BRIGHTNESS FROM THE BLACKEST NIGHT: 
BURSTS OF GAMMA RAYS AND GRAVITY WAVES FROM BLACK HOLE BINARIES

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Draft version September 21, 2018

ABSTRACT

We use recent results in binary stellar evolution to argue that binaries with at least one black hole dominate the rate of compact-object mergers. Two phenomena generally attributable to such mergers, gamma-ray bursts and gravity-wave bursts, are therefore likely to originate from near the event horizon of a black hole. In addition to sheer numbers, black holes have an added advantage over neutron stars in both phenomena. For gamma-ray bursts, the presence of an event horizon eases the baryon pollution problem, because energy can be stored into rotation until most baryons have been swallowed, and then released into a cleaner environment via the Blandford-Znajek process. For gravity-wave bursts, black holes offer higher luminosities due to their higher masses, thus enabling detection out to larger distances, which leads to a 30-fold increase in the predicted LIGO event rate.

Subject headings: binaries: close — black hole physics — gravitation — gamma rays: bursts — gamma rays: theory — stars: statistics

1. INTRODUCTION

Binaries containing a black hole, or single black holes, have been suggested for some time as good progenitors for gamma-ray bursts (Paczynski 1991, 1998, Mochkovitch et al. 1993, Woosley 1993, Fryer & Woosley 1998, MacFadyen & Woosley 1998). Reasons for this include the fact that the rest mass of a stellar mass black hole is comparable to what is required to energize the strongest GRB. Also, the horizon of a black hole provides a way of quickly removing most of the material present in the cataclysmic event that formed it. This may be important because of the baryon pollution problem: we need the ejecta that give rise to the GRB to be accelerated to a Lorentz factor of 100 or more, whereas the natural energy scale for any particle near a black hole is less than its mass. Consequently, we have a distillation problem of taking all the energy released and putting it into a small fraction of the total mass. The use of a Poynting flux from a black hole in a magnetic field (Blandford & Znajek 1977) does not require the presence of much mass, and uses the rotation energy of the black hole, so it provides naturally clean power.

In this paper, we discuss and combine a number of new developments in this area. First, the population synthesis calculations of Bethe & Brown (1998) provide good estimates of the formation rates of various suggested GRB progenitors. They stress the importance of black holes of relatively low mass (~ 2.4 \(M_\odot\)). Binaries with one neutron star and one such black hole are ten times more common than NS-NS binaries, and thus contribute much more to GRB and gravity wave rates. Second, three of us have recently reviewed the Blandford-Znajek (1977) mechanism as a possible central engine for GRBs (Lee, Wijers, & Brown 1999). We confirm that the basic mechanism works effectively, addressing the criticism of many authors.

In section 2 we discuss the various possible progenitors of GRBs and their potential for generating the right energy on the right time scale. In section 3 we discuss the formation rate of each of these. Then we combine these pieces of information to obtain estimates of the detection rates of GRBs and LIGO-detectable mergers (section 4), and summarize our findings (section 5).

2. STELLAR SOURCES OF GRAVITY WAVES AND GAMMA-RAY BURSTS

When a black hole forms from a single star, as in the collapsar model of MacFadyen & Woosley (1998) and the hypernovae scenario by Paczynski (1998) it is surrounded by a substantial stellar envelope, giving two potential GRB energy sources. First, accretion can release neutrinos in such large amounts that \(\nu\bar{\nu}\) annihilation produces up to 10\(^{52}\) erg in a pair fireball. Second, the very large rotation energy of the black hole can be extracted via the Blandford-Znajek mechanism if the surrounding matter carries a magnetic field.

Mergers of compact-object binaries are strong sources of gravity waves. The merger leaves a central compact object that is most likely a black hole, because it contains more than the maximum mass of a neutron star. Now little mass is left as surrounding debris, perhaps at most 0.1 \(M_\odot\). Both accretion and rotation energy are available, but due to the small ambient mass the accretion energy is less likely to suffice for a strong GRB in this case.

