neither bremsstrahlung nor double Compton scattering affect the total photon energy, the first because of limited time, and the second because it merely redistributes the photon energy, i.e., makes a softer spectrum. We have chosen our thickness such that compression heating proceeds at just about the rate that photon energy is lost by diffusion. To illustrate this point we take the diffusion photon density distribution between at a reflector at $x = 0$ and an outer boundary at X:

$$\rho = \cos\ (\pi x/2X)$$

The collision rate is

$$N_{coll} = \int_0^X c\sigma\rho\ dx$$

and the escape flux is

$$F = \frac{c\sigma}{3} \frac{d\rho}{dx} \bigg|_X \quad .$$

The escape per collision is $\pi^2/(12\tau^2)$. Hence if it requires 3 collisions on the average to double the photon energy, then the total retained photon energy will remain constant if the probability of escape per collision is $2^{-1/3}$, corresponding to $\tau = 1$. Hence a modest increase in τ, will effectively trap the photons and their total energy can increase without limit proportional to $\eta^{1/3}$. Hence we feel a natural limit to compression will be reached when γ-γ collisions lead to pairs that then substantially increase τ. This offers a natural photon energy limit to the spectrum that is flux sensitive.

It seems reasonable to assume that the photon diffusion terminates when pair production doubles the lepton density. The calculations do not include pair production or this limit.

CALCULATION PARAMETERS

The calculation of the figure is relatively insensitive ($\cong$ 20%) to changes in energy group size $(W_{i+1}/W_i) \leq \sqrt{2}$, number of zones $n \geq 10$, and $\Delta R/R \lesssim 0.005$. If the initial seed temperature of .35 keV is reduced, then the energy group size, and ΔR must be smaller and n greater to obtain a result not grossly sensitive to the discreteness of variables.

ASTROPHYSICS

The maximum magnetic field that can be permitted can be estimated from Liang[5] who estimates the electron density for equal emission from bremsstrahlung and synchrotron radiation to be

$$n_e = 2.3 \times 10^{31}\ T^{3/2}\ F(T)\ B_{12}^2\ Z^{-1}\ \text{cm}^{-3} \quad ,$$

where T is kT_e/mc^2 and F(T) is of order unity for $T \cong 1$. Hence to keep synchrotron radiation below bremsstrahlung in the low density plasma ($n_e = 10^{18}$ cm^{-3}) requires $B_{12} < 10^{-6.5}$, or $B \leq 3 \times 10^5$ gauss. Since bremsstrahlung is rather a weak limit on the process and the high energy photons come from compressed layers, a field of several 10^6 gauss would be acceptable. However, the limiting field is far less than what would control or funnel accretion, 3×10^8 gauss. In any event magnetic field precludes the usual interpretation of the spectral structure as due to a cyclotron line. Some of our calculations show features similar to the observed dips at a few tens of keV. Another possibility is that a parallel softer photon source gives rise to these features.[11]

We feel that one possible astrophysical circumstance in which the field-free accretion we describe could occur is the instability of a Keplerian disc when it intersects, i.e. touches, the neutron star surface. Friction and turbulence will then cause some low density mass to accrete. Other possible candidates are super-Eddington thermal conduction to the surface from the interior of the neutron star or shocks that sequentially blow off surface layers that subsequently fall back. In both these possible examples one difficulty is the high atomic number of the neutron star matter results in high opacity and high photon emission. Comet accretion into an orbit that subsequently decays by gravitational wave emission is another possibility.

It is a pleasure to acknowledge the many discussions with our colleagues - particularly Ed Fenimore, R. Ramaty, Don and Fred Lamb, S. Woosley, David Pines and many others. This work was supported both by the Astronomy Section of the National Science Foundation and by DOE.

REFERENCES

1. D. Gilman, A. E. Metzger, R. H. Parker, L. G. Evans, and J. I. Trombka, Astrophys. J. 236, 951 (1980).
2. T. L. Cline, Ann. N.Y. Acad. Sci. 262, 159 (1975).
3. T. L. Cline, and U. D. Desai, Astrophys. J. Lett. 196, L43 (1975).
4. F. K. Lamb, Gamma Ray Transients, edited by Lingenfelter, Hudson, and Worrall (American Institute of Physics, 1981) p. 249.
5. E. P. Liang, Nature 299, 321 (1982).
6. E. P. Liang, Astrophys. J. 268, L89 (1983).
7. E. E. Fenimore, R. W. Klebesadel, J. G. Laros, and R. E. Stockdale, Nature, 297, 665 (1982).
8. J. I. Katz, Astrophys. J. 260, 371 (1982).
9. W. D. Evans, E. E. Fenimore, R. W. Klebesadel, J. G. Laros, and N. J. Terrell, Astrophys. Space Science 75, 35 (1981).
10. E. P. Liang, in Proceedings of e^+e^- Workshop, "Emission Model of Gamma-Ray Bursts," (Goddard Space Flight Center, January 1983)
11. J. P. Lasota and B. M. Belli, Nature 304, 139 (1983).

SAC/rep:70A