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STANFORD E. WOOSLEY

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THE THERMONUCLEAR MODEL FOR γ -RAY BURSTS

S. E. Woosley

Lick Observatory, Board of Studies in Astronomy
and Astrophysics, University of California,
Santa Cruz, CA 95064

and

Lawrence Livermore National Laboratory
Livermore, CA 94550

ABSTRACT

The evolution of magnetized neutron stars with field strengths of $\sim 10^{12}$ gauss that are accreting mass onto kilometer-sized polar regions at a rate of $\sim 10^{-13} M_{\odot} \text{ yr}^{-1}$ is examined. Based on the results of one-dimensional calculations, one finds that stable hydrogen burning, mediated by the "hot" CNO-cycle, will lead to a critical helium mass in the range 10^{20} to $10^{22} \text{ g km}^{-2}$. Owing to the extreme degeneracy of the electron gas providing pressure support, helium burning occurs as a violent thermonuclear runaway which may propagate either as a convective deflagration (Type I burst) or as a detonation wave (Type II burst). Complete combustion of helium into ^{56}Ni releases from 10^{38} to 10^{40} erg km^2 and pushes hot plasma with $\beta > 1$ above the surface of the neutron star. Rapid expansion of the plasma channels a substantial fraction of the explosion energy into magnetic field stress. Spectral properties are expected to be complex with emission from both thermal and non-thermal processes. The hard γ -outburst of several seconds softens as the event proceeds and is followed by a period, typically of several minutes duration, of softer x-ray emission as the subsurface ashes of the thermonuclear explosion cool. In this model, most γ -ray bursts currently being observed are located at a distance of several hundred parsecs and should recur on a timescale of months to centuries with convective deflagrations (Type I bursts) being the more common variety. An explanation for "Jacobson-like" transients is also offered.

INTRODUCTION

Although the theoretical community has historically been far from unanimity in its views concerning the site and specific mechanism(s) involved in the production of γ -ray bursts, observational studies, in particular recent spectroscopic examinations¹, have led to concentrated effort on models whose common underlying theme is a magnetized neutron star. The attractive nature of a neutron star site has long been recognized. The 10^{39} erg needed for a typical γ -ray burst at a distance of, say, 1 kpc, is easily realized by the accretion of only $\sim 10^{19} \text{ g}$ of material or the thermonuclear burning of $\sim 10^{21} \text{ g}$ of helium. These small amounts of material can accumulate in a reasonable time and at a reasonable rate and allow the possibility of recurrent outbursts from the

same neutron star. Since the total number of neutron stars in the Galaxy is only $\sim 10^9$, such repetition is required in order to provide the more than 150 bursts per year already being observed¹ and presumably maintained over the 10^{10} yr lifetime of the Galaxy. The small size of a neutron star is also in good accord with the fine time structure (< 0.1 s) seen in many bursts which limits the dimension of the emitting region to no larger than 3×10^6 cm. As has been emphasized in recent papers^{2,3,4}, the hardness of the γ -ray burst spectrum requires the confining presence of a strong magnetic field in order to keep the super-Eddington luminosity from blowing the emitting plasma out to great distance where it cools to low temperature. If this occurs, the soft thermal radiation (~ 1 keV) would bear little resemblance to the 200 keV to 500 keV radiation customarily seen in γ -ray bursts (see also Wallace, Woosley, and Weaver⁵ and Howard, Wilson, and Barton⁶). In order to magnetically confine 200 keV plasma, one needs $B^2/8\pi > a^4$, or a field strength in excess of $\sim 2 \times 10^{12}$ gauss. While this simple argument assumes that all of the hard radiation in γ -ray bursts is produced thermally, which almost certainly is not the case, a field near this strength is still required in models that invoke non-thermal processes. Such strong fields are only expected on neutron stars and it is reassuring to find that spectral line features¹ in γ -ray bursts (attributed to cyclotron absorption and gravitationally red-shifted pair annihilation) seem to confirm this hypothesis. Finally, in the case of the March 5, 1979 event and, with less certainty, the event of October 29, 1977, one has evidence for periodicity in the event (8.0 s and 4.2 s respectively) that is to be associated with the rotation (or perhaps precession) period of an old neutron star.

If γ -ray bursts do in fact originate from magnetized neutron stars, two basic energizing mechanisms can be involved, gravitational collapse and/or thermonuclear explosion. In the case of a gravitational power source, at least three distinct scenarios have been discussed. These include neutron star quakes⁷ which energize surface oscillations and produce hot plasma by magnetic interactions⁸; sudden accretion of plasma as a result of a flaring companion star or magnetospheric instabilities⁹; and the accretion of a comet or asteroid^{2,6,10,11,12}. Difficulties of varying degree beset each of these models. The underlying cause of a hypothetical neutron star "super-quake" and its efficiency for coupling to large amplitude surface oscillations has yet to be addressed in the Ramaty et al model¹. Furthermore, if this alleged instability occurs only several times during the life of a neutron star, the requisite number of common γ -ray bursts cannot be provided (although this model might still function adequately for such special events as that of March 5, 1979). One must also wonder why γ -ray bursts are not customarily associated with known pulsar "glitches". Accretion from a flaring companion star does not appear likely to explain the rapid rise time and short duration of such γ -ray bursts as that of June 13, 1979 (ref. 13).

