INDUCTION OF SUPERNova-LIKE EXPLOSIONs BY GAMMA-RAY BURSTS IN CLOSE BINARY SYSTEMS

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ABSTRACT

We propose that a gamma-ray burst in one member of a binary may induce a supernova-like explosion of a close, white dwarf companion. Such an explosion might be brought about in rather light companions, which cannot undergo the standard accretion-induced explosion. This would give some supernovae associated with gamma bursts an appearance rather unlike that of the typical Type I supernova. GRB 980425, if indeed associated with SN 1998bw, is too weak to have produced the latter through our proposed mechanism.

Subject headings: gamma rays: bursts — supernovae: general — white dwarfs

1. INTRODUCTION

The prompt localization of gamma-ray bursts (GRBs) by BeppoSAX led to the discovery of long-lived GRB afterglows spanning the energy range from X-ray to radio (Costa et al. 1997; van Paradijs et al. 1997; Frail et al. 1997) and of associated host galaxies (Kulkarni et al. 1998). Detections of absorption and emission features at high redshifts (0.69 ≤ z ≤ 3.42) in optical afterglows of GRBs and in their host galaxies (e.g., Kulkarni et al. 1999) have clearly tipped the scale in favor of the cosmological origin of GRB sources (Usov & Chibisov 1975; van den Berg 1983; Paczyński 1986; Goodman 1986; Eichler et al. 1989).

Despite such great advances, the exact nature of the GRB progenitors is still unknown. Several currently popular models posit as the energy-releasing event coalescence of two neutron stars (Blinnikov et al. 1984; Paczyński 1986; Eichler et al. 1989), the collapse of a massive star (Woosley 1993; Paczynski 1998), or the formation of a millisecond pulsar with an extremely strong magnetic field (≈10^{15}–10^{16} G; Usov 1992; Thompson & Duncan 1993; Blackman, Yi, & Field 1996; Katz 1997; Kluźniak & Ruderman 1998; Vietri & Stella 1998).

The energetic ejecta of GRBs may affect their close surroundings in various observable ways. For example, the reprocessing of some of the GRB energy in the atmosphere of a companion might produce an optical afterglow, as discussed, e.g., by London & Cominsky (1983) and by Melia, Rappaport, & Joss (1986) for Galactic GRBs and recently by Blinnikov & Postnov (1998) for GRBs at cosmological distances. In this Letter, we discuss another possible interaction of the GRB ejecta with a companion: some GRB explosions might occur in a close binary companionship with a white dwarf (WD). This, in fact, is a prerequisite in the GRB model of Usov (1992). The interaction of the ejecta with the companion then may induce its explosion and the appearance of a supernova-like phenomenon. The supernovae that were recently claimed (e.g., Wheeler 1999) to be in association with GRBs are unlikely to have been produced in this way. In § 2 we consider the process of induced explosion and estimate the parameter values needed to actuate it. In § 3 we discuss possible observational consequences and other pertinent issues.

2. INDUCTION OF WHITE DWARF EXPLOSIONs BY GRBs IN CLOSE BINARYs

The observed fluxes of GRBs at cosmological distances imply total radiation energy output per unit solid angle within the beam of radiation of Q_{\gamma} \sim 10^{51}–10^{52} erg s^{-1} on a timescale of seconds. The total angular energy output Q is even larger, since only part of it is converted into the observed radiation. If the GRB source has a close binary companion that lies within the main beam, a powerful flux of energy impacts the latter. On near enough a companion, the effects may be staggering. We consider such possible effects and, in particular, the possibility that the impact can induce a supernova-like explosion of a WD companion. The energy that falls on a unit area of the surface of the secondary that is within the GRB beam is Q = 4\pi D^2, where D = 10^{20}D_\odot cm is the binary distance. The chances of an induced explosion are maximized when the companion is fully within the GRB beam, as we assume in our discussion below. In this case the total energy that hits the companion is ΔQ = πR^2q, where R = 10^3R_\odot cm is the radius of the companion.

