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GAMMA-RAY BURSTS AS THE DEATH THROES OF MASSIVE BINARY STARS

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ABSTRACT

We propose that gamma-ray bursts are created in the mergers of double neutron star binaries and black hole neutron star binaries at cosmological distances. Two different processes provide the electromagnetic energy for the bursts: neutrino-antineutrino annihilation into electron-positron pairs during the merger, and magnetic flares generated by the Parker instability in a postmerger differentially rotating disk. In both cases, an optically thick fireball of size $\lesssim$ 100 km is initially created, which expands ultrarelativistically to large radii before radiating. The scenario is only qualitative at this time, but it eliminates many previous objections to the cosmological merger model. The strongest bursts should be found close to, but not at the centers of, galaxies at redshifts of order 0.1, and should be accompanied by bursts of gravitational radiation from the spiraling-in binary which could be detected by LIGO.

Subject headings: accretion, accretion disks — black hole physics — gamma rays: bursts — gravitation — magnetic fields — stars: neutron

1. INTRODUCTION

Gamma-ray bursts were discovered 25 years ago, and for long it was assumed that they are associated with compact stars in the Galactic disk. However, recent results obtained with the Burst and Transient Source Experiment on the *Compton Gamma-Ray Observatory* (Meegan et al. 1992a, b) suggest strongly that the bursts originate at cosmological distances. The 262 bursts reported so far appear to be isotropic in the sky and to have a distribution of $V/V_{\max}$ that is consistent with a cosmological population extending to redshifts $z \sim 1$ (Mao & Paczyński 1992; Piran 1992; Dermer 1992). The required event rate is $\sim 10^{-6}$ yr^{-1} per L^* galaxy, and the typical energy released in a burst is $\sim 10^{51}$ ergs, assuming isotropic emission. The short rise times of the bursts imply a source size $\sim$ 100 km.

Even prior to these observations, several authors (Paczyński 1986; Goodman 1986; Eichler et al. 1989; Piran 1990; Narayan, Piran, & Shemi 1991; Paczyński 1991; Piran, Narayan, & Shemi 1992) suggested that γ-ray bursts arise at cosmological distances in the merger of binaries consisting of either two neutron stars (NS-NS) or a black hole and a neutron star (BH-NS). This suggestion is attractive for a number of reasons.

1. The model employs a known source population; four NS-NS radio pulsars have been discovered in the Galaxy, viz. PSR 1534+12, PSR 1913+16, PSR 2127+11C, and PSR 2303+46.
2. The scenario invokes orbital decay through the emission of gravitational radiation, for which there is direct observational evidence (Taylor & Weisberg 1989); moreover, three of the above four pulsars have merger times shorter than the Hubble time.
3. In a merger, an energy $>10^{53}$ ergs will be released in a time $\sim$ 1 ms and within a radius $<$ 100 km, satisfying the observational constraints.
4. NS-NS and BH-NS mergers occur at the rate of $\sim 10^{-6}$ to 10^{-5} yr^{-1} per L^* galaxy (Narayan et al. 1991; Phinney 1991), or possibly even $\sim 10^{-4}$ yr^{-1} per galaxy (Tutukov & Yungelson 1992), which is sufficient to explain the observed burst rate. In fact, if the merger rate is near the high end of the estimated range, then the proposed scenario may call for beaming of the γ-ray emission, which would lower the estimated energy per burst.

Many arguments have been made against cosmological scenarios in general and the merger model in particular. Among these, one objection appears at first sight to be quite serious. If 10^{51} ergs of γ-rays are created in a volume of size 100 km, the optical depth due to $\gamma + \gamma \rightarrow e^+ + e^-$ will be extremely large and the photons will apparently be trapped (Schmidt 1978). This objection was refuted by Paczyński (1986) and Goodman (1986) who showed that an optically thick ball of energy, a "fireball," will expand relativistically and radiate most of its energy when it becomes optically thin. Because of relativistic beaming, a distant observer receives a burst of radiation whose temperature and duration will be similar to the initial temperature and initial light-crossing time of the fireball. Relativistic beaming also circumvents the so-called "Ruderman limit" (Ruderman 1975), which sets an upper limit to the distance of a source for a given source temperature, flux, and variability time scale. (Beaming solves a related problem in the case of extragalactic radio jets.)

