HELIUM STAR/BLACK HOLE MERGERS: A NEW GAMMA-RAY BURST MODEL

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ABSTRACT

We present a model for gamma-ray bursts (GRBs) in which a stellar mass black hole acquires a massive accretion disk by merging with the helium core of its red giant companion. The black hole enters the helium core after it, or its neutron star progenitor, first experiences a common envelope phase that carries it inward through the hydrogen envelope. Accretion of the last several solar masses of helium occurs on a timescale of roughly a minute and provides a neutrino luminosity of approximately $10^{53}$–$10^{55}$ erg s$^{-1}$. Neutrino annihilation, 0.01%–0.1% efficient, along the rotational axis then gives a baryon-loaded fireball of electron-positron pairs and radiation (about $10^{50}$ ergs total) whose beaming and relativistic interaction with the circumstellar material makes the GRB (see, e.g., Rees & Mészáros). The useful energy can be greatly increased if energy can be extracted from the rotational energy of the black hole by magnetic interaction with the disk. Such events should occur at a rate comparable to that of merging neutron stars and black hole neutron star pairs and may be responsible for long complex GRBs but not short hard ones.

Subject headings: black hole physics — gamma rays: bursts — gamma rays: theory

1. INTRODUCTION

Many close, massive binaries are expected to pass through an evolutionary phase during which a compact object (neutron star or black hole) enters the envelope of its red giant companion. Some of these systems eject the hydrogen envelope and eventually evolve into doubly degenerate binaries such as the Hulse-Taylor pulsar system (Hulse & Taylor 1975; van den Heuvel 1995). In others, however, the orbital energy of the system is insufficient to remove the hydrogen envelope and thus shut off the drag before the compact object enters the helium core. As the compact object and helium core coalesce, the helium core is tidally disrupted into an accretion disk around the compact object with a radius equal to a fraction of the initial helium core, $\sim 10^5$–$10^6$ cm. Similar coalesced systems form if the compact object is enveloped by its helium star companion during the companion’s giant phase expansion (Woosley, Langer, & Weaver 1995). The accretion rate onto the compact object may be initially as large as the Bondi-Hoyle rate, almost a solar mass per second (Houck & Chevalier 1991; Brown 1995; Chevalier 1996; Fryer, Benz, & Herant 1996). Later, following disk formation, the accretion rate is limited by the viscous timescale, $(\alpha\Omega)^{-1} \sim 100$ s, where $\alpha$ is the disk viscosity parameter, typically 0.1, and $\Omega$ is the orbital angular velocity. During the merger process, the compact object becomes a black hole, if it was not one already.

The resultant object, an $\sim 3 M_\odot$ black hole accreting the remaining several solar masses of helium, resembles, except for the larger store of available mass and higher specific angular momentum, $j \sim 10^{48}$ cm$^2$s$^{-1}$, the class of accretion disk/black hole gamma-ray burst (GRB) models based on the merger of neutron star pairs (NS/NS) or black hole neutron star pairs (BH/NS). It also resembles, except for its larger angular momentum, rotating failed supernovae (Woosley 1993). Because of the large angular momentum, the accreting black hole will likely become a Kerr hole with a rotational speed near the maximum allowed by relativity. As the black hole spins up, the efficiency at which the gravitational energy is released rises from 0.06 for Schwarzschild (nonrotating) geometries to as much as 0.42$M_\odot c^2$ for Kerr geometries. Taking 0.1 as a representative value of this efficiency, the accreting black hole’s neutrino luminosity for 100 s is about $10^{51}$–$10^{52}$ erg s$^{-1}$. Conversion of 0.01%–0.1% of this energy (see below) into a pair fireball by neutrino annihilation along the rotational axis leads to burst energies in the range of $10^{49}$–$10^{51}$ ergs, which is equal to those achieved by NS/NS mergers (Ruffert et al. 1997). The strong beaming that will likely accompany accretion disk/black hole GRB models then allows sufficiently high effective energies to power the GRB.

As we shall also see, the rate of such helium mergers may be an order of magnitude greater than that of NS/NS and BH/NS binaries combined. GRBs from helium mergers differ from those of NS/NS and BH/NS mergers in that no appreciable gravitational wave signal should precede a helium merger gamma-ray burst as they would for gamma-ray bursts from the merger of NS/NS or BH/NS binaries. In addition, gamma-ray bursts from helium mergers occur immediately at their star formation sites, whereas the delay in the merger of NS/NS and BH/NS binaries allows these gamma-ray burst progenitors to leave not only the site of their formation before merging but, in some cases, their host galaxy as well.