Our proposal applies more generally, but, for the sake of concreteness, we consider system parameters that are natural in the GRB model that involves a strongly magnetized millisecond pulsar produced by accretion-induced collapse of a WD in a close binary (Usov 1992). An inherent feature of this model is that GRBs occur in binaries. The GRB progenitor is a strongly magnetized WD with a mass near the Chandrasekhar limit, ∼1.4 M_\odot. The secondary is a WD with a mass M_2 ≈ 0.3–0.5 M_\odot that fills its Roche lobe. For such a binary with M_1 = 0.5 M_\odot, we have R_1 ≈ 1, D_{10} ≈ 0.7, and ΔQ = 5 × 10^{50}Q_{52}, where Q_{52} = Q/10^{52} ergs cm^{-1}. This can easily be more than the binding energy of the secondary (GM_2^2/2R_1 ≈ 3 × 10^{46} ergs; e.g., Shapiro & Teukolsky 1983; Nomoto 1982). Therefore, for strong GRBs the energy ΔQ suffices to completely evaporate the secondary. This is still true for a 1.4 M_\odot companion.

The interaction between the relativistic GRB wind and the secondary is very complicated; it depends, among other factors, on the properties of the wind. For the GRB model involving a strongly magnetized, millisecond pulsar, the outflowing wind is dominated by a Poynting flux. The luminosity in electron-positron pairs and radiation is only ∼10^{-2} of the Poynting luminosity (e.g., Usov 1994). The Lorentz factor of the wind is ∼10^3–10^4. Typically, the diameter of the secondary WD is rather smaller than the thickness of the wind shell, which is ∼cτ, where τ ∼ 1–10 s is the characteristic time of deceleration of the pulsar rotation due to the action of the electromagnetic torque; this is roughly the GRB duration or less. The action of the relativistic, strongly magnetized wind on the secondary may
be roughly modeled by assuming that the external pressure on its surface facing the GRB increases instantly to

$$P_{\text{ext}} \approx \frac{Q}{D^2 c t} \approx 3 \times 10^{21} Q_{52} D_{10}^{-2} t_{-1}^{-1} \text{ ergs cm}^{-3}$$  \hspace{1em} (1)$$

for $t_1 = \tau/1 \text{ s} \approx 1-10$.

Inside WDs, electrons are free and strongly degenerated (except for a very thin surface layer with the density $\rho \approx 10^2 \text{ g cm}^{-3}$). At high density and low temperature, these electrons give the main contribution to the gas pressure irrespective of the elemental abundances. The equation of state is (e.g., Shapiro & Teukolsky 1983)

$$P_e(\rho) \approx 10^{23} \times \left( \frac{\rho_e}{\mu_e} \right)^{5/3} \text{ ergs cm}^{-3} \quad 10^{-4} \leq \rho_e < \mu_e$$

$$\left( \frac{\rho_e}{\mu_e} \right)^{1/3} \text{ ergs cm}^{-3}, \quad \rho_e > \mu_e,$$  \hspace{1em} (2)

where $\rho_e = \rho/10^6 \text{ g cm}^{-3}$ and $\mu_e$ is the mean molecular weight per electron. In WDs, helium, carbon, and oxygen dominate, so $\mu_e$ is nearly 2. The upper limit on the density for the validity of equation (2) is determined by neutronization and, for example, for helium it is $\rho_e \approx 10^5$.

The instantaneous increase of external pressure from zero to $P_{\text{ext}}$ results in formation of a strong shock that propagates into the high-density region. Equations (1) and (2) imply that when the density in front of the shock is

$$\rho \approx \bar{\rho} \approx 10^5 Q_{52} D_{10}^{1/5} t_{-1}^{1/5} \text{ g cm}^{-3}$$  \hspace{1em} (3)

the pressure may be neglected. In this case, the temperature behind the shock is about

$$T_s \approx T/10^9 \text{ K} \approx Q_{52}^{1/2} D_{10}^{-1/2} t_{-1}^{-1/4}.$$  \hspace{1em} (4)

For helium WDs, this temperature may be higher than the ignition temperature, which varies from about $6 \times 10^8 \text{ K}$ at $\rho \approx 10^7 \text{ g cm}^{-3}$ to $10^9 \text{ K}$ at $\rho \approx 10^8 \text{ g cm}^{-3}$ (e.g., Nomoto 1982).

In this case, the nuclear energy of the shocked matter is released within a dynamical timescale, i.e., almost instantaneously. At $\rho > \bar{\rho} \approx 10^6 \text{ g cm}^{-3}$, the process of thermonuclear burning propagates in the WD either as a supersonic detonation wave or as a subsonic deflagration wave (Khokhlov, Müller, & Höfschmidt 1993 and references therein). It is worth noting that a transition from deflagration to detonation is possible in the process of burning propagation (e.g., Khokhlov, Oran, & Wheeler 1997).