Magnetospheric gating is an attractive hypothesis, not only for γ -ray bursts, but also for a host of other high energy transient phenomena, including Type II x-ray bursts. Unfortunately, the nature of the magnetic instability and a quantitative description of its operation remain to be developed. Similarly, while accretion of a solid object may be a viable γ -ray burst model, the interaction of objects incident with non-zero impact parameter and the frequency of asteroid/neutron star collisions remain great uncertainties (although see ref. 14).

An alternative class of models relies on the sudden release of energy by a thermonuclear explosion near the magnetic polar cap of a neutron star^{4,13,16,17,18,19} and is the principal subject of the remainder of this paper. Such models invoke the nuclear combustion, either by detonation wave or convective deflagration, of a highly degenerate layer of helium or carbon in a "nova-like" outburst. The fuel reservoir is a result of slow mass accretion ($\sim 10^{-13} M_{\odot} \text{ yr}^{-1} \text{ km}^{-2}$), either from a binary companion star or in a supernova remnant or interstellar cloud, and the outburst repeats each time a critical mass of fuel is accumulated. Magnetic confinement of the explosively heated ashes is an essential ingredient. In the next section the results of one-dimensional numerical simulations⁵ of thermonuclear explosions on slowly accreting neutron stars are briefly reviewed. Without magnetic confinement, little hard radiation is produced and the observable consequence is a rapid x-ray transient, not a γ -ray burst. The third section then deals with modifications resulting from the introduction of a strong magnetic field ($\sim 4 \times 10^{12}$ gauss). Further observable properties of the γ -ray burst model, as well as instrumental requirements for its proper study, are discussed in the conclusions.

ONE DIMENSIONAL CALCULATIONS

In a recent paper⁵, Wallace, Woosley, and Weaver have numerically simulated (non-magnetized) neutron stars accreting compositions of various metallicities at rates in the range 10^{-11} to $10^{-9} M_{\odot} \text{ yr}^{-1}$. A standard neutron star of radius 14.3 km and mass $1.41 M_{\odot}$ was employed in all calculations. For the assumed parametrizations, hydrogen burning in the accreted material is mediated by the β -limited CNO cycle²⁰ and is therefore stable. Thick helium shells in the mass range 10^{23} to 10^{25} g accumulate, ignite under highly degenerate circumstances, and explode. For specific illustration, I shall consider here only 2 models, called I and II, which exemplify the two qualitatively distinct modes of outburst⁵ expected for accretion rates in this range. The numerical results⁵ from these two models are summarized in Table 1 which gives the total accretion rate, mass, density, temperature, and thickness of the hydrogen and helium shells; total energy output in electromagnetic radiation and in neutrinos; peak temperatures at the base of

the burning helium shell; rise time; duration of Eddington luminosity; recurrence time; mass loss rate; total mass lost; and total energy expended in driving mass loss. The low value of metallicity used in Model II is not critical to the results that follow. Other combinations of (more nearly solar) metallicity and (slightly larger) accretion rate can give similar behavior⁵. Owing to the high conductivity of degenerate matter and the thinness of the helium shell, it is assumed that the ignition temperature of the helium shell is set by the steady state burning temperature of hydrogen.

Aside from strictly quantitative differences resulting from its slower accretion rate and cooler hydrogen shell, Model II differs categorically from Model I in the manner of its burning. The runaway propagates as a detonation wave that, with a velocity of roughly 9000 km s^{-1} (Mach 1.5), sweeps around the entire neutron star in about 5 ms (ref. 16), igniting the entire helium layer as it goes. Since the propagation time for this wave to reach the surface from the base of the helium layer is far shorter than this (7.2 μs) and since the surface luminosity rises to near its peak (Eddington) value in only about 1 ms (as a result of the gravitational energy released as the suddenly expanded material falls back to the neutron star surface), this implies a rise time of ~ 2.5 ms for Model II.

The ignition of the helium layer in Model I, on the other hand, must wait for a convective burning front to move around the star, an occurrence that takes much longer than the sonic transit time. The 1 ms rise time given in Table 1 for Model I is a purely formal result of the one-dimensional calculation and is a gross lower bound. Calculation of a realistic ignition time for the entire star in Model I is a difficult problem since it depends on the rate of convective entrainment of surrounding unburned helium into the burning front. Ignition will proceed as a wave (like a burning fuse or candle) and will be faster than simple conduction. Providing that it does not exceed the 320 s formal (1D) duration of the event, the ignition timescale will once again give the rise time for the transient which could, in principle, be quite long.

