The central engine of gamma-ray bursters

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Gamma-ray bursts (GRBs) are thought to arise in relativistic blast-wave shocks at distances of $10^{15.5\pm 1.0}$ cm from the point where the explosive energy is initially released.\textsuperscript{1,2} To account for the observed duration and variability of the \ensuremath{\gamma}-ray emission in most GRBs, a central engine powering the shocks must remain active for several seconds to many minutes but must strongly fluctuate in its output on much shorter timescales.\textsuperscript{2} We show how a neutron star differentially rotating at millisecond periods (DROMP) could be such an engine. A magnetized DROMP would repeatedly wind up toroidal magnetic fields to about $10^{17}$ G and only release the corresponding magnetic energy, $E > 10^{50}$ erg, when each buoyant magnetic field torus floats up to, and breaks through, the stellar surface. The resulting rapid sub-bursts, separated by relatively quiescent phases, repeat until the kinetic energy of differential rotation is exhausted by these events. Calculated values of the energy released and of the various timescales are in agreement with observations of GRBs. The amount of matter ejected (baryon loading) in each sub-burst may also be consistent with theoretical requirements for a blast wave capable of giving the X-ray, optical and radio afterglows recently observed\textsuperscript{3–7} from cosmological distances. DROMPs could be created in several kinds of astrophysical events; some of these would be expected to occur at about the observed GRB rate of $\sim 10^{-6}$/y per galaxy. The requisite very strong internal differential rotation could be imparted to neutron stars as they are born or at the end of their existence: one consequence is that some DROMPs may be created close to star forming regions while others may arise far from galaxies.
Compelling evidence\textsuperscript{3–7,8} now points to the cosmological origin of GRBs. Observed fluences imply a typical total $\gamma$-ray energy release $E_0 \sim 10^{51}$–$10^{52}$ erg for GRB sources at 3 Gpc. The lack of any high energy cutoff in the spectrum shows that the emission region is optically thin to $\gamma$-rays above the pair creation threshold—this is only possible if the effective radius, $d$, of that region is hugely larger than the several light seconds travelled by a photon in the GRB duration time ($t$), i.e. $d > > ct$. Therefore, the immediate source of the $\gamma$-rays must move towards the observer at relativistic speed with a Lorentz factor $\Gamma > > 1$.

In contrast to the observed spectra of GRBs, which typically have a power-law shape at high energies, photons emitted from a “fireball” with radiation in thermodynamic equilibrium with matter would have a nearly thermal spectrum.\textsuperscript{9,10} It appears necessary, therefore, for the observed emission to arise in nonthermal processes in a region sufficiently distant from “ground zero” of the explosion that the expanding plasma has finally become optically thin to electron scattering and pair creation by $\gamma$-rays.\textsuperscript{2} The relativistic blast-wave model, in which an external shock (and a reverse shock) is formed as a consequence of the significant slowing down of the expanding relativistic ejecta (initial baryon mass $M_0$) after a mass $M_0/\Gamma$ has been swept up from the ambient medium, satisfies various theoretical constraints for forming GRBs at cosmological distances. The model has been especially successful in explaining, and even predicting,\textsuperscript{11–13} the long-lived X-ray, optical and radio afterglows observed after some GRBs.

The detailed model of the blast wave depends on both the energy released and the density of the ambient medium. A match with observations can be obtained for an explosion in an ambient density not exceeding that of the interstellar matter (ISM) if the initial kinetic energy, $E_0$, of the relativistic ejecta is of the order of a tenth of a percent of the rest-mass energy of a neutron star, i.e. $E_0 \sim 10^{51}$ erg, and $\Gamma \geq 100$. These values suggest that a violent process involving a neutron star, such as its merger with another comparably compact object or its sudden creation as a millisecond pulsar, may power the blast waves which give rise to a GRB. However, even taking account of relativistic expansion and beaming, the observed rapid variability of flux would require a remnant central engine which must remain active for time $t$, with the power output varying on timescale up to $10^6$ times shorter (i.e., as short as a ms), and then turn off. The $\gamma$–ray emission could arise from internal shocks\textsuperscript{2,14,15}, as successive shells of relativistically moving plasma run into each other. The essential requirement is finding an engine which emits such blasts with the correct time-scales for the energy release, one in which the baryon loading of the ejecta satisfies the necessary constraint $M_0 \leq E_0 \Gamma^{-1} c^{-2} \sim 10^{-5} M_\odot$ (for $\Gamma \sim 100$), and one for which all of this is not kept from being observed by an opaque shell released in some initial blast.