For a helium secondary of reasonable mass (not too close to the Chandrasekhar limit), the nuclear energy is enough for its complete disruption. The detonation of such explosions is then similar in some respects to that of Type I supernovae (see below).

The temperature given by equation (4) is at least a few times smaller than the ignition temperature for carbon-oxygen mixtures at $\rho \approx 10^5-10^6 \text{ g cm}^{-3}$ (e.g., Nomoto 1982). However, an explosion might still occur for a carbon-oxygen WD if there is enough amplification of the inward shock due to the converging geometry of the phenomenon. For an exactly spherical geometry, the amplification is very large (e.g., Zeldovich & Raizer 1969), but ours is only a semispherical implosion.

The equation of state for matter of hot WDs is (e.g., Cox & Giul 1968; Shapiro & Teukolsky 1983)

$$P_e(\rho, T) = P_e(\rho) + \Delta P_e(\rho, T),$$  \hspace{1em} (5)

where $P_e(\rho)$ is the pressure of completely degenerated electrons, given by equation (2), and $\Delta P_e(\rho, T)$ is the thermal part of the electron pressure $P_e(\rho, T)$. For $\rho > 10^6 \mu_e \text{ g cm}^{-3}$, we have

$$\Delta P_e(\rho, T) = 2 \left( \frac{\pi}{3} \right)^{2/3} \frac{k T^2}{c^2 h} \left( \frac{m_e}{\mu_e} \right)^{2/3} P_e(\rho),$$  \hspace{1em} (6)

where $k$ is the Boltzmann constant, $c$ is the speed of light, $h$ is the Planck constant, and $m_e$ is the proton mass.

For $\mu_e = 2$, equations (2) and (6) yield

$$\Delta P_e(\rho, T) = 4 \times 10^{22} \rho^{1/2} T^{5/2} \text{ ergs cm}^{-3}.$$  \hspace{1em} (7)

Without detailed calculations similar, e.g., to the two-dimensional hydrodynamic simulations of supernova models by Livne & Arnett (1995) and Livne (1999), we cannot tell whether, when the disturbance reaches the center of the WD, the temperature there is raised high enough for burning to occur there. We do not know how effective the shock convergence may be in amplifying the shock. We just parameterize the convergence effect by $\alpha$, the ratio of the thermal, electron pressure reached at the center, $\Delta P_e(\rho, T)$, to that produced by the impact on the surface, $P_{\text{ext}}$. Using equations (1) and (7), we then have

$$T_{c, 9} \approx 10^{1/3} Q_{52}^{1/2} D_{10}^{-1/2} t_{-1}^{-1/4} \rho_e^{-1/3},$$  \hspace{1em} (8)

where $\rho_e$ is the density at the stellar center. For $Q_{52} \approx 3$, $D_{10} \approx 0.7$, $t_1 = 1$, and $\rho_e \approx 10$, from equation (8) we can see that for $\alpha > 20$ the temperature $T_c$ is higher than the ignition temperature, which is $\approx 7.1 \times 10^9 \text{ K}$ for carbon-oxygen mixtures at the density of $10^7 \text{ g cm}^{-3}$ (e.g., Nomoto 1982). In this case, explosion is expected to occur at the center.

Since detonation waves in WD matter have a finite width, it is important to compare this with the size of the star. In carbon-oxygen WD matter, the detonation wave has roughly three spatially separated zones. The foremost is a sharp shock. The shock compresses and heats the material behind it, and carbon burning can start. This reaches a peak energy output within some distance $\Delta l_\text{c}$, which typifies the carbon-burning zone. This scale roughly equals the speed of propagation of the shock multiplied by the carbon burning time. The third zone is the region in which matter is incinerated into nuclear statistical equilibrium (NSE) composition. The energy release in this layer is rather small, so it is not so important in the dynamics of the detonation wave, but it is important in determining the composition of the ashes and the subsequent appearance of the explosion remnant.