In both cases the sudden burning of large amounts of helium to iron-group elements (chiefly ^{56}Ni) leads to an enormously super-Eddington luminosity at the base of the neutron star atmosphere. When we originally carried out these calculations, it was hoped that this large luminosity would translate into a high effective emission temperature, i.e., a γ -ray burst. What we found instead, obvious in retrospect, is that the excess radiation pressure blows the envelope out to a fairly large distance (50 km to 100 km) thereby storing its excess energy in the form of a gravitational "battery". At this large radius the super-heated neutron star emits soft radiation (~ 1 keV) at a rate that, except during the first millisecond (free-fall timescale), differs very little from the Eddington value. As the event proceeds the stored

gravitational potential energy is gradually converted back into heat and radiated away. This energy input, along with continued helium burning, especially in Model II, gives an enduring x-ray transient with properties given in Table 1. During the time that the photosphere is receding back to the "surface" of the neutron star at near constant luminosity, one sees first a hardening of the emission spectrum followed by a softening as the surface of the neutron star cools in the tail of the event. This spectral behavior should be evident in all x-ray transients operating at or above the Eddington luminosity.

An interesting side effect of the enduring and slightly super-Eddington luminosity is the existence of a strong stellar wind of roughly 10^{18} g s^{-1} . Since the radiatively driven material comes off at about the escape velocity of the neutron star, $\sim 0.5 c$, it consists of very energetic electrons and protons. Indeed, from 3% (Model II) to 20% (Model I) of the total explosion energy goes into driving this mass loss (total mass lost is ΔM in Table 1). Interaction of these energetic particles with either a surrounding (weak) magnetosphere or other plasma in the vicinity (the flow itself is likely to be Rayleigh-Taylor unstable) may lead to hard non-thermal radiation accompanying these soft x-ray transients. This is particularly interesting in light of "Jacobson-like" γ -line transients^{21, 40}. Roughly 10^{40} to 10^{42} erg would be produced here in the form of high energy ($E > 200 \text{ MeV/nucleon}$) protons and α -particles and the event could easily last as long as the 20 minute observed duration of the June 10, 1974 event. The gravitational red-shift, however, would be no larger than at the photosphere ($\sim 50 \text{ km}$) or less than about 10%, considerably smaller than at the surface of a cold neutron star. If this explanation is correct, then Jacobson *et al* saw the high energy portion of a rapid x-ray transient, due primarily to inelastic nuclear scattering and spallation, and missed the softer emission due to the limited response of the detector. A search for γ -ray lines in the spectra of other known x-ray transients would be interesting. Unless the lines originate in a region far above the photosphere where the gravitational field is small or else in a very thin region just above the photosphere it is difficult to understand the narrow line widths. Differential gravitational broadening would be expected to give a width equal to some substantial fraction of the red-shift.

EFFECTS OF A STRONG MAGNETIC FIELD

Now consider the modifications to the above picture resulting from the introduction of a magnetic field of roughly 4×10^{12} gauss, consistent with that inferred from the observed cyclotron features. First, accretion will no longer be spherically symmetric but will be focused onto the magnetic polar caps of the neutron star^{22, 23, 24}. The area and geometry of the accreted layer is highly uncertain but I shall adopt a circular region of radius 1 km both for illustration and consistency with the current

literature. As was pointed out by Woosley and Taam¹⁵, the principal effects of this focused accretion are a smaller critical mass, explosion energy, and requisite accretion rate for given hydrogen and helium shell parameters, explosion characteristics, and recurrence timescale. The accretion rates for the geometrically modified Models I and II now become $4.3 \times 10^{-13} \text{ M}_{\odot} \text{ yr}^{-1}$ and $2.5 \times 10^{-14} \text{ M}_{\odot} \text{ yr}^{-1}$ respectively for accretion on $\pi \text{ km}^2$. These accretion rates give rise to a steady and potentially observable soft x-ray luminosity of $8 \times 10^{32} \text{ M}_{13} \text{ erg s}^{-1}$ with $\dot{M}_{13}$ the mass accretion rate in units of $10^{-13} \text{ M}_{\odot} \text{ yr}^{-1}$. The emission temperature would be around $5 \times 10^6 \text{ K}$. It is interesting that within the locational error box for the event of November 19, 1978 there is a weak x-ray source¹⁶. The inferred luminosity, roughly $10^{32} \text{ erg s}^{-1}$ at 1 kpc, is consistent with the thermonuclear model although perhaps a little low (depending on the actual distance to the event, the effect of anisotropic emission on the steady x-ray flux, and whether the November 19, 1978 event corresponded to Model I or Model II). Substantially lower limits on x-ray emission, which should be continuing even at the present time, from other γ -ray burst error boxes could greatly constrain, and even rule out, the thermonuclear model for specific events.