2. PREBURST EVOLUTION

Our model begins with a close binary system of two massive stars (each greater than 8 $M_\odot$). As the more massive star (primary) evolves off the main sequence, it fills its Roche lobe and transfers mass onto its companion (secondary). If the system remains bound after the supernova explosion of the primary, a binary composed of a neutron star and a massive main-sequence star results, possibly a massive X-ray binary. When the secondary, in turn, evolves off the main sequence and overflows its Roche lobe, the neutron star enters a common envelope with the secondary and begins to spiral toward the secondary’s helium core. The inward motion continues for roughly 1 (Sandquist et al. 1998) to 1000 years (Taam, Bodenheimer, & Ostriker 1978), until either the secondary’s hydrogen envelope is completely ejected and the system becomes a helium star/neutron star binary or the compact star merges with the helium core.

Whether or not the neutron star then finally merges with its
secondary companion depends on one of the most uncertain parameters in population synthesis studies: the common envelope efficiency ($\alpha_{\text{CE}}$). This single parameter describes the efficiency at which the orbital energy, when injected into the companion’s hydrogen atmosphere as the neutron star inspirals during a common envelope phase, drives off the companion’s envelope. Using $\alpha_{\text{CE}}$ one can estimate the final orbital separation ($A_f$) in terms of the initial separation ($A_1$) of the binary after common envelope evolution (Webbink 1984):

$$A_f = \frac{\alpha_{\text{CE}}A_1^2}{2} \left(\frac{M_{\text{He}}}{M_{\text{He}} - M_{\text{He}} + (1/2)\alpha_{\text{CE}} r_1 M_{\text{NS}}} \right).$$

(1)

where $M_1$, $M_{\text{He}}$, and $M_{\text{NS}}$ are, respectively, the mass of the secondary, the mass of the secondary’s helium core, and the mass of the neutron star, and $r_1 = R_1/A_1$ is the dimensionless Roche lobe radius of the secondary. Some hydrodynamical models have simulated this inspiral, but only for specific systems. Although a general consensus of the value of the common envelope efficiency has not been achieved, best estimates give $\alpha_{\text{CE}} \sim 0.5$ (Taam et al. 1997).

During the inspiral, the neutron star accretes material at the Bondi-Hoyle rate, releasing the accretion energy via neutrino emission (Houck & Chevalier 1991; Chevalier 1993, 1996; Brown 1995; Fryer et al. 1996). Bethe & Brown (1998) have calculated that in the hydrogen inspiral alone, a neutron star is likely to accrete $\sim 1 M_\odot$, leading to the collapse of that neutron star into a black hole. In the tenuous layers of the hydrogen envelope, Chevalier (1996) show that if the infalling material had sufficient angular momentum, the temperature of the material on the neutron star surface may not get high enough to emit neutrinos, and the Eddington limit would constrain the accretion rate. However, near or below the surface of the helium star, where most of the accretion occurs, the densities (and the subsequent Bondi-Hoyle accretion rates) are so high (>1 $M_\odot$ yr$^{-1}$) that angular momentum will not prevent super-Eddington accretion via neutrino emission (Chevalier 1996). The analysis of Chevalier assumes that all of the mass that accretes onto the neutron star flows through the disk, but accretion along the angular momentum axis dominates the flow (Fryer & Kalogera 1998). In addition, three-dimensional simulations of Bondi-Hoyle accretion suggest that the amount of angular momentum accreted in common envelopes may be much less than that assumed by Chevalier (see, e.g., Ruffert & Anzer 1995 and Ruffert 1997), again weakening the effects of angular momentum. Thus, for all of these reasons, the Bethe & Brown (1998) estimate of the accreted mass is valid.

