Gamma-ray binaries: stable mass transfer from neutron star to black hole

Simon F. Portegies Zwart
Dept. of General System Studies, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153, Japan

Received ______________; accepted ______________

Japan Society for the Promotion of Science Fellow
ABSTRACT

Gamma-ray bursts are characterized by a duration of milliseconds to several minutes in which an enormous amount of radiation is emitted.

The origin of these phenomena is still unknown because proposed models fail to explain all the observed features.

Our proposed solution to this conundrum is a new class of mass-exchanging binaries in which a neutron star transfers mass to a black hole. According to recent studies binaries which contain a neutron star and a black hole are much more frequent than was previously believed. Mass exchange is driven by the emission of gravitational waves but the redistribution of mass in the binary system prevents coalescence. The phase of mass transfer is surprisingly stable and lasts for several thousands of orbital revolutions (about a minute). With a simple analytic model we demonstrated that this new class of binaries could provide an excellent candidate for the observed phenomena known as gamma-ray bursts.

Subject headings: binaries: close — gamma rays: bursts — methods: analytical — stars: evolution — stars: neutron
1. Introduction

The identification of the optical counterparts to gamma-ray bursts GRB 970228 (Groot et al. 1997) and GRB 970508 (Heise et al. 1997) and the measurement of a redshift of \( z \geq 0.853 \) (Metzger et al. 1997) for the latter makes a cosmological origin for this phenomenon hard to circumvent. If indeed cosmological, they must be tremendously energetic: the maximum luminosity is many times the energy output of an entire galaxy and the total energy emitted is at least \( 10^{51} \text{ erg} \).

The rapid rise in luminosity and the short timescale variability suggest that the radiation is generated in an area of only a couple of hundred kilometers (a few light milliseconds). The duration of the burst (seconds to minutes) indicates that something within this region is relatively stable. The complex temporal structure of the energy release reflects the activity of a highly variable inner engine (Sari & Piran 1997; Kobayashi et al. 1997).

Suggestions have ranged from coalescing neutron-star binaries (Blinnikov et al. 1984), compact objects merging with the central massive black hole of a galaxy (Roland et al. 1994) to hypernovae (Paczyński 1998). However all these models have great difficulty explaining the duration (Mészáros 1998) and the intrinsic variability (Sari & Piran 1997) of the burst.

Detailed studies of the stability of binaries where one neutron star transfers mass to another neutron star reveal that coalescence is inevitable within a few orbital revolutions owing the Darwin-Riemann instability (Clark et al. 1977; Lai et al. 1993). Stable mass transfer can be achieved only if the mass of the secondary is smaller than 67\% of the primary (Jaranowski & Krolak 1992). A neutron star which transfers mass to a black hole with mass \( \gtrsim 6M_\odot \) cannot have a stable orbit (Lattimer & Schram 1974). Binaries of a neutron star and a lower mass black hole have not been considered because a lack of
observational evidence. Recent understanding of accretion on to a neutron star (Chevalier 1993; Brown 1995; Fryer et al. 1996) has changed this view completely, at least in the theoretical side. The birthrate (and also the merger rate) of such systems might exceed the number of binary pulsars by an order of magnitude (Portegies Zwart & Yungelson 1998; Bethe & Brown 1998; Lipunov 1998).

2. Formation and evolution

A binary consisting of two neutron stars is formed via a standard scenario (van den Heuvel & Heise 1972) in which a stable phase of mass exchange is followed by a supernova explosion, after which a common envelope phase reduces the orbital separation (see scenario I in Portegies Zwart & Yungelson 1998 for a detailed description). Recent understanding of accretion on to a neutron star which is engulfed by its companion in a common envelope allows the accretion rate to be highly super Eddington (Chevalier 1993; Fryer et al. 1996), as much as $10^8$ times larger or about $1\,M_\odot$ per year. The neutron star cannot support this extra mass and collapses to a black hole. The result is a close binary system consisting of a neutron star and a black hole. At the end of the common-envelope phase the mass of the black hole is between $2.4\,M_\odot$ and $7.0\,M_\odot$ (Wettig & Brown 1996; Bethe & Brown 1998), the distribution within this mass interval is uncertain.

The separation between the two stars shrinks due to gravitational wave radiation (see Peters & Mathews 1963) until the neutron star (with mass $m$) fills its Roche lobe. Mass transfer from the neutron star to the black hole (with mass $M$) is still driven by the emission of gravitational waves. The redistribution of mass in the binary system, however, increases the separation and prevents coalescence (Kaluźniak & Lee 1997). The time taken for material to travel from the neutron star to the black hole is only a few milliseconds and the neutrons do not have time to decay. The accretion rate is therefore not Eddington
limited and no mass is lost in the transfer process; mass transfer proceeds conservatively, i.e.: $\dot{M} = -\dot{m}$. This assumption is not that bold as in the first few orbital revolutions the accretion stream passes the event horizon of the black hole and the material falls in without forming an accretion disc (see sect. 4). The angular momentum carried by this material is largely returned to the binary orbit before it reaches the event horizon of the black hole.