Following the anisotropic accretion of matter onto polar caps, it is important to know whether the accreted material remains localized or spreads over the neutron star surface. The heat generated by accretion and hydrogen burning, once it has ignited, melts the neutron star crust in the vicinity of the accretion so that it sags beneath the weight of the accumulated material. Were the crust and accreted material of the same composition then the accreted layer would not project substantially above the surrounding neutron star surface, but because hydrogen and helium have electron mole numbers that differ from the surrounding iron (^{56}Fe) substrate, the surface of the accreted layer floats, in hydrostatic equilibrium, several meters above the surrounding iron. Were it not for the necessity of crossing strong magnetic field lines the accreted material would flow some considerable distance, ultimately covering the entire star. It must be realized, however, that the change in altitude of the neutron star surface does not occur abruptly at any point. Rather there is a lateral pressure gradient and this lateral gradient, if small enough, can be maintained by strong magnetic field lines pinned to the deep interior of the neutron star. Diffusion across the field does occur, but on a very long timescale⁴, typically thousands of years for a field strength of 4×10^{12} gauss, and is negligible given the short time spent by the accreted matter in that part of the hydrogen shell above the median neutron star radius. In Model I this distance (which may be computed from Table 1) is 6.7 m and the time spent there by accreted matter is 5 hours. In Model II the corresponding numbers are 16 m and 47 days.

Although it is not quite so obvious, accreted material is in even greater jeopardy of "blowing out" near its base than it is of

spreading over the surface (Fig. 1). This is because the hydrogen and helium layers have pressure scale heights that are different from iron and therefore experience a different pressure at a given radius. The absolute value of the pressure difference is greatest about one pressure scale height above the base of the helium layer, far below the surface of the neutron star. It turns out once again that magnetic field lines can inhibit the subsurface spreading in Model I (if one neglects plasma instabilities), but prove inadequate in Model II (ref. 4). Helium in Model II is therefore expected to break out and spread some distance away from the locality of the accretion. This break-out may also occur in Model I if the interchange instability allows material to squeeze between magnetic field lines. Once the material has spread over an additional kilometer or so, however, the temperature of the iron/helium mixture falls below the freezing point and the strong shear modulus of the neutron star crust²⁶, about 10^{24} dyne cm⁻², comes into play. This solidification prevents further spreading when the accreted material still covers a small fraction of the neutron star surface⁴. Subsurface spreading does, however, introduce an additional degree of freedom into the models in that the region that eventually explodes may be considerably larger than the area of accretion. This gives rise to larger critical masses, greater explosion energies, and longer recurrence timescales than would occur without spreading. Providing that only a small fraction of the neutron star surface is covered, a γ -ray burst is still possible. Indeed, in Model I, the slow speed of the convective ignition wave would allow a γ -ray burst to occur as a precursor to an x-ray transient⁴.

Multiplying the critical masses in Table 1 by the ratio of accretion area to neutron star area (1.2×10^{-3} in the cases under discussion) gives the masses involved in the γ -ray outburst. Once these helium masses have accumulated (the recurrence timescale should be little modified from Table 1), an explosion ensues. In Model I the explosion proceeds by convective deflagration, consuming $\sim 3 \times 10^{10}$ g of helium and releasing $\sim 5 \times 10^{48}$ erg. Once again, because of the difficulty in estimating the lateral propagation velocity of the burning front, both the rise time and duration of the outburst cannot be easily estimated for Model I. An upper bound on the ignition timescale is the time required for thermal diffusion to go 1 km at the base of the helium layer, or a few hundred seconds⁴. It seems reasonable to associate this time, which could realistically be on the order of 10 s, with the duration of such "long and irregular"¹³ bursts as the April 27, 1972 (Apollo) event. The irregular variations in intensity seen during such bursts would be attributed to "sputtering" of the burning wave (due perhaps to an uneven distribution of fuel on the surface of the neutron star) and to magnetic instabilities in the plasma pushed above the surface of the star by the explosion (see below). The rise time for such events would also be uncertain. Some emission would commence as soon as the convective burning front came

close to the surface (~ 1 ms) but, unless the plasma pushed above the surface cools very rapidly, emission at a fraction of the maximum luminosity can occur only after a substantial fraction of the entire helium layer has been ignited. Thus the event would have a sudden onset, but at a very low luminosity, a gradual rise to peak, and then a slow decline as the fuel is exhausted and all thermal energy is extracted from the explosively heated material. Such behavior is consistent with that observed in γ -ray bursts of this type.

Model II will ignite by a detonation wave and the rise time, given by the time required to heat most of the plasma in the polar cap region and push it above the surface, will be quite short. At a velocity of roughly 9000 km s^{-1} (ref. 16) the wave will propagate across the 1 km radius of the polar cap in about 0.1 ms . During this time $\sim 10^{22} \text{ g}$ of helium is ignited. The burning continues for a considerable time following the passage of the detonation wave, and ultimately releases $\sim 10^{40} \text{ erg}$. Unless stopped by a physical barrier, such as a region void of thermonuclear fuel, the detonation wave will ignite the entire layer in one swift passage¹⁶. Thus one expects a "single spike" event whose duration is given by the cooling time (or characteristic timescale of some non-thermal process) at the spectral energy where measurements are carried out. Examples of such events would be the events of March 5 and June 13, 1979.