For carbon-oxygen mixtures, the width of the NSE relaxation layer is many orders larger than the width of carbon burning: $\Delta l_{\text{NSE}} \gg \Delta l_\text{c}$. For $\rho_e \approx 10$, we have $\Delta l_\text{c} \approx 1 \text{ cm}$ and $\Delta l_{\text{NSE}} \approx 10^3 \text{ cm}$ (e.g., Khokhlov 1989). Since $\Delta l_\text{c} \ll R_\rho$, the detonation wave may form in the vicinity of the stellar center and propagate to the surface. In the process of propagation of the outward detonation wave, the width of the carbon-burning zone is small ($\Delta l_\text{c} \ll R_\rho$), except in a rather thin surface layer of the WD, and therefore most of the nuclear energy is released by the time the detonation wave reaches the surface. As noted above, the nuclear energy released is enough for the WD to be completely disrupted.

The kinetics of helium burning differs substantially from that of carbon-oxygen burning. The leading reaction is $3^4\text{He} \rightarrow$
\(^{12}\)C. At the same densities, the rate of this reaction is much smaller than that of carbon burning. As a result, the width of the nuclear-burning zone is many orders larger (e.g., Khokhlov 1989). Still, for \(\rho_s \sim 0.1\)–1 the width of the helium-burning zone is small enough \((\Delta l_{\text{H}} \approx 10^4 \text{ cm } \ll R_c)\) so that we can take this zone to be small compared with the other relevant scales. Thus, an inward detonation wave can lead to the WD explosion as we discussed above.

For rather massive WDs, \(M_s \approx 0.8 M_\odot\), which can undergo accretion-induced explosions, the mean density of the bulk matter is \(\approx 10^7 \text{ g cm}^{-3}\), and the NSE relaxation width is small, \(\Delta l_{\text{NSE}} \ll R_c\). In this case, incineration is effective and the remaining ashes consist mostly of \(^{56}\)Ni, which decays and provides energy for the long-duration radiation of Type I supernovae (e.g., Nomoto 1982; Woosley, Taam, & Weaver 1986).

In contrast, for low-mass WDs \((M_s \leq 0.3 M_\odot)\), which cannot be exploded by gas accretion without significant increase of their masses, the great fraction of the mass is at lower densities \((\rho \lesssim 10^7 \text{ g cm}^{-3})\) for which \(\Delta l_{\text{NSE}} \gg R_c\) and the production of \(^{56}\)Ni is strongly suppressed irrespective of the abundances (Khokhlov 1989; Nomoto 1982; Woosley et al. 1986). Therefore, for such a low-mass WD the mass of \(^{56}\)Ni that is produced in the GRB-induced explosion is very low, and this explosion leads to a weak supernova-like phenomenon, which differs qualitatively from known supernovae. Observation of such a phenomenon correlated with GRBs could confirm our idea on the GRB-induced explosions of secondary WDs.

3. DISCUSSION

It is generally believed that Type I supernovae are produced by thermonuclear explosions of WDs (e.g., Nomoto 1982; Woosley et al. 1986; Niemeyer & Woosley 1997). Such explosions may be brought about by accretion of matter onto the WDs. In the process, thermonuclear burning that is triggered near the surface propagates either in the form of a supersonic detonation wave or as a subsonic deflagration. This results in the incineration of most of the WD matter into \(^{56}\)Ni, which is ejected from the star. The radioactive decay \(^{56}\)Ni \(\rightarrow^{56}\)Co \(\rightarrow^{56}\)Fe can provide a sufficient amount of late-time energy input to power the light curves of Type I supernovae.

In this Letter, we have argued that a similar fate may befall a WD that is exposed to the ejecta of a GRB explosion in a very close binary companion. The GRB angular energy output \(Q\) near the binary plane that is necessary for the WD explosion is \(\sim 10^{53} \text{ ergs sr}^{-1}\). This is a typical value of \(Q\) in the model of GRBs we considered. Indeed, the rotational energy of millisecond pulsars that is a plausible source of energy for GRBs may be as high as a few times \(10^{53}\) ergs, and almost all of this energy may be transformed into the energy of a relativistic, strongly magnetized wind (e.g., Usov 1994). The angular distribution of the wind flux depends on the angle \(\theta\) between the rotational and magnetic axes and varies within a factor of 2–3 or so. Such a moderate collimation of the outflowing wind may be either along the rotational axes of the pulsar at \(\theta = 0\) (Bendford 1984; Michel 1985) or near the equator at \(\theta = \pi/2\) (Belinsky et al. 1994). For a very close WD + WD binary that is the predecessor of the GRB source, one expects the secondary WD to be near the equator of the millisecond pulsar, which forms by accretion-induced collapse of the primary WD. In this case, the \(Q\) value in the WD direction is typically \(~10^{52}–10^{53}\) ergs sr\(^{-1}\), the maximum value being reached when both the pulsar rotation is extremely fast and the magnetic axis of the pulsar is perpendicular to its rotational axis.