Another common argument is that cosmological models cannot explain the absorption or emission lines that are claimed to be present (e.g., Mazets et al. 1981; Yoshida et al. 1992) in the spectra of some bursts. However, the issue of spectral lines has been fairly controversial (e.g., Laros et al. 1982; Harding, Petrosian, & Teegarden 1986). Mazets et al. (1981) claimed that single "cyclotron absorption lines" were present in 20 bursts, with a broad distribution of line energies (27–70 keV), but with only five lines having energies under 50 keV. This is in conflict with the Ginga experiment which discovered three systems of lines, all with nearly identical energies, all under 50 keV (Yoshida et al. 1992). Similarly, while there have been some claims for "annihilation features" in a few spectra, Messina & Share (1992) found no evidence for line features above 300 keV in time-integrated spectra from a large

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sample of 177 bursts observed with the *Solar Maximum Mission.* Finally, no lines have been detected with any experiment on the *Compton Gamma Ray Observatory*. In view of the uncertainty in the evidence, we choose to ignore the claims for spectral lines until confirmed with new experiments. (However, the reader should note that our scenario involves magnetic fields of the right strength to explain cyclotron features, if confirmed.)

In addition to the above, several other objections have been raised against the cosmological merger model.

1. How is the energy converted into γ-rays?
2. How can one avoid baryon contamination, which will significantly modify the evolution of the relativistic fireball?
3. How can one obtain bursts with durations from 5 ms to 10^3 s when the dynamical time scale is $\lesssim 1$ ms?
4. Why are burst profiles so complex and individually unique?
5. Why do some bursts have an apparent precursor several seconds before the primary burst?
6. What produces the power-law γ-ray spectrum, which extends up to a few hundred MeV?
7. Why have no galaxies been found in the vicinities of bright γ-ray bursts with well-determined positions?

The aim of this *Letter* is to describe a qualitative scenario for the production of γ-ray bursts in mergers of NS-NS and BH-NS binaries at cosmological distances, that solves several of these problems. Our model applies to the "classical gamma-ray bursts," which comprise the bulk of the observed bursts, but not to the "soft gamma repeaters," which are widely regarded to be a separate population.

2. MERGER SCENARIO

The progenitors of close NS-NS and BH-NS binaries must be massive X-ray binaries consisting of an O or B main-sequence star and a neutron star or a black hole (e.g., Vela X-1, Cyg X-1; cf. Trimble 1991 for a review). When the main-sequence star evolves, the binary very likely undergoes a common envelope phase, after which one has a tight binary consisting of the helium core of the OB star and its compact companion. Cyg X-3 ($P_b = 4.79$ hr) appears to be an excellent example of this stage of evolution (van Kerkwijk et al. 1992).

We are interested in Cyg X-3–like binaries with separations a_0 ranging from $\sim$few $\times 10^{10}$ cm, the radius of the helium core (assuming that it behaves like a helium main-sequence star), to $\sim$few $\times 10^{11}$ cm, the limit beyond which gravitational radiation losses in the double degenerate binary phase are too slow to cause a merger within the age of the universe. To make a NS-NS binary, the helium core needs to have a mass $M_{\rm He}$ between $\sim 2.5\ M_\odot$ (in order to have a supernova explosion) and $4.2\ M_\odot$ (in order to leave behind a bound NS-NS binary, assuming a symmetric supernova explosion and a neutron star mass of $1.4\ M_\odot$). After the explosion, we are left with a NS-NS binary with an orbital eccentricity $e = (M_{\rm He}/2.8) - 0.5$, periastron separation a_p equal to the preexplosion separation a_0, and a recoil velocity $v_{\rm recoil} = 180\ (M_{\rm He} - 1.4)(M_{\rm He} + 1.4)^{-1/2}(a_p/10^{11}\ {\rm cm})^{-1/2}$ km s^{-1}. Similar estimates for a BH-NS binary give somewhat lower orbital eccentricities and space velocities.