Any attempt to examine the spectral properties of these models leads us to consider the interaction of multi-billion degree plasma, heated and pushed above the surface by the explosion, with a very strong magnetic field. Thermodynamic conditions in Models I and II are plotted in Fig. 2 as a function of the altitude above the surface. This particular figure⁴ has been prepared assuming a field of infinite strength, i.e., $\beta = 0$, so that no lateral expansion can occur. In actual fact, a field of $4 \times 10^{14} \text{ gauss}$ is not able to effectively confine such hot plasma and some lateral expansion must occur, especially in Model II. As the plasma expands, thermal energy in the plasma is converted into and stored as magnetic field stress. In Model II, for example, roughly $1/2$ of the energy in plasma pushed above the surface, which in turn is about 20% of the total explosion energy, is stored in this form. Such highly distorted field configurations (Fig. 3) are unstable (for example to the interchange instability) and, without a continuing source of energy input, will return to a force-free configuration in some uncertain, but presumably quite brief, time. There may be continuous input, however, from convection and continued nuclear burning below the surface. While never again so large as when the explosion first occurs, this sustained input can cause plasma instabilities to continue throughout the event. One then has a highly complex picture of the plasma configuration and emission properties. In the vertical direction the plasma rests in near hydrostatic equilibrium, with a small amount of mass continually driven up the column as a wind (like that

obtained in the 1D calculations). In the lateral direction, motion is greatly affected by magnetic interaction, instabilities, and the energy being fed from below. So long as the vertical temperature gradient remains superadiabatic, convection is able to effectively transport heat up the column even when the β of the plasma becomes small²⁷. This occurs through a phenomenon known as "overstable convection" in which heat is transported by conduction back and forth between fingers of plasma oscillating in the vertical (field-aligned) direction. Vertical energy transport proceeds on a timescale much more rapid than ordinary conduction.

The spectrum of a γ -ray burst generated by the thermonuclear model will also be complex and will have two components: a thermal component which comes from both the top and magnetically confined sides of the plasma blob, and a non-thermal component which comes from magnetic interactions and/or the radiatively driven wind moving up the plasma column. The thermal component itself is far from simple since there is no unique temperature. Instead, emission from different heights in the plasma column is characterized by different temperatures, with cooler plasma at higher altitudes. A preliminary, and thus far unpublished, calculation by Wilson, Barton, and Woosley shows that the surface of the plasma column cools rapidly and, ignoring non-thermal effects and plasma instabilities, emits in a temperature range roughly 10 to 50 keV with a temperature scale height of roughly 50 m. Although this radiation may account for the bulk of the bolometric emission of a " γ -ray" burst and for such soft-spectrum events as that of March 5, 1979, it is not adequate to explain the hard emission found, especially early on, in the spectra of many common γ -ray bursts.

Non-thermal emission may result from at least three processes. First, because a substantial fraction of the explosion energy is stored in, and continues to be transformed into magnetic field stress, there is the possibility of non-thermal particle acceleration by magnetic recombination. As a specific example, consider plasma breaking out of the foot of the column (Fig. 3) by the interchange instability. This plasma has within it a strong magnetic field and as it squeezes through the surface of the plasma column (photosphere) in finger-like projections, field lines of opposite directionality come into close proximity. If magnetic recombination occurs, then charged particles, chiefly electrons, can be accelerated to high energy and emit synchrotron radiation. Second, consider the fact that the surface of the magnetically confined plasma column is not static. For example, following the thermonuclear outburst in Model II, the surface of the star (in the 1D calculation) undergoes rapid, large amplitude oscillations (Fig. 4). One should think of the plasma "bubble" in Fig. 3 as continually "jiggling". As the surface of the superconducting plasma moves back and forth through the strong magnetic field, intense non-thermal radiation will result³. This configuration has an added advantage over the model of Ramaty, Lingenfelter, and Bussard³ (based on a neutron starquake) in that the

plasma surface is quite naturally everywhere parallel to the magnetic field lines. This is an assumption that must be introduced artificially in the Ramaty *et al* model. A third possibility for non-thermal emission involves the "stellar wind" discussed in the previous section. There are particles moving with high velocity along the field lines in an optically thin region above the top of the plasma column. They are accelerated by the super-Eddington radiation pressure streaming up from the neutron star (electrons) and by the strong electric field created by charge separation (nuclei). Direct interaction of these particles (perhaps in a Rayleigh-Taylor unstable region), or acceleration of other non-thermal particles by the strong electric field, can give hard radiation.

