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THE CENTRAL ENGINE OF GAMMA-RAY BURSTERS

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ABSTRACT

Cosmic gamma-ray bursts (GRBs) are thought to be created when relativistic blast waves that are powered by "central engines" emit gamma rays between 10 and 10,000 AU from where the explosive energy has been released. To account for the observed duration and variability of GRBs, the central engines must remain active from several to very many seconds and must usually fluctuate strongly in their output on much shorter timescales. We show how neutron stars that are initially rotating differentially at millisecond periods could be such engines, emitting, on the observed timescales, energetic pulses of the right variety and power for as long as the differential motion remains sufficiently vigorous. The energy stored in the differential rotation would be released mainly in sub-bursts, as toroidal magnetic fields are repeatedly wound up to $\sim 10^{17}$ G and, only then, pushed to and through the surface by buoyant forces. The same mechanism could also operate in nuclear density tori. The differentially rotating neutron stars or tori could be formed in several ways and at rates sufficiently high to explain the observed frequency of occurrence of GRBs.

Subject headings: accretion, accretion disks — gamma rays: bursts — instabilities — magnetic fields — stars: neutron — stars: rotation

1. INTRODUCTION

Compelling evidence points to a cosmological origin for gamma-ray bursts (GRBs) (Fishman & Meegan 1995; Fruchter et al. 1997; Djorgovski et al. 1997; Kulkarni et al. 1998). Observations indicate a typical total gamma-ray emission of $E_0 \sim 10^{51}$–10^{53} ergs. The diversity of the observed GRB light curves is remarkable in itself, suggesting that the emission sources have many variable parameters. The tremendous variety of GRBs and their observed durations and rapid variability in gamma-ray flux are difficult to understand unless relativistic shocks are emitted and powered by a complex, relatively long-lived, but strongly fluctuating source—the central engine.

If an energy of $E_0 \sim 10^{53}$ ergs were suddenly converted into thermal energy, as in a rapid gravitational implosion of a white dwarf or a neutron star, or in the final stages of the coalescence of a binary neutron star system, the gradual neutrino cooling and the creation of electron-positron plasma would result in an event with a smooth luminosity profile and a duration of several seconds (Katz 1997; Wilson, Salmonson, & Mathews 1998). But no more than a few of the about 2000 known GRBs have such a profile and duration. Instead, many GRB light curves exhibit tremendous fluctuations on timescales as short as several milliseconds.

The emitting system will be transparent to photons carrying this much energy only if its physical size is at least light-hours or light-days across—otherwise, the photon cloud would be opaque because of pair creation and electron scattering. But the duration of most gamma-ray bursts (a fraction of a second to minutes) is much shorter than the light-travel time across such a large region. This implies a relativistic motion of the emitting zone toward the observer. The X-ray, optical, and radio afterglows that are expected (Paczyński & Rhoads 1993; Katz 1994; Mészarós & Rees 1997a; Vietri 1997) when the ultrarelativistic shock from such an explosion runs into the ambient medium have now been observed in some gamma-ray burst events (Costa et al. 1997; van Paradijs et al. 1997; Frail et al. 1997)—in each of these, the afterglow fluences are comparable to the GRB fluence.

If a single explosion of comparable energy release creates a relativistically expanding shell with $\sim 10^{28}$ g in nucleons, the eventual interaction of the shell with interstellar matter is expected (Mészarós & Rees 1993) to give rise to a GRB when the shell has grown to a radius of $\sim 10^{3\pm1}$ AU. The expected gamma-ray light curve has only a single "fast rising exponentially decaying" pulse (Fenimore & Sumner 1997), but the majority of the observed GRBs have more than one peak in the gamma-ray light curve. In the longer bursts, quiescent intervals of many seconds, or even minutes, may separate individual sub-bursts, each perhaps exhibiting millisecond rise times and/or spikes. It is implausible that inhomogeneities in the expanding shell or the ambient matter would be able to reproduce the often complex variations in the energy flux of GRBs without at the same time extending the duration of the burst to the light-travel time (many hours or days) across the shell. It is therefore thought (Sari & Piran 1997) that much of the time structure seen in GRB light curves reflects the intrinsic timescales of the primary energy release at the source. The gamma rays must be released from "internal" shocks (Sari & Piran 1997; Daigne & Mochkovitch 1998) as successive, relativistically expanding shells are driven by the activity of the central engine, and this activity should last for the duration of the GRB, i.e., up to a million times longer than the dynamical time for the gravitational collapse or merger of neutron stars.