For typical numbers, the recoil velocity of the binary is large enough for the system to escape from a small galaxy (though probably not from an L^* galaxy). There is growing evidence that the blue extragalactic light is dominated by faint dwarf galaxies between 22 mag and 24 mag (Colless et al. 1990, and references therein). These galaxies are observed at modest redshifts ($z \sim 0.2$–0.4) and are very numerous (one and six per square arcmin at 22 mag and 24 mag). If supernovae are strongly correlated with the blue light, then most compact binaries will be born in low-mass galaxies, escape from their hosts, and move distances $\sim 100(v_{\rm recoil}/100\ {\rm km\ s^{-1}})(t/10^9\ {\rm yr})$ kpc before merging, where t is the lifetime to merger; for reasonable parameters, the distance traveled is in the range 1–1000 kpc (Tutukov & Yungelson 1992). The lack of obvious host galaxies associated with γ-ray bursts is then not surprising (Schaefer 1992). The bursts will frequently be offset from their parent galaxies by an arc minute or more, and at this separation the association will be confused by several other faint galaxies in the field. However, in some cases, in particular for the strongest and presumably nearest bursts, it may be possible to identify the parent galaxy, particularly if it happens to be a normal galaxy, but one will have to search deeper than has been done so far.

For a NS-NS binary in a near-circular orbit, the time to merge is given by $t_{\rm merge} = 38\ (a/10^{7.5}\ {\rm cm})^4\ {\rm s} = 160\ (P_b/0.1\ {\rm s})^{8/3}$ s. During the late stages prior to the merger, some energy could be released through tidal interactions, crustquakes, and spin-up, but this energy will not be sufficient to produce a burst that is visible from a cosmological distance (Haensel, Paczyński, & Amsterdamski 1991; Kochanek 1992; Mészáros & Rees 1992; Blaes et al. 1989; Bildsten & Cutler 1992).

Once the two stars merge, there will be $\sim 10^{53.5}$ ergs of energy divided more-or-less equally into three forms: (1) thermal energy, (2) ordered rotational energy, and (3) "nonuniform" kinetic energy (either chaotic motions or differential rotation). The third form of energy will be quite significant and will be located quite far from the center, particularly if there is strong splashback during the merger due to the rotations of the two stars not being synchronized with the orbit. Each of the three energy forms will be released through a different channel.

The thermal energy is radiated mostly as neutrinos and antineutrinos. Goodman, Dar, & Nussinov (1987) showed that in Type II supernovae the finite cross section associated with the reaction, $\nu + \bar{\nu} \rightarrow e^+ + e^-$, results in $\sim 10^{51}$ ergs being converted into electromagnetic energy. Eichler et al. (1989) proposed that this mechanism produces γ-ray bursts in binary mergers. The time scale of the process is the neutrino cooling time, $\sim$few seconds.

Modest variability is expected in neutrino emission because of the chaotic (possibly convective) flows in the postmerger fluid. Some variability will also arise if the gamma rays have to make their way through gaps in a surrounding baryon cloud. We suggest that the neutrino mechanism may produce the subclass of bursts with relatively smooth profiles and time durations $\sim$few seconds.

The rapid rotation of the postmerger object will almost certainly cause the fluid to be dynamically unstable, leading to rapid loss of energy and angular momentum on a time scale $\sim$few ms. This instability dies down when the ratio of kinetic to gravitational energy falls below ~ 0.27. At this stage the rotating system will collapse directly to a black hole if the total mass is greater than the maximum mass of neutron star (some stiff equations of state permit neutron stars more massive than $2.8\ M_\odot$), and if the angular momentum J is smaller than GM^2/c. If $Jc/GM^2 > 1$, collapse is temporarily prevented, but the system will continue to exhibit a secular instability through which it will lose angular momentum on a time scale of a few seconds or longer (Friedman 1983; Cutler, Lindblom, & Splinter 1990).

A fraction of the original mass will not participate directly in the central instability, but will form a surrounding disk/torus which may itself undergo dynamical instabilities (e.g., Narayan & Goodman 1989). We consider it likely that after an initial unstable phase a significant amount of residual kinetic energy, $\lesssim 10^{52}$ ergs, will survive in a relatively long-lived differentially rotating disk, and we believe that this energy can be tapped almost entirely through electromagnetic processes.