The process is auto-regulated in that the increase in separation due to the mass exchange over compensates the decrease in separation due to the angular momentum loss, leading to a net increase in orbital separation.

If the neutron star can be represented by the ideal neutron gas (a Newtonian polytrope with index $n = 3/2$) its radius $r$ is inversely proportional to the cube root of its mass \cite{Abhyankar1991}. The smallest possible mass of such a neutron star is around $0.1 M_\odot$. If the mass drops below this limit $\beta$ decay and nuclear fission drive the explosion of the unstable neutron star \cite{Coppi1993}.

The rate of mass transfer can be computed from the change in orbital angular momentum $\dot{J}$ which has four components: $\dot{J} = \dot{J}_{\text{orb}} + \dot{J}_{\text{gw}} + \dot{J}_{\text{bh}} + \dot{J}_{\text{ns}}$, where $\dot{J}_{\text{orb}}$ is given by the redistribution of mass in the binary system, $\dot{J}_{\text{gw}}$ gives the loss of angular momentum due to the emission of gravitational waves \cite{Peters1963, Peters1964} and $\dot{J}_{\text{bh}}$ and $\dot{J}_{\text{ns}}$ are the variation in angular momentum for the rotation of the black hole and neutron star, respectively. The latter has a negligible contribution but $\dot{J}_{\text{bh}}$ might be significant. For the remainder of the discussion we assume both $\dot{J}_{\text{ns}}$ and $\dot{J}_{\text{bh}}$ to be zero. (The increase in orbital separation found in the hydrodynamical simulations performed by Kaluźniak & Lee 1997 is only about 25% smaller than if conservation of mass and angular

\footnote{Using a realistic equation of state for the neutron star shortens the binary lifetime but the main picture is unchanged (C-H. Lee, private communication)}
Fig. 1.— The mass transfer rate as a function of time for a $3 \, M_\odot$, $4 \, M_\odot$ and a $5 \, M_\odot$ black hole all accompanied by a $1.4 \, M_\odot$ neutron star (the three lines are very similar). The $\circ$ indicates the moment when the accretion stream no longer crosses the last stable orbit around the black hole. The $\bullet$ at the right end of the curve indicates the moment that the mass of the neutron star drops below $0.1 \, M_\odot$. The phase of mass transfer for the binary containing the $3 \, M_\odot$ black hole lasted for approximately 1.5 minutes, the higher mass binaries live shorter.

Combining the equations with the requirement that the donor fills its Roche-lobe $r_l$ (see Paczyński 1971 for an approximate equation) and keeps doing this as mass is transferred, i.e.: $r_l = \dot{r}$, results in an expression for the required rate of mass transfer

$$\dot{m} = \frac{32G^3}{5\kappa^4c^5} \frac{m^{16/3}}{q^{2/3}(q + 1)^{1/3}(q - 2/3)},$$

(1)

Here $q \equiv m/M$ and $G$, $c$ are the gravitational constant and the speed of light. The constant $\kappa \approx 2.2M_\odot^{1/3}r_\odot \approx 4.1 \times 10^{17} \text{[cm g}^{1/3}]$, with $r_\odot$ the radius of a $1 \, M_\odot$ neutron star. Figure 1 presents the mass accretion rate as a function of time.

We computed the birth rate of such binaries with the detailed binary population
synthesis program SeBa \cite{Portegies_1996, Yungelson_1998}. It is $10^{-4.3}$ per year in the Galaxy. In comparison, the birthrate of double neutron star systems is $10^{-5.2}$ per year. The majority of these systems begin mass transfer within a billion years after formation resulting in a merger rate of $\sim 10^{-4.5}$ per year. Bethe \& Brown (1998) independently compute birth- and merger rates and obtain similar results. A somewhat smaller rate is derived from the observed population of neutron star binaries by Phinney (1991) and Narayan et al. (1991).

3. Stability

Gravitational wave radiation circularizes the orbit of the binary and let the separation shrink. The spiral in owing to the emission of gravitational waves can be arrested by mass transfer from the neutron star to the black hole if the mass ratio is less than $2/3$ (Eq. 1, see also \cite{Jaranowski_1992, Kochanek_1992}). Two neutron stars in observed binary pulsars have almost the same mass and coalescence is expected to occur within a few orbital periods upon Roche-lobe contact. To prevent immediate coalescence the mass of the accretor must exceed $2.1 \, M_\odot$ if the donor is a Chandrasekhar mass neutron star ($1.4 \, M_\odot$).