In §§ 3 and 5, we suggest a specific mechanism by which the central engine stores and releases the energy in repeated sub-bursts, thus eventually powering the internal shocks in the ultrarelativistic blast. We also discuss the formation of central engines possessed of this mechanism (§ 4) and show that such a central engine has the properties required for observations of GRBs, which we review in § 2.

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2. PROPERTIES OF THE CENTRAL ENGINES

In addition to simply storing energy for eventual release (of up to $\sim 10^{53}$ ergs), the central engine of gamma-ray bursters must have the following six properties to account for the typical fluence in each observed gamma-ray sub-burst ("peak"), for the rapid rise times and variability, for the great variety of bursts, for the number of peaks, N_p, in a GRB, and for the typical time interval between peaks, τ:

1. If baryonic matter is released by the central engine, it must be accelerated to ultrarelativistic speeds along the line of sight (so that the individual blasts from the engine expand enough to become transparent to gamma rays but still give observed emission peaks of a relatively short duration lasting for several seconds); the Lorentz factor of an expanding shell should be not less than $\sim 10^2$.
2. An energy of $E_0 \sim 10^{51}$ ergs must be released in each sub-burst.
3. The engine should be capable of attaining its peak power within milliseconds and of exhibiting large fluctuations thereafter.
4. There should be large variations among GRBs and, usually, between peaks in individual GRBs.
5. Typically, $1 \leq N_p \leq 10$.
6. Between sub-bursts, the central engine should often be dormant for intervals $\tau \sim 1$ to $\sim 10^3$ s.

3. NATURE OF THE CENTRAL ENGINE

In the gravitational collapse or merger of very compact objects of about a solar mass, up to $\sim 10^{53}$ ergs of energy can be released, about a tenth of the rest energy. Frequently, about as much again is initially present in rotational or orbital kinetic energy. It has already been noted by several authors that a rapidly rotating object, such as a millisecond pulsar (Usov 1992) or the very dense torus (Paczyński 1991), possibly arising in the coalescence of a neutron star with a black hole or in the merger of two neutron stars, could release its kinetic and gravitational binding energy over a relatively extended period of time. It has also been realized that for a canonical GRB to result, it seems necessary for that energy to be released electromagnetically (Katz 1997; Narayan, Paczyński, & Piran 1992; Blackman, Yi, & Field 1996; Mészarós & Rees 1997b) rather than released into weakly interacting thermal neutrinos from a hot fireball.

In most scenarios of the rapid gravitational compression of matter, the resulting spinning object is formed with internal relative velocities comparable in magnitude to the average rotational velocity. The maximum kinetic energy of a differentially rotating, collapsed object (DROCO) is certainly not less than could be stored in rigid rotation, e.g., up to about 3×10^{53} ergs for neutron stars (Cook, Shapiro, & Teukolsky 1994); this is sufficient to account for the inferred energy release in the gamma rays of GRB 971214 at the reported redshift of $z = 3.4$ (Kulkarni et al. 1998). We have considered the primary mode of release of this energy and find that neutron stars, or similar structures of nuclear density (e.g., remnant tori) with millisecond spin periods and comparable differences in the rotation period between the interior parts of the "star," satisfy the six properties required of the central engine. We propose such stars as candidates for the required, relatively long-lived central engines of GRB sources. Moreover, such neutron stars or tori can be created in several kinds of astrophysical events at rates approximating those implied by GRB observations.

4. FORMATION SCENARIOS

It has been argued (Paczyński 1991) that the rate of coalescence of Hulse-Taylor–type neutron star binaries, $\sim 10^{-6}$ yr^{-1} per galaxy, corresponds closely to the observed GRB rate. If the correct equation of state of dense matter is sufficiently stiff—as recent observations of kilohertz quasi-periodic oscillations in accreting neutron stars may imply (Kluźniak 1997)—the postmerger core need not directly collapse into a black hole: a massive neutron star, rotating with a period of $P_0 \sim 1$ ms, might be formed instead. On the other hand, if the equation of state is sufficiently soft, a torus rotating about a black hole may be formed in the coalescence of a black hole neutron star binary (Lee & Kluźniak 1998) that is expected to occur at a similar rate (Narayan, Piran, & Shemi 1991).