The central engine of gamma-ray bursters must have the following properties to account for the typical fluence in each observed $\gamma$–ray sub-burst ("peak"), for the number of peaks, $N_p$, the time interval between peaks, $\tau$, and for the rapid rise times and variability:
a) an energy of \( E_0 \sim 10^{51}\text{erg} \) must be released in each sub-burst;

b) \( N_p \sim 10; \)

c) between sub-bursts, the central engine should be dormant for intervals \( \tau \sim 1\text{s} \) to \( \sim 10^3\text{s}; \)

d) the engine should be capable of attaining its peak power within milliseconds and of exhibiting large fluctuations thereafter.

Further, to allow the formation of the relativistic shocks and the ultimate emission of \( \gamma \)-rays at the distance \( d \), discussed above,

e) no more than \( 10^{-5}M_\odot \) of baryons may be carried in each successive sub-burst.

We will argue that neutron stars with internal motions corresponding to differential rotation with millisecond periods have at least four of these properties and propose that they are the required relatively long-lived central engines of GRBs. Moreover, such neutron stars can be created in several kinds of astrophysical events at rates approximating those of GRBs.

In the absence of interior magnetic fields, the differential rotation would not be erased in a very hot neutron star (e.g., by Ekman pumping) in less than a day. However, magnetic field in the stellar interior could lead to a series of explosive releases of the kinetic energy of differential rotation until most of that energy is used up. The total available energy is then \( \hat{I}\Omega_d^2/2 \), where \( \Omega_d \) is the effective difference in angular frequency of rotation and \( \hat{I} \) is the corresponding effective moment of inertia, (which in a two-component model of differential rotation, is less than a quarter of the total stellar moment of inertia \( \hat{I} < I/4 \)). (For later convenience, we will write the initial differential rotational frequency as \( \Omega_\phi = \Omega_4 \times 10^4\text{s}^{-1} \), effective differential moment of inertia as \( \hat{I} = \hat{I}_{44} \times 10^{44}\text{g cm}^2 \), and initial interior field strength as \( B_0 = B_{12} \times 10^{12}\text{G}. \))

In a differentially rotating neutron star internal poloidal magnetic field (\( B_0 \)) will be wound up into a toroidal configuration and amplified (to \( B_\phi \)) as one part of the star (e.g. exterior) rotates about the other (e.g. core). After \( N_\phi \) revolutions, \( B_\phi = 2\pi B_0 N_\phi \). The toroidal field will be sufficiently buoyant to overcome fully the (approximately radial) stratification in neutron star composition only when a critical field value, \( B_f \), is reached. Because neutron-star matter would be brought up from the deep interior to the stellar surface too quickly for weak interactions to adjust its composition to the changing ambient neutron to proton ratio, \( y \), the difference in \( y \) between the interior and the subsurface layers results in a fractional difference, \( f \), between the density of transported and ambient matter (at the same pressure \( P \)), \( f = \rho^{-1} (\partial \rho/\partial y)_P \Delta y \sim 2\% \). For hydrostatic equilibrium of a magnetic torus brought from the deep interior to near the surface its magnetic buoyancy must be balanced by the anti-buoyancy from its baryon ratio gradient. [We have neglected the effects of thermal gradients in this discussion]. Then, \( B_f^2/(8\pi) = f \rho (\partial P/\partial \rho) = f \rho c_s^2 \), so that

\[
B_f \approx 7 \times 10^{16}\text{G} \times \left( \frac{\rho}{10^{14}\text{g cm}^{-3}} \right)^{1/2} \text{G},
\]

where we take the speed of sound \( c_s \approx c/\sqrt{10} \). The magnetic energy stored in a torus with
this $B_f$ is (for $\rho = 3 \cdot 10^{14}\text{g/cm}^3$)

$$E_p \approx 6 \cdot 10^{50}(10 \frac{V_B}{V_*}) \text{erg},$$  \hspace{1cm} (2)

Here $V_B/V_*$ is the fraction of the volume of the star occupied by the torus. This $E_p$ is independent of the initial magnetic field and of the initial differential rotational period of the DROMP, as long as $\dot{I} \Omega_4^2/2 > E_p$.

Only after the magnetic field reaches the critical value of eq. [1] will the buoyant torus be able to float up to break through the stellar surface. The emergence of the torus is accompanied by huge spin-down torques, reconnection of the new surface magnetic field and the quick release of an energy exceeding $E_p \sim 10^{51}\text{erg}$ (eq. [2]). This would be a sub-burst, satisfying condition a). The rapidity of the reconnection processes (occurring typically in $\sim 10^{-4}$s, the stellar radius divided by the Alfvén speed) would be expected to lead to exceedingly short rise-times and large fluctuations of power, possibly in agreement also with condition d).