The orbital separation at Roche-lobe contact must exceed the last stable orbit, i.e, $a > 3R_{\text{Sch}}$ where $R_{\text{Sch}} \equiv 2GM/c^2$ is the Schwarzschild radius. For a Kerr black hole, which is more appropriate for our discussion, the stability limit is even more relaxed.

At the onset of mass transfer the horizon radius of the black hole is a considerable fraction of its Roche lobe and the accretion stream falls in practically radially: there will be no accretion disc. Once the orbital separation has increased sufficiently a neutron rich disc can form around the black hole. Figure 3 illustrates the evolution of such binaries and the stability criterion.
The time scale for orbital decay by gravitational radiation is shorter than the time scale for tidal synchronization ([Bildsten & Cutler 1992; Lai et al. 1994], note however that the liquefaction of the neutron star just before Roche-lobe overflow [Kochanek 1992], speeds up synchronization [Lai et al. 1993]) so that the binary is not tidally synchronized at the moment mass transfer begins and the Roche-geometry is strictly speaking not applicable. What effect this has on the computation is unknown. It possibly increases the mass transfer rate and decreases the systems’ lifetime, but the binary does not become tidally unstable ([Kaluźniak & Lee 1997]).

4. Gamma-ray production

The energy available from the infall of material into the potential well of the black hole, \( L \propto GM\dot{M}/R_{\text{Sch}} \), is not likely to drive the gamma ray burst, because the transformation of this energy into gamma-rays is not efficient enough (Shapiro 1973; Shrader & Titarchuk 1998).

How to get the energy out in the form of gamma-rays is not clear. An interesting model is based on the Blandford-Znajek (1977) mechanism where the rotation of a rapidly spinning Kerr black hole is used as an energy source (see e.g. Mészáros & Rees 1997 and Katz 1997 for details). The rotational energy of such a black hole is approximately \( 10^{54} \) erg, but the fraction which is liberated is considerably smaller (Macdonald et al. 1986):

\[
L \approx 10^{50} \left( \frac{\mu M}{3[M_\odot]} \right)^2 \left( \frac{B}{10^{15}[G]} \right)^2 \text{[erg s}^{-1}] \].
\]

Here \( \mu \) is the angular momentum of the black hole relative to that if maximally rotating. An enormous magnetic field \( B \) is required and how it is generated is not well understood. However, strong magnetic fields in black holes have gained a lot of support over the last few years (see e.g. Paczyński 1998 for an overview). The strong magnetic field is anchored in
the disc but the power comes from the spin energy of the black hole (Kats 1997).

The magnetic field causes the radiation to be collimated along the axis of the black hole. If the opening angle of the emission is limited to \( \lesssim 10^\circ \) the efficiency of the radiation process can be small \( \lesssim 10^{-4} \) and still produce a phenomenon energetic enough to power a high redshift gamma-ray burst (Mészáros & Rees 1997). Such a small opening angle also conveniently increases the low occurrence rate of gamma-ray bursts of about \( 10^{-7} \) Mpc\(^{-3}\) yr\(^{-1}\) to the rate of mergers between compact objects as given earlier.

### 5. Baryon pollution

The gamma-ray production would be greatly reduced if too many baryons (which absorb the photons) would pollute the vicinity of the black hole. Basically there are two sources of baryons; the inner edge of the accretion disc, and the baryon loaded wind from the neutron star surface.

In the presented model a disc is formed only after a phase of radial infall in the black hole, and little or no baryon pollution is expected in this phase. After the formation of a disc (at which point the accretion rate has dropped by three orders of magnitude) the region near the axis of the black hole is still expected to be reasonable free of material; the black hole easily accretes material with angular momentum below a specific value (Fishbone & Moncrief 1976, see however Chakrabarti 1998 for counter arguments). Whether or not the vicinity of the black hole is clean enough to allow for the high Lorentz factors required to produce the gamma-ray burst is unclear.

The neutron star is heated by the tidal friction as it is forced into co-rotation (see Kochanek 1992). This may result in a baryon loaded wind from the neutron star surface which pollutes the environment. The contamination of baryons due to this tidal heating is
computed by Mészáros & Rees (1992). In the presented model the binary spirals outwards instead of inwards, and the heat production due to tidal friction decreases in time.

6. Discussion

The time structure of gamma ray bursts must reflect the time structure of their energy release (Sari & Piran 1997). About three quarters of the observed gamma-ray bursts have a duration of seconds to several minutes (Mukherjee et al. 1998). Fireball models can only explain this duration with an enormous time dilation (Rees & Mészáros 1992) and are unable to explain the temporal structure.