Another process that might lead to the formation of massive millisecond pulsars at the rate of $\sim 10^{-6}$ yr^{-1} per galaxy is accretion onto neutron stars in low-mass X-ray binaries, if, 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 into a black hole, possibly by as long as 10^9–10^{10} yr, the pulsar spin-down time). We would expect the onset of collapse to initiate differential rotation, i.e., the creation of a short-lived DROCO, and the occurrence of a GRB if the DROCO phase precedes the collapse into a black hole by a sufficiently long time (eq. [4]). The accretion-induced collapse (AIC) of a neutron star to a black hole may also give rise to a DROCO.

The AIC of a magnetic white dwarf (Nomoto & Kondo 1991; Bailyn & Grindlay 1990) with an appropriate composition may also lead to a rapidly rotating, strongly magnetized neutron star (Usov 1992), which most likely would be born with strong internal differential rotation. The radio pulsar PSR 1718−19 in the globular cluster NGC 6342 (Lyne et al. 1993), with a rotational period of 1 s, a 10^{12} G field, and a low-mass binary companion, has the properties expected of the remnant of a DROCO GRB formed in this way.

The "sudden" formation of a DROCO may or may not be accompanied by a huge explosion. But if it is, that blast must not eject a nonrelativistically moving shell that is opaque enough to keep the effects of subsequent bursts of emission from the remnant central engine from being observed as peaks of gamma rays. If such an initial explosive blast carries away an energy $E_B \sim 10^{51}$ ergs, the ejecta must move relativistically and carry a baryonic rest mass $M_b < 10^{-5}\ M_\odot$. To the extent that the DROCOs may be formed in binary mergers or by AIC, which forms the basis of previously discussed scenarios for the formation of GRBs, the "baryon poisoning" of the *initial* blast that accompanies the birth of a DROCO would be no higher or lower than in the previous scenarios. At least for mergers, both Newtonian and general relativistic calculations of the angular distribution of expelled matter indicate that there may be directions in which baryon poisoning is small enough to be acceptable (Rasio & Shapiro 1992; Mathews, Wilson, & Maronetti 1997; Kluźniak & Lee 1998). We show below that a DROCO, once formed, expels very little matter in its subsequent eruptions.

5. INTERNAL MECHANISM OF THE CENTRAL ENGINE

Very soon after the sudden formation of a hot neutron star DROCO, the initial convective and hydrodynamical instabilities will have been greatly diminished, while the initial differential rotation on cylinders about a common spin axis (the

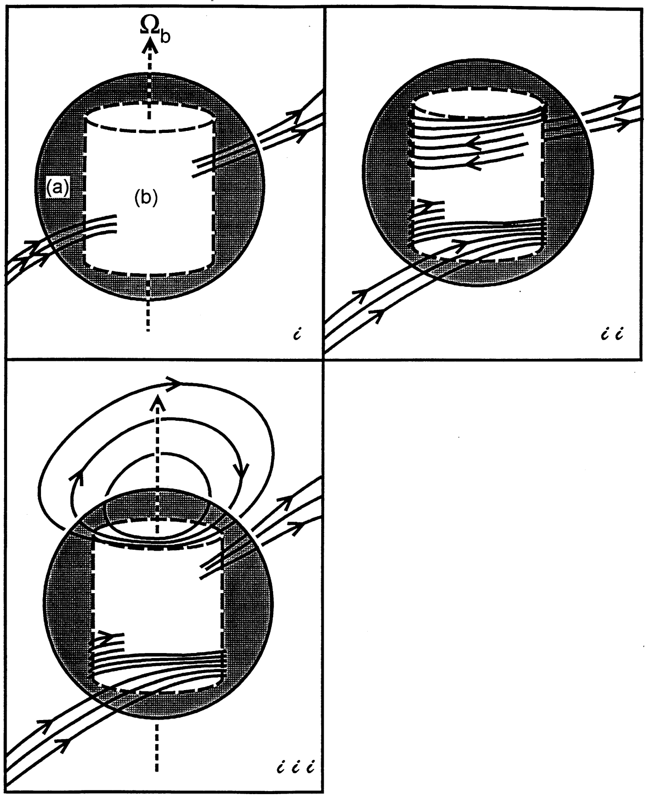

FIG. 1.—Magnetic field development in a DROCO. (i) Poloidal field passing through the (*a*) outer region of the star and the (*b*) central cylinder before differential rotation begins. (ii) Wound-up toriodal field after several turns about the common spin axis of (*b*) relative to (*a*). (iii) The breaking free and penetration of the stellar surface of one of the two wound-up tori that float up along cylinders on which the angular velocity is constant. For an inital 5×10^{12} G polar field, this will not occur before about 10^4 revolutions of (*a*) around (*b*), after which the winding begins again.

allowed Taylor-Proudman steady state motion) survives longer. In the absence of interior magnetic fields, the remaining differential rotation would not be erased in very hot DROCOs (e.g., by Ekman pumping) in less than 10^4 s if the mean free path of its neutrinos sufficiently exceeds the stellar radius. However, a significant initial magnetic field in the stellar interior should lead to a series of explosive releases of the kinetic energy of the differential rotation until most of that energy is used up.