The duration of a γ -ray burst produced by a thermonuclear explosion is difficult to estimate since it involves a complicated magnetic interaction, but it is likely to be characterized by different timescales at different spectral energies. In Model I, where the ignition of new fuel is expected to continue throughout the event, one may expect that the spectral hardness would stay relatively constant during (most of) the event. In Model II, the strongest magnetic interactions and hence the hardest radiation, should occur early on during the early "impulsive" phase of the event, with gradual spectral softening expected as the event proceeds and the distorted field sorts itself out into a nearly force-free configuration. In general, the spectral hardness of the event should also be correlated with the strength of the magnetic field. Stronger fields confine the plasma at higher temperatures and are likely to produce more energetic particles by non-thermal processes. An observational study addressing the correlation, if any, between cyclotron absorption energy and spectral hardness would be interesting. So too would a study of the time history of the width of the cyclotron absorption line. Early on, especially in detonating models, considerable broadening is expected due to the highly inhomogeneous field near the surface of the neutron star (Fig. 3). Later, as the field becomes more ordered, the absorption line may become narrower.

Because the plasma column can radiate from its sides, it is not expected to be optically thick at such large radii as obtained in the 1D calculations (~ 50 to 100 km). Roughly speaking, the top of the optically thick plasma column (upper photosphere) should occur at a radius where the time scale for energy transport from below, by conduction and convection, balances the timescale for lateral conduction and escape from the column. Since the flux of energy up the column, along magnetic field lines, is still essentially Eddington limited, the conduction timescale from the center of the column near the upper photosphere should be given by $s\Delta M/fL_{\text{Edd}} \sim \kappa \rho R^2/c$, where s is the average internal energy per gram in the mass ΔM (per unit area) contained in the photosphere (or, roughly, the mass external to the photosphere), fL_{Edd} is the luminosity up the column (i.e., f times the Eddington value), κ

is opacity, ρ the density at the photosphere, R roughly 1 km, and c , the speed of light. From the 1D calculations²⁶ one finds a self-consistent solution to this equation for Model I at an altitude of several hundred meters. There $\epsilon \sim 10^{19}$ erg g⁻¹, $\Delta M \sim 5 \times 10^{15}$ g km⁻², $f \sim 1$, $X \sim 0.2$, and $\rho \sim 1$ g cm⁻³. This corresponds to a conduction time across the column of about 0.1 s. Conditions for Model II are similar but at a somewhat higher altitude, ~ 1 km.

The time required to transport a substantial fraction of the energy out of the plasma pushed above the surface by the explosion will probably be less than that time required for heat to diffuse ~ 50 m (the density scale height) at a density of $\sim 2 \times 10^3$ g cm⁻³ (density at the base of the column following lateral expansion to $\beta \sim 1$) or about 20 s. This will be accelerated by convection²⁷, plasma instabilities, and the reduction of the electron scattering opacity along the strong magnetic field. On the other hand, the cooling time will be lengthened by the transport of additional energy from beneath the surface of the star. Further numerical calculations coupling all these effects will be necessary to estimate the actual cooling time.

Since roughly 3/4 of the energy of the explosion is contained in plasma that is never pushed above the surface, there should be a period of softer emission following the hard outburst as these subsurface ashes cool. So long as a locally super-Eddington luminosity is maintained, one expects some continued magnetic interaction. Thus the spectral hardness cannot be accurately calculated. It will, however, be no softer than 2 keV, the Eddington temperature for our neutron star, and probably not much harder than 50 keV, since one expects the principal emission processes in the late stages to be thermal. The luminosity itself will be at least Eddington, or about 2×10^{35} erg s⁻¹ for the explosion area we have assumed. The duration will be shorter than the event timescales given in Table 1 for the 1D models since we now have additional and more effective ways of removing energy from the explosively heated plasma. All in all, a timescale of from one hundred to several hundred seconds appears reasonable. As the luminosity falls below the Eddington value there should be a soft thermal tail to the event (~ 50 s in Model I, ~ 1000 s in Model II) during which the temperature gradually declines below 2 keV and the neutron star cools off. Measurements of the characteristics of this tail of the light curve would be especially useful in diagnosing the amount of mass involved in the outburst and in distinguishing thermonuclear and accretion based models.

SUMMARY AND INSTRUMENTAL CONSIDERATIONS

The thermonuclear model is capable of producing a wide variety of high energy transient phenomena including Type I x-ray bursts²⁸, rapid x-ray transients⁵, γ -ray bursts, and, perhaps Jacobson-like γ -line transients. The key characteristics