We suggest that the resulting explosion is similar in some respects to Type I supernovae, but may differ substantially in others, especially if the mass of the WD is small \((M_s \lesssim 0.3 M_\odot)\). First, because the trigger mechanism is different, a different elemental abundance may result. Second, the postexplosion WD remnant has ample time \((\sim 10 \text{ s or more})\) to interact with the relativistic wind outflowing from the GRB source. This can lead to additional acceleration of the explosion debris even, for some parts, up to relativistic velocities. Therefore, for GRB-induced supernovae, the maximum of their light curves is expected to be observed substantially earlier than for typical Type I supernovae. Taking also into account that typically the amount of radioactive \(^{56}\)Ni produced in GRB-induced supernovae is low, the luminosities of these supernovae may decrease quickly after the maximum without long-lived tails.

At present, several supernova/GRB associations have been suggested (for a review, see Wheeler 1999). Among them, SN 1998bw, possibly associated with GRB 980425 (Galama et al. 1998), is the most famous and best established candidate for such an association. SN 1998bw was very powerful and thus could not have been produced by our mechanism, which produces rather weak optical supernovae. The amount of radioactive \(^{56}\)Ni produced in SN 1998bw has been estimated to be \(\sim 0.5–0.75 M_\odot\) (e.g., Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999), much more than the explosion we discuss can make. Also, if GRB 980425 is connected with SN 1998bw, its total energy release, even if it is isotropic, is only \(~10^{48}\) ergs. This is about 4 orders of magnitude less than what is necessary for induction of a WD explosion. And third, the optical properties of SN 1998bw indicate that the progenitor star (like the progenitor stars of all other supernovae possibly associated with GRBs) was a massive star with a mass at least a several times larger than the maximum possible mass of WDs (Iwamoto et al. 1998; Woosley et al. 1999). While the observations of GRB 980425–SN 1998bw may be explained fairly well in the collapsar model (e.g., MacFadyen & Woosley 1999), we suggest that at least some cosmological GRBs may be associated with rather weak supernova-like explosions of low-mass \((\lesssim 0.3–0.5 M_\odot)\) WDs. In our scenario, GRBs and supernovae associated with each other are different phenomena, while in the collapsar model the two events are one.

Recently, possible evidence for the existence of iron K-shell emission lines has been found in two GRBs: GRB 970508 and GRB 970828 (Piro et al. 1999; Yoshida et al. 2000). The presence of dense matter very close \((\lesssim 10^{16} \text{ cm})\) to the GRBs, which is not expanding relativistically, is required by these observations. The remnants of the GRB-induced explosions of WDs may be responsible for emission of the iron lines. For this, it is necessary that a small fraction of the remnant matter with iron mass of \(\sim 10^{-5} \text{ to } 10^{-4} M_\odot\) be accelerated by the GRB wind to subrelativistic velocities and generate the Fe line emission at the distance of \((1–3) \times 10^{25} \text{ cm}\) from the GRB source. It is worth noting that rather strong, high-redshift \((z \geq 1)\) GRBs, like GRB 970828, with X-ray afterglows (for their prompt localization) and without standard optical afterglow are the best candidates for searching the possible weak, supernova-like explosions posited here.

Induction of supernova-like explosions by GRBs is similar in many respects to ablation in laser and heavy-ion fusion (for review, see Meyer-ter-Vehn, Atzeni, & Ramis 1998). It is well known that the symmetry of the irradiation of the fusion fuel...
is crucial for its successful explosion. Otherwise, only the outer layers may be affected. The same may be true for carbon-oxygen WDs if the driving external pressure $P_{\text{ext}}$ is not spherical enough. Other obstacles to successful explosion might result from numerous instabilities that may develop at the surface. In our case, though, plasma instabilities at the surface at which the GRB wind interacts with the WD matter may be suppressed by a very strong magnetic field of the GRB wind.

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