The shortest bursts can still be understood as the merging of two neutron stars or as the cases where mass transfer from a neutron star to a black hole is unstable. The tail of the light curve is not necessarily detected in its full extent because the luminosity of the burst drops below detector sensitivity. The presented model therefore explains a range of timescales from milliseconds to minutes and predicts a relative frequency of at least 1 short burst to 17 long bursts (given by the relative frequency of merging neutron stars and mass transferring neutron star–black hole systems (Portegies Zwart & Yungelson 1998). In fact 3 out of ten observed bursts are short (Mukherjee et al. 1998).

In the accretion phase our class of objects is very similar to that of low-mass X-ray binaries with an accreting black hole, and the active cores of galactic nuclei (Protheroe & Kazanas 1983). The X-ray binaries are highly variable (Zhang et al. 1994; Belloni et al. 1997) and the detection of gamma rays have been reported (Grove et al. 1998).

When the neutron star reaches its lower-mass limit it explodes generating a luminosity of $10^{49}$ to $10^{51}$ erg/s accompanied by a burst of anti-neutrinos of $10^{51}$ to $10^{52}$ erg/s (Coppi et al. 1993). By this time the energy emitted in gamma-rays has probably stopped or
decreased below detector sensitivity. The radius of the neutron star at that moment (at a mass of about 0.1 $M_\odot$) is about 33 km, and the orbital separation is more than 250 km. The escape velocity from the black hole at this distance is less than $10^5$ km/s. With an expansion velocity for the exploding neutron star of several $10^4$ km/s (Coppi et al. 1993) only a small fraction of its mass can escape, so the black hole is released with a velocity of only a few tens of kilometers per second.

With a birth rate of $10^{-4.5} \text{yr}^{-1}$ (Portegies Zwart & Yungelson 1998) our Galaxy has produced about $10^{5.5}$ low velocity black holes with a mass between $4 M_\odot$ and $8 M_\odot$ over the last 10 Gyr (for a constant star formation rate). Per event about $10^{-3} M_\odot$ of neutron star material is ejected enriching the Galaxy with a total of $10^3 M_\odot$ in r-processed elements so that the majority of the Galactic thorium enrichment could have originated in gamma-ray bursts. This enrichment is about two orders of magnitudes larger than previous estimates based on mergers between neutron stars (Ruffert et al. 1997).

7. Conclusion

The recent understanding of the super Eddington accretion process on to a neutron star in a common-envelope phase predicts the formation of a large number of close binaries in which a neutron star is accompanied by a low mass ($\lesssim 7 M_\odot$) black hole. Model computations predict that the formation rate of such binaries exceeds the formation of classical high-mass binary pulsars by about an order of magnitude. These binaries are therefore expected to contribute appreciably to the rate of any associated observable phenomena.

There are three possible forms of mass transfer from a neutron star to its companion: unstable mass transfer to another neutron star and stable and unstable transfer to a black
hole. Also for gamma-ray bursts there is evidence for three types: short and faint bursts, long and bright and a third class of intermediate bursts (Mukherjee et al. 1998).

In the stable binaries the duration of mass transfer lasts for about a minute after which the neutron star explodes. An accretion disc with a mass \( \lesssim 0.4 M_\odot \) around the black hole develops about a second after the onset. The gamma-ray burst is powered by using the rotational energy of the black hole via the Blandford-Znajek (1977) mechanism. If the neutron star finally explodes it is accompanied by a burst of luminosity as well as anti neutrinos. The accompanying black hole is released with a low velocity. As the binary spirals outwards instead of inwards a reversed chirp in the gravitational wave signal is expected, the signal-to-noise, however, drops considerably during this process.

In our model gamma-ray bursts are another exciting class of mass-exchanging binary stars. We propose to call them gamma-ray binaries.

I am grateful to Gerald Brown, Junichiro Makino, Gijs Nelemans and Chirstopher Tout for discussions and checking computations as well as English.
Fig. 2.— Evolutionary tracks for a 3 M$_\odot$ black hole, a 4 M$_\odot$ and a 5 M$_\odot$ black hole accompanied by a 1.4 M$_\odot$ neutron star through the phase of mass transfer (left, middle and right solid lines, respectively). The mass of the black hole is on the horizontal axis the vertical axis gives the orbital separation in kilometers. The evolution ends at the • when the neutron star becomes unstable. The dotted line gives the separation below which the binary is gravitationally unstable (3$R_{\text{Sch}}$). The dashed line gives the initial orbital separation at the moment mass transfer starts. The initial and also minimum orbital separation (dashed line) is larger than 3$R_{\text{Sch}}$ for black holes with a mass smaller than about 5.8 M$_\odot$. The square to the left of the dashed line indicates the minimum mass for the accretor in order to have stable mass transfer from a 1.4 M$_\odot$ neutron star.

The ◦ indicates the moment in the evolution of the binary at which a disc around the black hole can be formed. From that moment the accretion stream remains well outside the last stable orbit.
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