distinguishing among these various possibilities are the accretion rate and magnetic field strength. If the field is weak, then slow accretion ($< 10^{-9} M_{\odot} \text{ yr}^{-1}$) gives large critical masses and x-ray transients shining at the Eddington luminosity with nuclear burning all over the stellar surface. More rapid accretion rates (but still with weak fields) give smaller critical masses, lower energy outbursts that may even be sub-Eddington, and more rapid recurrence timescales. These are the Type I x-ray bursters. With a magnetic field and very low accretion rates it has been argued, both here and elsewhere^{4,15}, that one expects phenomena resembling γ -ray burst. An interesting, and as of yet unresolved question, centers on the evolution in accreting magnetized systems with accretion rates still smaller than considered here (i.e., $\dot{M} \ll 10^{-13} M_{\odot} \text{ yr}^{-1}$). Such low accretion rates might be typical for single neutron stars in the interstellar medium and may have to be considered if the steady state x-ray fluxes required by our present models are not observed. For such low accretion rates, even with magnetic focusing, hydrogen burning will not be β -limited. However, hydrogen burning can again lose its temperature sensitivity at such high densities that it is mediated by electron capture [the critical rate being $p(e^{-}, \nu)n$]. Thus a thick helium shell can still accumulate. Unfortunately, the study of this problem is currently hampered by inadequate knowledge of the pycnonuclear screening correction for the triple- α reaction at densities exceeding 10^8 g cm^{-3} . If, as Kuderman argues¹⁶, the helium burning reaction also loses all temperature sensitivity at such high densities, then it may be that there is no runaway at all and the helium (or carbon) neutronizes directly without ever igniting. If the helium burning reaction retains some temperature sensitivity, however, or if the accretion rate should increase for some reason, say because the neutron star passes through an interstellar cloud, then an energetic detonation-type event may occur^{4,17}. One must be concerned, however, that the accretion rate not become so low as to spread over the entire neutron star surface²⁴. Further calculations of this interesting range of parameters would be interesting.

Adopting for now our Models I and II as representative, we can examine the demands made on the model by present γ -ray burst statistics. Is it in fact possible to have a sufficient number of magnetic neutron stars accreting at the proper rate? Because of its more rapid recurrence cycle, Model I should be the more common γ -ray burster (even though Model II is visible from a greater distance). The total energy output by Model I is about $5 \times 10^{38} \text{ erg}$ of which we shall assume about 20% is emitted in the form of hard radiation visible to a γ -ray burst detector. A 10^{38} erg event would give a total flux of $10^{-6} \text{ erg cm}^{-2}$ (roughly the threshold of Mazets et al¹) if located at a distance of approximately 400 pc. Within this distance one expects about 2×10^5 neutron stars, which with a recurrence period of 0.4 yr, gives the observed rate of 150 bursts per year if only 0.03% of all neutron stars have

strong magnetic fields and are currently experiencing accretion rates in the right range. It does not seem that this small value would pose a severe constraint on the systematics of accreting neutron stars. Events corresponding to Model II would be from 1 to 2 orders of magnitude more energetic than those from Model I and could thus be typically located from 3 to 10 times farther away. This volume of the Galaxy would encompass many more neutron stars and would partly compensate for the long recurrence cycle of detonation events.

Within the context of the thermonuclear model, the March 5, 1979 event would have been a detonation event. Several solutions are possible⁴, but a typical case would place the site about 800 pc away with an accretion rate and area the same as in Model II. Due to subsurface spreading, the explosion encompasses an area 10 times larger than the accretion area. The total explosion energy would be 10^{41} erg and the recurrence period 2400 yr. The soft, pulsing tail of the event (~ 12 keV; ref. 29) would be the cooling surface layer described in the previous section modulated by rotation. The one to three subsequent bursts from the same general location as the March 5 event would be difficult to explain within the context of this model. If the association is real, one would have to invoke "spotty" accretion with several pockets of fuel concurrently accreting in various localities near the polar caps, or else entirely abandon a thermonuclear origin for this one event. It is also possible, although somewhat artificial, to construct a thermonuclear model that would place the March 5 event in the LMC (55 kpc). The helium layer would, however, have to cover the entire neutron star to a depth of ~ 300 m. Recurrent bursts would again be difficult to explain, but might be attributable to crust quakes following the major outburst (see ref. 4 for further details).

Many uncertainties exist in the theoretical scenario I have outlined and much careful analysis and thought is required before γ -ray bursts can be said to be understood. Numerical studies of magnetically confined, high temperature, optically thick plasma should be carried out to clarify the spectrum expected from such situations. Instabilities in $\beta \sim 1$ plasma in a 4×10^{12} gauss field need examination along with the stability and properties of the wind driven up the plasma column by super-Eddington emission. Realistic two-dimensional calculations of the lateral propagation of a convective deflagration are important, not only for γ -ray burst models, but also for a host of other astrophysical phenomena such as novae and thin helium shell flashes in intermediate mass stars. Pycnonuclear screening corrections for helium at densities exceeding 10^8 g cm^{-3} are required before realistic studies of still lower accretion rates can be carried out. Finally, the nature of convection and "overstable" convection in a strongly magnetized plasma should be explored with numerical models.

On the observational front the principal goals remain much as in the past: 1) accurate source locations, 2) broad band (i.e., x-ray and γ -ray) studies and time histories, and 3) high resolution spectroscopy.

The highest priority at the present time (although possibly not on any space mission planned for the distant future) should be given to obtaining accurate source locations. A beginning has already been made in that direction for 7 events²⁵ using timing considerations. Only with accurate source locations can we respond to such important questions as periodicity, steady state accretion luminosity, nature of binary companion star (if any), etc. The results of such observations will quickly prove or disprove the models theorists have been discussing.