2.1. The Blandford-Znajek mechanism

When a rapidly rotating black hole is immersed in a magnetic field, frame dragging twists the field lines near the hole, which causes a Poynting flux to be emitted from near the black hole. This is the Blandford-Znajek (1977) mechanism. The source of energy for the flux is the rotation of the black hole. The source of the field is the surrounding accretion disk or debris torus. We showed (Lee, Wijers, & Brown 1999) that at most 9% of the rest mass of a rotating black hole can be converted to a Poynting
flux, making the available energy for powering a GRB

\[ E_{BZ} = 1.6 \times 10^{58} \frac{M}{M_\odot} \text{erg}. \]  

(1)

The power depends on the applied magnetic field:

\[ P_{BZ} \sim 6.7 \times 10^{50} B_{15}^2 \frac{M}{M_\odot} \text{erg s}^{-1} \]  

(2)

(where \( B_{15} = B/10^{15} \text{G} \)). This shows that modest variations in the applied magnetic field may explain a wide range of GRB powers, and therefore of GRB durations. There has been some recent dispute in the literature whether this mechanism can indeed be efficient (Li 1999) and whether the power of the BH is ever significant relative to that from the disk (Livio, Ogilvie, & Pringle 1999). The answer in both cases is yes, as discussed by Lee, Wijers, & Brown (1999).

The issue, therefore, in finding efficient GRB sources among black holes is to find those that spin rapidly. There are a variety of reasons why a black hole might have high angular momentum. It may have formed from a rapidly rotating star, so the angular momentum was there all along (‘original spin’, according to Blandford 1999); it may also have accreted angular momentum by interaction with a disk (‘venial spin’) or have formed by coalescence of a compact binary (‘mortal spin’). We shall review some of the specific situations that have been proposed in turn.

2.2. NS-NS and NS-BH binaries

Neutron star mergers are among the oldest proposed cosmological GRB sources (Eichler et al. 1989, Goodman, Dar, & Nussinov 1987, Paczynski 1986), and especially the neutrino flux is still actively studied as a GRB power source (see, e.g., Ruffert & Janka 1998). However, once the central mass has collapsed to a black hole it becomes a good source for BZ power, since it naturally spins rapidly due to inheritance of angular momentum from the binary (Rees & Mészáros 1992). Likewise BH-NS binaries (Lattimer & Schramm 1974) will rapidly transfer a large amount of mass once the NS fills its Roche lobe, giving a rapidly rotating BH (Kluzniak & Lee 1998). The NS remnant may then be tidally destroyed, leading to a compact torus around the BH. It is unlikely that this would be long-lived enough to produce the longer GRB, but perhaps the short (\( t \lesssim 1 \text{s} \)) ones could be produced (e.g., Fryer, Woosley & Hartmann 1999). However, mass transfer could stabilize and lead to a widening binary in which the NS lives until its mass drops to the minimum mass of about 0.1 \( M_\odot \), and then becomes a debris torus (Portegies Zwart 1998). By then, it is far enough away that the resulting disk life time exceeds 1000 s, allowing even the longer GRB to be made. Thus BH-NS and NS-NS binaries are quite promising. They have the added advantage that their environment is naturally reasonably clean, since there is no stellar envelope, and much of the initially present baryonic material vanishes into the horizon.

2.3. Wolf-Rayet stars

The formation of a black hole directly out of a massive star has been considered for the production of GRB, either as hypernovae (Paczyński 1998), failed supernovae (Woosley 1993) or exploding WR stars (MacFadyen & Woosley 1999).

Another significant source of such events is the formation of a BH of about 7 \( M_\odot \) in black hole transients, which is discussed by Brown, Lee, & Bethe (1999). These BHs form from a helium star, because spiral-in of the companion has stripped the primary of its envelope.