As the compact object merges with the helium core, the Bondi-Hoyle accretion rate in the helium core can reach $\sim 1 M_\odot$ s$^{-1}$. From population synthesis calculations using the code developed by Fryer, Burrows, & Benz (1998), the helium core and compact object have average masses of $\sim 4$ and 2 $M_\odot$, respectively, at the time of merger, and the mean specific angular momentum of the system is $j \approx M_{\text{He}} M_{\text{NS}} [GM_{\text{He}}/(M_{\text{He}} + M_{\text{He}})^{5/3}] \sim 10^{18}$ cm$^2$ s$^{-1}$, where $G$ is the gravitational constant and $M_{\text{He}}$ is the black hole mass when it reaches the helium core radius ($R_{\text{He}}$). As the two objects coalesce, the orbital energy will drive off what remains of the hydrogen envelope as well as some of the helium core. The angular momentum will be injected into the system to form a rotating disk of helium around the black hole.

### 3. MAKING THE BURST

Whether or not the resultant system is a feasible model depends upon the energy of the explosion (Rees & Mészáros 1992), which, in turn, depends on the accretion rate of the disk onto the black hole. Based on the $\nu \nu$ annihilation paradigm for black hole–disk GRB models (Goodman, Dar, & Nussinov 1987; Paczynski 1991; Woosley 1993; Ruffert et al. 1997), we can estimate the energy produced in electron-positron pairs for our model. For thin-disk accretion, the efficiency at which gravitational potential energy is emitted in radiation (neutrinos) is well known (see, e.g, Shapiro & Teukolsky 1983): 5.7% for Schwarzschild black holes and 42.3% for maximally rotating Kerr black holes. The black hole not only gains mass from the accreting material but also angular momentum, which is roughly equal to the angular momentum of the material at the last stable orbit. The black hole will reach its maximal rotation after accreting $\Delta M = 1.846 M_\odot$ for thin-disk accretion (Thorne 1974) or $\Delta M \approx M_{\text{BH}}$ for thick-disk accretion (Abramowicz & Lasota 1980). In the helium merger model, $\sim 4 - 5 M_\odot$ accrete onto the 1.4 $M_\odot$ progenitor neutron star/black hole. The early accretion will accrete along the angular momentum axis, but enough may accrete along the equator to spin up the black hole, and gravitational energy conversion efficiencies may be as high as 10%–20% for these models.

This neutrino emission, if emitted in a disk, is then converted into electron-positron pairs with an efficiency (Ruffert et al. 1997)

$$L_{\text{pair}} \approx 3 \times 10^{46} \left(\frac{L_\nu}{10^{51} \text{ ergs s}^{-1}}\right)^2 \left(\frac{\langle \epsilon_{\nu} \rangle}{13 \text{ MeV}}\right) \times \frac{20 \text{ km}}{R_d} \text{ ergs s}^{-1},$$

(2)

where $L_\nu$ is the total neutrino luminosity (all flavors), $\langle \epsilon_{\nu} \rangle$ is the mean neutrino energy, and $R_d$ is the inner disk radius. To estimate a maximum energy in electron-positron pairs that will then drive the GRB, we assume an accretion rate equal to the Bondi-Hoyle rate ($1 M_\odot$ s$^{-1}$) for a Kerr black hole accreting $1 M_\odot$: $\sim 10^{52}$ ergs. However, for a Schwarzschild black hole accreting $1 M_\odot$ at accretion disk rates of $M_{\text{disk}}/(\alpha \Omega) = 0.01 M_\odot$ s$^{-1}$, the energy drops to $10^{48}$ ergs. Typical values for a 4 $M_\odot$ accretion disk scenario lead to energies between $10^{50}$ and $10^{51}$ ergs, quite comparable to the burst energies of NS/NS mergers (Ruffert et al. 1997).

A more promising model relies on a strong magnetic field being produced in the accretion disk, which can then tap the rotational energy of the black hole in order to power a GRB (Blandford & Znajek 1977; MacDonald et al. 1986; Paczynski 1991, 1997; Woosley 1993; Mészáros & Rees 1997; Katz 1997; Hartmann & Woosley 1995):

$$L_{\text{rot}} = 10^{50} \left(\frac{j c}{GM_{\text{BH}}}\right)^2 \frac{M_{\text{BH}}}{3 M_\odot} \frac{(B/10^{15} \text{ G})^2}{\text{ ergs s}^{-1}},$$

(3)

where $j$ is the specific angular momentum of the black hole and $B$ is the magnetic field strength in the disk. The large disks of our helium merger model will spin up the black hole, and this will provide sufficient energy and power for the strongly magnetic fields to produce more than $10^{52}$ ergs of beamed energy over 100 s, assuming that a fraction on the order of 1%.
of the equipartition field value, \(B^2/8\pi \sim \rho v^2\), is attained in the inner disk.