In a differentially rotating neutron star, the internal poloidal magnetic field (B_0) will be wound up into a toroidal configuration and amplified (to B_ϕ) as one part of the star (e.g., the exterior) rotates about the other (e.g., the core). After N_ϕ revolutions, $B_\phi = 2\pi B_0 N_\phi$. The field thus amplified forms a toroid that encloses some neutron star matter. This magnetic toroid will float up from the deep interior only when a critical field value is reached, B_f, that is sufficient to overcome fully the (approximately radial) stratification in neutron star composition.

There are three principal factors that affect the stability of the configuration: the distribution of angular momentum, thermal gradients, and the compositional stratification. We assume that the distribution of angular momentum is stable (against the interchange of angular momentum in neighboring cylinders). In the following discussion, we ignore thermal gradients, even though they may be the principal stabilizing factor. We estimate the compositional difference for a zero temperature ground state. It would be very helpful to know how the antibuoyancy effect of the stratification in baryon number would differ in more realistic DROCO genesis scenarios from these calculated here for a cold star. For example, the partial equilibration of matter inside the torus (as it floats up) with that outside would oppose the effects of stratification and lead to lower estimates of B_f.

To estimate B_f, we assume that the surfaces of constant composition coincide with those of constant density. The forces of buoyancy then carry matter that is trapped in the magnetic toroid across principally these surfaces and along cylinders of constant angular momentum. Because neutron star matter would be brought up from the deep interior to the stellar surface too quickly for weak interactions to adjust their composition to the changing ambient neutron–to–proton ratio, y, the difference in composition between the interior and the subsurface layers results in a fractional difference, $f = \rho^{-1}(\partial\rho/\partial y)_P \Delta y \sim$ 2%, between the density of transported and ambient matter. The resulting antibuoyancy will be offset by the decreased pressure inside the flux tube. For the toroid to be neutrally buoyant as it floats up, the magnetic pressure must reach the value $B_f^2/(8\pi) = f\rho(\partial P/\partial\rho) = f\rho c_s^2$. Taking the speed of sound to be $c_s \approx c/\sqrt{10}$ and $\rho = 3 \times 10^{14}$ g cm^{-3}, we find $B_f \approx 10^{17}$ G. Only after the magnetic field reaches this critical value will the buoyant toroid be able to float up to and break through the stellar surface.

A crucial question is how much matter is lofted above the stellar surface and expelled in the process. The conducting fluid that is initially inside the flux tube stays within the star, but if too much matter external to it were to be carried above the stellar surface by the emerging flux-tube field, and possibly then expelled when some of that field reconnects, ultrarelativistic expansion would be impossible. An upper limit to the mass ejected follows from considering the net buoyant force. If the field in the flux tube is B_f, then the toroid would be neutrally buoyant. However, as the toroid floats up from the deep interior, the magnetic field in it continues to increase linearly with time over the value B_f computed above, because the field increases by $2\pi B_0$ with every revolution of one part of the star relative to the other (Fig. 1). Solving the equations of motion with the buoyant force increasing linearly with time, we obtain an estimate of the time it takes to float up and also, consequently, of the increase in the magnetic field above B_f, i.e., an estimate of the excess buoyancy. We find a net buoyancy capable of lifting a mass M given by

$$\frac{M}{M_*} \approx \frac{V_B}{V_*}\left[f\left(\frac{3\Omega_d^2 R_*}{\pi^2 g}\right)\left(\frac{B_0^2}{4\pi\rho c_s^2}\right)\right]^{1/3}$$

$$\approx 2 \times 10^{-5}\frac{V_B}{V_*}(\Omega_4 B_{12})^{2/3} . \quad (1)$$

Here V_B is the volume of the toroid, V_* and M_* are the volume and mass of the star, $\Omega_d \equiv \Omega_4 \times 10^4$ s^{-1} is the characteristic differential angular rotation speed, and $B_0 \equiv B_{12} \times 10^{12}$ G. For the numerical estimate on the right-hand side of equation (1), we inserted the values of ρ and c_s^2 used above, a typical value for the gravity in a neutron star, $gR_* \approx c^2/6$, and a radius of the star $R_* = 10^6$ cm.