It is my own personal feeling that in the not too distant future, perhaps with GRO, at least one non-ambiguous identification of γ -ray burst site will be made (besides the seemingly unique event of March 5, 1979!) and then that particular type of object will begin to be discovered in or near many previous error boxes. While a gamble of sorts, this suggests that perhaps in the long run, eg. for a proposed transient explorer class satellite that might go up near the end of the decade, the highest priority should be given to high resolution spectroscopy over a broad band of wavelengths and with good time resolution. These studies would yield the highest density of information and should enable us not only to understand qualitatively what a γ -ray burst really is, but also to examine in considerable detail the evolution and physics of an outburst. Since both the thermonuclear and accretion models predict x-ray emission associated with and following the hard outburst (cooling of a hot region on the neutron star surface), it is important that " γ -ray" burst detectors have good sensitivity in the region traditionally assigned to x-rays ($1 \text{ keV} < E < 100 \text{ keV}$). Otherwise a great deal of useful information, including the actual bolometric energy associated with a γ -ray burst, may not be obtained.

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TABLE 1
NUMERICAL MODEL CHARACTERISTICS

	Model I	Model II
$\dot{M}$ ($M_{\odot} \text{ yr}^{-1}$)	3.5(-10)	2.1(-11)
$\dot{M}_{\text{H}}$ (g)	8.0(20)	2.4(22)
ρ_{H} (g cm^{-3})	1.0(5)	1.1(6)
T_{H} (K)	1.2(8)	7.5(7)
Δ_{H} (m)	10	23
$\dot{M}_{\text{He}}$ (g)	2.7(23)	1.0(25)
ρ_{He} (g cm^{-3})	9.6(6)	1.2(8)
Δ_{He} (m)	36	73
T_{9peak} (10^9 K)	3.2	6.0
E_{γ} (erg)	1.3(41)	1.9(42)
E (erg)	3.9(38)	1.5(43)
τ_{rise} (ms)	~ 2	> 1
τ_{L} (s)	320	6500
τ_{rec} (yr)	0.4	240
$\dot{m}$ (g s^{-1})	5(17)	1(18)
ΔM (g)	2(20)	6(21)
$\Delta M v_{\text{esc}}^2 / E_{\text{tot}}$ (%)	20	5

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FIGURE CAPTIONS

- Figure 1. Magnetically focused accretion onto a neutron star gives rise to a blister of hydrogen and helium having dimensions roughly as shown in (a) for Model I. Curvature of the blister surface and interface have been exaggerated for purposes of illustration. In (b) the iron surface of the neutron star has been approximated by a plane and the curvature of the blister again exaggerated. Pressures at equal depths in the helium layer (points A and B) are very nearly equal, a small difference arising due to the varying thickness of the blister. The pressure at an equivalent depth in the iron substrate, however, is substantially less due to its smaller pressure scale height. The pressure gradient from point B to point C must be balanced by magnetic and crustal shear forces. The pressure at points D and E are equal.
- Figure 2. Thermodynamic conditions in plasma pushed above the surface of the neutron star by explosion in Model I (a) and Model II (b). Conditions have been evaluated at a time 1 ms following the sudden increase in surface luminosity due to convective energy transport (Model I) and shock wave break-out (Model II) and any lateral expansion has been neglected. The radius R_0 corresponds to the pre-explosive value of the surrounding iron surface of the star. The top scale gives the mass external to the given altitude. Magnetic "pressure" corresponding to a field strength of 10^{12} gauss is indicated. Plasma expansion is expected to occur in that region where its pressure dominates the magnetic field (a somewhat smaller region if, as is assumed in the text, $B = 4 \times 10^{12}$ gauss).
- Figure 3. Hot plasma pushed above the surface by the explosion in (in either Model I or Model II) expands causing the magnetic field to become highly distorted. For a field strength of $\sim 10^{12}$ gauss, pressure equilibration ($\beta \sim 1$) occurs when the internal plasma temperature has fallen to about 2 billion degrees. Most of the mass and explosion energy is contained in material still beneath the surface but thermal radiation from the magnetically confined photosphere, as well as non-thermal radiation produced as a result of the magnetic instabilities to

which this configuration is subject, is escaping from matter above the surface and producing a γ -ray burst. A small and highly uncertain amount of mass is driven up the magnetic column by the locally super-Eddington luminosity. Enormous electric fields ring the base of this column and may also accelerate electrons to high energy.

Figure 4. Radius and temperature at the boundary of several representative mass shells during the early evolution of Model II (see Model C, ref. 5). The mass indicated is the mass in grams external to the given zone boundary in the one dimensional calculation (multiplied by 1.2×10^{-3} for equivalent masses in the magnetically focused case). The original radius of the cold neutron star was 14.30 km, so $\sim 10^{24}$ g of material have been pushed above the surface in the 1D calculation. The duration of these oscillations was not determinable with our numerical hydrodynamics code due to the inherent damping in an implicit method.

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(a) $B = 4 \times 10^{12}$ gauss
 $\dot{M} = 4.3 \times 10^{-13} M_{\odot} \text{ yr}^{-1}$

Figure 1

Figure 2

Figure 3

Figure 4