The number of sub-bursts is the number of times the critical field is built up and the magnetic toroid ejected. Then,

$$N_p = \frac{3\dot{I} \Omega_4^2}{B_f^2 R^3} \left( \frac{V_*}{V_B} \right) \approx 6\Omega_4^2 \dot{I}_{44},$$  \hspace{1cm} (3)

in plausible agreement with condition (b) for typical values $\Omega_4 \sim 1, \dot{I}_{44} \sim 1$. The interval between sub-bursts, i.e. the time to build up the critical fields is

$$\tau = \frac{2\pi B_f}{\Omega_d B_0} \approx 20s \times B_{12}^{-1} \Omega_4^{-1},$$  \hspace{1cm} (4)

in fair agreement with condition c). (Note the sensitive dependence on the initial value of $B_0$.)

Eqs. (3) and (4) yield a total duration of $t \approx 120s \times B_{12}^{-1} \Omega_4$, after which the (differential kinetic) energy stored in the central engine is exhausted, or at least no longer capable of fully winding up another torus so that it too can be released: the gamma-ray burster turn off, apparently never to be seen again.

We now turn to the expected birth rate of DROMPs, keeping in mind the severe upper limits to the baryon loading of the initial blast wave accompanying the turn-on of the central engine. We are aware of four processes which may give rise to DROMPs at a rate sufficient to account for observed GRBs.

It has been argued\textsuperscript{16,17} that the rate of coalescence of Hulse-Taylor type neutron star binaries, $\sim 10^{-6}/y$ per galaxy, corresponds closely to the observed GRB rate. According to Newtonian calculations\textsuperscript{18} the matter ejected in the merger is mostly confined to the vicinity of the orbital plane, with no more than $10^{-5}M_\odot$ of the baryons contained in the cone of opening half-angle $45^\circ$ around the rotation axis. If the correct equation of state of
dense matter is sufficiently stiff—as recent observations of kHz quasi-periodic oscillations in accreting neutron stars may imply (ref. 19)—the post-merger core would not directly collapse to a black hole. A massive neutron star rotating with a period of $P_0 \sim 1$ ms could be formed instead. The same outcome would be achieved if the initial masses of the merging neutron stars were very low, $M \leq 1M_\odot$.

Another process which might lead to the formation of massive ms pulsars at the rate $\sim 10^{-6}/y$ per galaxy is accretion onto neutron stars in low-mass X-ray binaries (LMXBs). It seems plausible that at the end of mass transfer many of the neutron stars are on the supramassive sequence, i.e. they are supported by rapid rotation which delays a collapse to a black hole possibly by as long as $10^8$y–$10^{10}$y (the pulsar spin-down time). We would expect the onset of collapse to initiate differential rotation, i.e. in the creation of a short-lived DROMP and the ensuing GRB.

A third possibility is the rapid spin-up of a neutron star in a catastrophic accretion event, perhaps resulting from a collision with a white dwarf in a globular cluster.

Accretion induced collapse$^{20}$ (AIC) of certain evolved white dwarfs, mainly$^{21}$ in globular clusters (GC), may be the ideal process in which a DROMP giving rise to a GRB could be created. There is some evidence$^{22}$ that a large fraction of the ms pulsars in GCs have not been spun up in LMXBs and it has been suggested that they are a product of AIC. If AIC occurs DROMPs are nearly certain to result. Several AM Her type systems are known with the white dwarf rotation rate of $\sim 10^{-3}$s$^{-1}$ and magnetic fields $\sim 10^7$G, both values are expected to be amplified by a factor of $\sim 10^6$ in collapse to a neutron star, as pointed out by Usov$^{23}$ (who suggested AIC creation of ms pulsars with a $10^{15}$G dipole field which could directly energize the blast-wave with their spin-down power, thus giving rise to a single-peaked GRB of $\sim 30$s duration). The critical question is whether an initial blast wave associated with the AIC formation of the strongly magnetized ms pulsar has sufficiently small mass to allow the subsequent GRB phase to be observable. On the other hand, if that blast carries away considerable mass$^{24}$, the remnant neutron star mass would be much less than $1.4M_\odot$. Then, in the dense cores of GCs, Hulse-Taylor-like neutron star binaries might be formed with much lighter neutron stars, whose subsequent merger would almost certainly lead to the formation of DROMPs.

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REFERENCES

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FIGURE CAPTION

Fig. 1 The magnetic torus emerging from the neutron star.