As long as it does not exceed the energy in the initial differential rotation, the magnetic energy, E_p, stored in a toroid with the critical B_f does not depend on the initial magnetic field or on the initial differential rotational period of the DROCO:

$$E_p \approx 6 \times 10^{51} \frac{V_B}{V_*} \text{ ergs.} \quad (2)$$

A comparison of equations (1) and (2) shows that the minimum average Lorentz factor of the matter expelled as the energy is released is $\Gamma = E_p/(Mc^2) \geq 100(\Omega_4 B_{12})^{-2/3}(1.4\ M_\odot/M_*)$, satisfying the first condition mentioned in § 2. Note that this value of Γ is attained for any volume of the expelled toroid, i.e., regardless of the energy in the sub-burst.

The emergence of the toroid is accompanied by huge spin-down torques, the reconnection of the new surface magnetic field, and the quick release of an energy exceeding $E_p \sim 10^{51}$ ergs (eq. [2]). This would be a sub-burst, satisfying the second condition mentioned in § 2. 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, as required by the third condition mentioned in § 2.

The number of sub-bursts is the number of times the critical field is built up and the magnetic toroid ejected. This is just the ratio of the initial kinetic energy in the differential rotation, E_R, to E_p:

$$N_p = \frac{6E_R}{B_f^2 R^3}\left(\frac{V_*}{V_B}\right) \sim 10, \quad (3)$$

in agreement with the fifth condition (§ 2) for $E_R(V_*/V_B) \sim 10^{53}$ ergs.

We note that the fourth condition is expected to be met by almost any model in which the GRB parameters depend on some initial magnitude and distribution of the magnetic field and the differential rotation, both of which could vary greatly among newborn DROCOs. Thus, E_R may limit the number, N_p, of tori ejected to only one (or τ may be so great that only one ejection is recognized as an individual GRB). The toroid may penetrate the surface and thereby create a hugely magnetized pulsar with a 10^{-3} s spin period (Usov 1992) that gives rise to an ultrarelativistic wind, rapidly decaying in a smooth fashion, or it might break through and reconnect at the surface, giving rise to a much more complicated sudden ultrarelativistic blast. A succession of toroids from an initially larger E_R can give rise to much more complication. Similarly, the initial B_0 is almost certainly not reproduced after toroids have been wound up and floated to the surface, so timescales vary between and within GRB events.

The typical interval between sub-bursts, i.e., the time to rebuild the critical field, is

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

in fair agreement with the sixth condition (§ 2) if $B_{12} \sim 1$, which is characteristic of young radio pulsars, and $\Omega_4 \sim 1$. (Note the sensitive dependence of τ on the initial value of B_0. The product $N_p E_p \approx E_R$ is not sensitive to B_0.)

Equations (3) and (4) yield a total duration of $t_d \approx 120 \text{ s} \times B_{12}^{-1}\Omega_4$, after which the (differential kinetic) energy stored in the central engine is exhausted or at least no longer capable of fully winding up another toroid so that it too can be released. The gamma-ray burster then turns off (but if a significant remnant surface field $\geq 10^{15}$ G is still present, the burster may go on for several more seconds, until the neutron star also loses the kinetic energy stored in "rigid" rotation; Usov 1992).

6. FINAL REMARKS

We have shown how a rapidly and differentially rotating compact object of supranuclear density would release its huge kinetic energy in repeated sub-bursts, in a manner consistent with observations of gamma-ray bursts, and their theoretical interpretation. In the detailed discussion above, the central engine has been considered to be a single collapsed object, specifically a neutron star, but (as remarked in § 4) it may well be more complicated. The DROCO could be a torus rotating about a spinning black hole. In such a DROCO, an energy of about $\sim Jc^3/(10GM)$ could be extracted from the black hole of mass M and angular momentum J by the magnetic field that threads both the torus and the black hole. As the "accretion" torus builds up and ejects its magnetic toroids, in the manner described above, its differential rotation would be maintained by the black hole spin. Such activity could also modulate the magnetic field that the torus supplies to the black hole, which would then lose energy and emit in the way proposed by Blandford & Znajek (1977) in their model of active galactic nuclei (Mészarós & Rees 1997b).

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