4. EVENT RATES

Our burst energy estimates are well within the limits to drive a GRB, especially if the strong beaming, which is likely to occur, is included. But for helium mergers to be a viable gamma-ray burst model, they must also have a sufficiently high formation rate to explain the observations. Population synthesis studies of massive binaries are fraught with a variety of unknown parameters, e.g., kicks imparted onto neutron stars at birth, common envelope efficiency \(\alpha_{CE}\), the initial mass function, and the binary mass ratio distribution. Even the stellar radii during giant phases are not known to accuracies better than a factor of \(\sim 2-5\). Using a slightly modified version of the Monte Carlo code described in Fryer et al. (1998a), we have run a series of population synthesis calculations (Fryer, Woosley, & Hartmann 1998b). Here we present specific results of two simulations using two delta-function kick magnitudes (50 and 150 km s\(^{-1}\)) directed isotropically.\(^1\)

In Figure 1, we compare the population synthesis results of the formation rate versus age of gamma-ray bursts from helium mergers with that from NS/NS and BH/NS binaries combined for a galaxy with a burst of star formation and a galaxy with a constant supernova rate of \(10^{-2}\) yr\(^{-1}\). These rates depend sensitively on the supernova kick and on many of the binary parameters that may alter the formation rate by over an order of magnitude (Fryer et al. 1998a, 1998b), but the rate for helium mergers remains comparable to, and generally greater (often by an order of magnitude) than, the gamma-ray burst rate from NS/NS and BH/NS binaries combined. The rate is enough to provide the observed bursts, even if a large beaming factor is invoked (Wijers et al. 1998).

Whereas helium merger GRBs tend to occur in the star formation regions in which they are born, NS/NS and BH/NS binaries may not persist until long after their creation and, therefore, may leave these regions before exploding as a GRB. Many NS/NS and BH/NS binaries form with systemic velocities that not only drive them out of their places of birth but may also drive them beyond their host galaxies. Assuming that the host galaxy’s gravitational potential has no effect on the outmoving binary (systemic velocities are \(\sim 100-200\) km s\(^{-1}\)), so this assumption is valid for low-mass galaxies), we can estimate the distribution of distances these binaries travel prior to merging as a GRB (Fig. 2).

The dominant factor governing the distance estimates is the merger timescale for the binaries. This timescale, in turn, depends sensitively on the relation of the helium star radius with its mass. For our simulations, we use following helium star mass-radius relation:\(^2\)

\[
\log R_{\text{He},\text{max}} = \begin{cases} 
2.398 - 2.013 \log M_{\text{He}} , & M_{\text{He}} \leq 2.5 M_\odot , \\
-0.699 + 0.0557 \log M_{\text{He}} - 0.172 \leq 2.5 M_\odot . 
\end{cases}
\]

(4)

For those compact objects whose inspirals take them within the helium star radius, the system merges and becomes a helium merger GRB, not a NS/NS or BH/NS binary. Hence, to form a NS/NS or BH/NS binary, before the supernova explosion of the helium star, the helium star/compact object separation must be greater than this radius. This limiting preexplosion separation defines the orbital separation distribution after the supernova explosion of the helium star. As the helium star radius decreases, so then does the mean orbital separations of the NS/NS and NH/NS binaries, and hence the merger times and distances traveled before the merger decrease as well. In Figure 2, we see that the mean distance traveled at the time of merger is roughly \(\sim 100-1000\) kpc. If the helium star radii were a factor of 5 higher, this mean would increase to \(\sim 1\) Mpc. Thus, it is possible that GRBs driven by the merger of compact binaries

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\(1\) We set \(\alpha_{CE} = 0.5\), and we use a Scalo (1986) initial mass function and a flat mass ratio distribution (see Fryer et al. 1998a, 1998b for details).

\(2\) This relation uses a radius scaled down by a factor of 5 from the mass-radius relation derived in Kalogera & Webbink (1998) in order to match the radii from Woosley et al. (1995).
may not occur in their host galaxy, whereas helium mergers will all occur therein.

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