Both the above scenarios suffer from a problem found by Spruit & Phinney (1998) with rotation of neutron stars: magnetic fields grown by differential rotation in the star may efficiently couple the core and envelope, prohibiting the core to ever rotate rapidly. Then the black holes formed in the above two ways would not contain enough spin energy to power a GRB, leaving only the more limited \( \nu \bar{\nu} \) energy.

A third variety of black hole in a WR star would come from BH-WR mergers (Fryer & Woosley 1998). These happen in the same kinds of systems that form BH-NS binaries as discussed above, in cases where the initial separation is smaller, so that spiral-in leads to complete merger rather than formation of a binary. In this case, the BH and WR star are both spun up during the spiral-in process (i.e., part of the orbital angular momentum of the binary becomes spin angular momentum). Then there is enough spin in the system to power a GRB via the Blandford-Znajek process.

3. Progenitor Formation Rates

In order to evaluate the birth rates of the various progenitors discussed above, we need to establish the evolutionary paths from initial binaries taken by each, and then compute the fraction of all ZAMS binaries that evolve into the desired system. Such a population synthesis calculation is often done with large Monte Carlo codes (e.g. Portegies Zwart & Yungelson 1998). Here we follow the treatment by Bethe and Brown (1998), because it is analytic and thus it is relatively transparent how the results depend on the initial assumptions. It is limited to systems in which at least one star is massive enough to produce a supernova. Their final numbers agree remarkably well with the Monte Carlo simulations by Portegies Zwart & Yungelson (1998), if the same assumptions about stellar evolution are used in both.

To normalize their rates, Bethe & Brown (1998) used a supernova rate of \( \alpha = 0.02/\text{yr per galaxy} \), and assumed that this equaled the birth rate of stars with mass greater than 10 \( M_\odot \). The birth rate of stars more massive than \( M \) scales as \( M^{-n} \). Therefore, the supernova rate in mass interval \( dM \) is

\[ d\alpha = \alpha n \left( \frac{M}{10 M_\odot} \right)^{-n} dM \]  

(3)

In their analysis, Bethe & Brown use \( n = 1.5 \). Half of all stars are taken to be close binary systems with separations, \( a \), in the range 0.04 – 4 \( \times 10^{13} \text{ cm} \). The distribution of binary separations within this range is taken to be flat in \( \ln a \). The distribution of mass ratios, \( q \), in binaries with massive primaries is uncertain, especially at small mass ratios, and we here follow Bethe & Brown by taking it to be flat in \( q \). All these assumptions, as well as the details of the evolution scenarios, introduce some amount of uncertainty, but the good agreement between recent analytic and numerical work suggests that the formation rates we
quote below can be trusted to a factor few. The results of the discussion on birth rates are summarized in table 1.

3.1. NS-NS and NS-BH binaries

In the population synthesis of Bethe & Brown (1998), the formation rate of NS-NS binaries comes out to be $10^{-5}$ per year in the Galaxy, or 10 GEM (Galactic Events per Megayear). This rate is considerably lower than estimates from population synthesis calculations prior to Bethe & Brown (1998) and Portegies Zwart & Yungelson (1998), but in good agreement with the estimated merger rate from the observed neutron star binaries (Phinney 1991, Van den Heuvel & Lorimer 1996). The discrepancy between the older theoretical estimates and newer ones is due to a few factors: some earlier studies did not include kick velocities, and none included the destruction of neutron stars by hypercritical accretion. This last process is an important difference between the Bethe & Brown analysis and previous work: they argued that when a neutron star spirals into a red giant, it accretes matter at a very high rate of up to $1 M_\odot$/yr. Then photons are trapped in the flow and the flow cools by neutrino emission, hence the high rate of up to $1 M_\odot$/yr.

In the absence of hypercritical accretion, or when the accretion flow from its companion fails to directly form a binary neutron star (LBH), the neutron star is the second-born companion in a few million years and 100 times less likely to be seen. In BH-NS binaries, the neutron star is the second-born compact object, hence unrecycled and short-lived. With a ten times higher birth rate but 100 times shorter visible life, one expects to see ten times fewer of them, and thus the fact that none have yet been seen is understandable.