In the merger of a BH-NS binary, the neutron star will be tidally disrupted, with some of the matter being swallowed by the black hole, and the remainder forming a torus, generating heat and neutrinos in the process. Subsequent evolution should proceed in a similar fashion in both the BH-NS and NS-NS scenarios, and it is not clear at this time which of the two is more efficient as a γ-ray burster.

The mechanism we propose to produce γ-ray bursts with complex time profiles is based on magnetic fields. Immediately after the merger the field strength is probably $\sim 10^{12}$ G, but instabilities such as the Balbus & Hawley (1991) mode, or failing that simply the shearing action of the differentially rotating disk, will cause the field strength to increase. The field is likely to build up to $\sim 10^{16}$–10^{17} G and come into equipartition with the energy in differential rotation. This is a reasonable assumption since, in the only differentially rotating astrophysical fluid that we can observe directly, viz. the interstellar medium, there is strong evidence for equipartition field strengths. Note that, while electric fields are limited to a maximum strength of $\sim 10^{13}$ V cm^{-1} by the pair creation threshold, magnetic fields can build up to much higher strengths (cf. Zaumen 1976).

Once the field achieves equipartition, it will exhibit the Parker instability, in which the field will float up and break out of the disk (relativistically in our case) on a dynamical time, leaving the matter behind. Particularly near the top of the magnetic loop, the baryonic contamination will be quite low, making the conditions favorable for a gamma-ray burst. The burst itself will probably be created as a series of explosive reconnection events in the rising magnetic field, just as in solar flares. For the assumed field strength, the temperature of the flare will be $\sim$few $\times 10^{11}$ K, the photons will have characteristic energies ~ 10 MeV, and the total energy in a single burst will be $\sim 10^{50}$ ergs for linear dimensions ~ 1–10 km. The resulting optically thick fireball will expand relativistically as described by Paczyński (1986), Goodman (1986), Shemi & Piran (1990), and Paczyński (1990).

A feature of the model is that the energy dissipation occurs above the disk, and, because of the relativistic outward motion of the flare, very little energy returns to the disk. If this aspect of the scenario works efficiently (which needs to be demonstrated), then we have a viable solution to the problem of separating the photons from the baryons. Note that, in contrast to a supernova, where a massive stellar envelope smothers the photons and converts most of the explosion energy into kinetic energy, we are postulating low mass loading. Therefore, the photon energy is hardly diluted.

The flare activity will make the burst profile quite complex, with many subbursts, just as with flares on the Sun. Also, the total duration over which the successive subbursts occur will be quite variable from one object to another, depending on the details of the postmerger fluid configuration. The important point is that the model has two distinctly different time scales: first, a dynamical time ~ 1 ms, which is related to the rise times of individual flares (because the Parker instability, once it gets going, operates essentially on a dynamical time), and, second, an accretion (or magnetic "viscosity") time, probably ~ 1–1000 s, related to the duration of the whole γ-ray burst. We cannot calculate the second time scale from fundamental theory, but we note that in other objects with disks, such as cataclysmic variables and X-ray binaries, the accretion time is typically many orders of magnitude longer than the dynamical time.

A generic problem with any cosmological model is that the huge initial energy density implies a large optical depth to pairs, thermalization of the fireball (Paczyński 1990), and a blackbody spectrum. This is in clear conflict with the observed spectra of γ-ray bursts, which have a significant excess of X-rays and very hard γ-rays compared to any Planck spectrum. There are at least two possible solutions to this problem, both related to the flarelike energy release and rapid variability. First, even if the instantaneous spectrum of a local flare is Planckian, the superposition of many Planck curves with a wide range of temperatures and intensities can appear as a very broad broken power law. Second, apart from γ-rays, the bursts in our scenario will also produce $\sim 10^{51}$ ergs of energy in ultrarelativistic ejecta, i.e., cosmic rays, with little or no nonrelativistic matter. These ejecta should, through collisions with one another at large radii and low optical depths, give a non-Planckian spectrum by various nonthermal mechanisms. For instance, given the strong magnetic fields, synchrotron processes might naturally produce the observed power-law spectrum. The ejecta should much later also produce something similar to a supernova remnant.