3.2. Wolf-Rayet stars

The rate at which the various progenitors involving WR stars discussed above (Sect. 2.3) are formed can be calculated easily from the Bethe & Brown (1998, 1999) model in the same way they calculated the merger rates.

Helium stars (WR stars) with a low-mass black hole (LBH) in them are formed from almost the same binaries that make LBH plus NS systems; the only difference is that they come from smaller initial orbits, in which the spiral-in does not succeed in ejecting the companion envelope and thus goes on to the center. From the total available range in orbital separations, $0.04 < a_{13} < 4$, LBH-NS binaries are only made when $0.5 < a_{13} < 1.9$ (where $a_{13}$ is the separation in units of $10^{13}$ cm). Inside that range, for $0.04 < a_{13} < 0.5$, the LBH coalesces with the He core. Hence, using a separation distribution flat in ln$a$, coalescences are more common than LBH-NS binaries by a factor of $\ln(0.05/0.04)/\ln(1.9/0.5) = 1.9$. In Bethe & Brown (1998) the He star compact object binary was disrupted $\sim 50\%$ of the time in the last explosion, which we do not have here. Thus, the rate of LBH, He-star mergers is 3.8 times the formation rate of LBH-NS binaries which merge, or $R = 3.8 \times 10^{-4}$ yr$^{-1}$ in the Galaxy, i.e. 380 GEM.

Bethe & Brown (1999) found that single stars need to have a ZAMS mass of at least 80 $M_\odot$ to directly form a massive BH, based on evolution calculations by Woosley, Langer and Weaver (1993). It is now understood that their He-star mass loss rates were a factor of at least 2 too high. Calculations with lower mass loss rates carried out by Wellstein & Langer (1999) give somewhat higher He-star & CO core masses. The further evolution of the CO core has not been calculated yet, but may lower somewhat the Bethe & Brown mass limit for high-mass black-hole formation. Staying with the $80 M_\odot - 100 M_\odot$ range for this route, the rate is $2.5 \times 10^{-4}$ yr$^{-1}$ in the Galaxy.

In addition, we consider the formation of massive black holes of about 7 $M_\odot$ that are seen in soft X-ray transients like A 0620−00. Their evolution was discussed by Brown, Lee, & Bethe (1999), who found a formation rate of $9 \times 10^{-5}$ yr$^{-1}$ in the Galaxy.

4. OBSERVABLE RATES

4.1. Binary Mergers for LIGO

The combination of masses that will be well determined by LIGO is the chirp mass

$$M_{\text{chirp}} = \mu^{3/5} M_1^{2/5} M_2^{3/5} (M_1 + M_2)^{-1/5}. \quad (4)$$

The chirp mass of a NS-NS binary, with both neutron stars of mass $1.4 M_\odot$, is $1.2 M_\odot$. A birth rate of 10 GEM implies a rate of 3 yr$^{-1}$ out to 200 Mpc (Phinney 1991). Kip Thorne informs us that LIGO’s first long gravitational-wave search in 2002–2003 as discussed for binary neutron stars is expected to see binaries with $M_{\text{chirp}} = 1.2 M_\odot$ out to 21 Mpc.

The chirp mass corresponding to the Bethe & Brown (1998) LBH-NS binary with masses 2.4 $M_\odot$ and 1.4 $M_\odot$, respectively, is $1.6 M_\odot$. Including a $-30\%$ increase in the rate to allow for high-mass black-hole (HBH)-NS mergers (Bethe & Brown 1999) gives 26 times higher rate than Phinney’s estimate for NS-NS mergers ($10^{-5}$ yr$^{-1}$ in the Galaxy). These factors are calculated from the signal to noise ratio, which goes as $M_{\text{chirp}}^{5/6}$, and then cubing it to obtain the volume of detectability, which is therefore proportional to $M_{\text{chirp}}^{5/2}$. We then predict a rate of $3 \times$
(21/200)3 × 26 = 0.09 yr⁻¹. This rate is slim for 2003. The enhanced LIGO interferometer planned to begin in 2004 should reach out beyond 150 Mpc for $M_{\text{chirp}} = 1.2 M_\odot$, increasing the detection rate to $3 \times (150/200)^3 \times 26 = 33$ yr⁻¹, and HBB-NS mergers used in these estimates should be considered a lower limit (Sect. 3.2). We therefore find that inclusion of black holes in the estimates for LIGO predict that we will see more mergers per month than NS-NS mergers per year.

4.2. Gamma-ray bursts

Because gamma-ray bursts have a median redshift of 1.5–2 (e.g. Wijers et al. 1998), and the supernova rate at that redshift was 10–20 times higher than now, the gamma-ray burst rate as observed is higher than one expects using the above rates. However, for ease of comparison with evolutionary scenarios we shall use the GRB rate at the present time (redshift 0) of about 0.1 GEM. (Wijers et al. 1998) found a factor 3 lower rate, but had slightly underestimated it because they overestimated the mean GRB redshift; see Fryer, Woosley, & Hartmann (1999) for more extensive discussions of the redshift dependence). An important uncertainty is the beaming of gamma-ray bursts: the gamma rays may only be emitted in narrow cones around the spin axis of the black hole, and therefore most GRBs may not be seen by us. An upper limit to the ratio of undetected to detected GRB is 600 (Mészáros, Rees, & Wijers 1999), so an upper limit to the total required formation rate would be 60 GEM. We may have seen beaming of that factor or a bit less in GRB990123 (Kulkarni et al. 1999), but other bursts (e.g. 970228, 970508) show no evidence of beaming in the afterglows (which may not exclude beaming of their gamma rays). At present, therefore, any progenitor with a formation rate of 10 GEM or more should be considered consistent with the observed GRB rate.

5. CONCLUSIONS

We have shown that rapidly rotating black holes are an attractive power source for gamma-ray bursts. Via the Blandford-Znajek mechanism (1977) they can supply sufficient energy at a high rate. They also occur often enough to explain the observed GRB rate, even if the gamma-ray emission of a typical GRB is beamed to less 1% of the sky. Because of the requirement of rapid spin, the direct collapse of a stellar core to a black hole is a less likely candidate for making GRB (at least via the BZ effect). Therefore, mergers are much more attractive, which implies a natural connection between GRBs and strong sources of gravity waves. With advanced LIGO, the detection rate of mergers is predicted to become large enough that direct verification of events that produce both gravity wave and gamma-ray signals will become feasible, and will directly constrain GRB beaming. We have used the population synthesis calculations of Bethe & Brown (1998, 1999) to estimate the LIGO detection rate. We found it to be dominated by black-hole, neutron-star mergers, and to be higher by a factor 26 than previous estimates. As a result, we conclude that the most energetic phenomena in astrophysics stem from black holes, whose defining characteristic is paradoxically that no radiation can escape from them.

We would like to thank Roger Blandford, Chris Fryer, Sterl Phinney, Simon Portegies Zwart, Kip Thorne and Stan Woosley for useful suggestions and advice. This work was partially supported by the U.S. Department of Energy under Grant No. DE-FG02-88ER40388. HKL is also supported partly by KOSEF 985-0200-001-2.

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Table 1
Summary of the formation rates of various sources of gamma-ray bursts (GRB) or gravity waves (GW).
L(H)BH means low- (high-) mass black hole.

| object                        | GRB | GW | rate [GEM\(^3\)] |
|-------------------------------|-----|----|------------------|
| NS - NS merger                | X   | X  | 10               |
| NS - BH merger                | X   | X  | 100              |
| WR star - LBH merger          | X   |    | 380              |
| hypernova (HBH formation)     | X   |    | 250              |
| BH in soft X-ray transient    | X   |    | 90               |

\(^1\)GEM means Galactic Events per Megayear; rates are quoted for redshift 0.