An important point to note is that the observed photon energy $h\nu_{\rm obs}$ is related to the emitted energy in the frame of the radiating fireball $h\nu_{\rm em}$ by the large relativistic $\gamma \sim 10^2$–10^3 of the expansion (Paczyński 1986; Goodman 1986). Therefore, a cutoff at 511 keV in the emitter frame translates to a cutoff at $\gamma \times 511$ keV for the observer, which can correspond to several hundred MeV.

Finally, as the disk cools through neutrino emission, it might at some point make a transition to a superconducting superfluid. The separation of the field and the baryons, which is critical for our model, may be particularly effective in such a state.

3. CONCLUSIONS

We propose a scenario for gamma-ray bursts that involves merging binaries at cosmological distances. The scenario is capable of explaining the qualitative features of most of the observations, and circumvents many of the arguments against cosmological models. The model employs two kinds of objects, NS-NS and BH-NS binaries, and two distinct mechanisms, magnetic flares and neutrino interactions. The former mechanism probably creates complex bursts, while the latter may produce relatively simple profiles. The occurrence of both mechanisms in some bursts may explain apparent precursors. The model incorporates three different time scales: a dynamical time ~ 1 ms, a neutrino cooling time $\sim$few seconds, and an accretion time which may be many seconds or minutes long.

A general test for all cosmological models is the expected positive correlation between the faintness of a burst (correlated with distance) and redshift signatures through the burst duration and spectrum (Paczyński 1992; Piran 1992). This correlation could be masked by large intrinsic variations among bursts, but should eventually be observed when enough data accumulate. In fact, there seems to be an indication for such a correlation in the data from the Phebus γ-ray burst experiment (Lestrade et al. 1992).

In addition, there are testable predictions specific to the merger model. We expect the terminal mergers of massive binary stars to occur where most of the blue light is, i.e. among dwarf galaxies (Colless et al. 1990). The binaries probably escape from dwarf galaxies and merge at a median distance ~ 50 kpc (Tutukov & Yungelson 1992). This corresponds to an angular distance $\sim 25''$ from the parent galaxy if the events occur at a redshift of order 0.1 as expected for the strongest bursts. A fraction of the binaries will form in normal galaxies and will not be able to escape. These will have their terminal mergers inside their parent galaxies, typically at several kiloparsecs from the galactic nuclei. Schaefer (1992) found no galaxies brighter than 21 mag in a few cases with γ-ray burst error boxes as small as $\sim (1')^2$. Deeper searches of this kind may provide a practical test of our scenario and could distinguish it from other cosmological scenarios that involve supermassive black holes or other objects located in the centers of galaxies (Prilutski & Usov 1975; Carter 1992; McBreen, Plunkett, & Metcalfe 1992; Hoyle & Burbidge 1992).

The scenario makes another definite prediction. If and when LIGO is commissioned (Abramovici et al. 1992), strong γ-ray bursts should be accompanied by gravity wave detections, though the reverse need not necessarily be true if the γ-rays are beamed. Since the signature of the gravitational radiation signal from a premerger binary is well understood and the strength can be calculated accurately, LIGO should provide good distance estimates to individual bursts (Schutz 1986) and should also pinpoint the exact time of the merger. This information will be invaluable for detailed interpretation of the γ-ray burst observations.

Finally, we emphasize that, within the cosmological framework, the proposed scenario is the most conservative one possible at the present time since it employs the most obvious source population that we can think of, viz. double compact binaries. We know that this population definitely exists, we know its members will merge, we can be certain that huge quantities of energy will be released in such mergers, and we find the merger rate to be comparable to the observed burst rate. Unfortunately, we are unable at this time to make any quantitative predictions about the power or the spectrum of γ-ray emission.

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Note added in proof.—B. Teegarden has announced at the Columbus, Ohio AAS meeting that the lack of cyclotron lines in the first year of CGRO data makes it unlikely (at the 97% confidence level) that the two experiments have sampled the same intrinsic population.