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Distribution of black hole binaries around galaxies

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Abstract. Compact object mergers are one of the favorite models of GRBs. It has been noted that in contrast to the collapsars, compact object mergers do not necessarily take place in the host galaxies, and may travel outside of them. With the discovery of afterglows and identification of host galaxies one can measure the distribution of GRBs with respect to their host galaxies. This distribution has been calculated using different population synthesis codes, and for different galactic potentials (Bloom et al., 1999; Bulik et al., 1999a; Fryer et al., 1999). In this paper we compare the distributions of different types of compact object binaries: double neutron star systems (NS-NS), black hole -neutron star systems (BH-NS) and double black holes (BH-BH). We calculate the orbits and distributions of the projected distances on the sky for two extreme cases: a massive galaxy like the Milky Way, and empty space (corresponding to e.g. a globular cluster), and consider a wide range of possible kick velocity distributions. We find that BH-NS are more likely gamma-ray burst counterparts, since they lie close to the host galaxies, contrary to the NS-NS binaries.

Key words: stars: binaries: general – stars: evolution – stars: neutron – gamma rays: bursts

1. Introduction

The discovery of X-ray (Costa et al., 1997) and later optical afterglows (Groot et al., 1997b) of gamma-ray bursts led to identification of gamma-ray burst host galaxies (Groot et al., 1997a). Such host galaxies were expected in the cosmological model, since most of the theories identified GRBs with some, perhaps extreme, stages of stellar evolution. However, various physical models of GRBs gave different predictions regarding the location of GRBs with respect to the host galaxies. In the framework of the collapsar model, and in general all models that relate GRBs to the final stages of evolution of massive stars (Colgate, 1968), one expects that GRBs are found in star forming regions. In the second class of models where bursts are associated with mergers of compact object binaries such associations are not obvious. Compact object binaries may live for quite a long time before they merge, and given the possibility that they could have high velocities they may travel away from the place they were formed.

The distribution of compact object mergers can be found using stellar population synthesis codes. The main problem of this approach is that such codes contain a number of poorly known parameters, which may affect the results. One of the most important parameters is the kick velocity a newly born compact object receives at birth.

The distribution of double neutron star systems around galaxies has been calculated for a few types of galaxies by Bloom et al. (1999). Bulik et al. (1999a) calculated such a distribution for the case of a massive galaxy such as the Milky Way, and for the case of empty space, using four different kick velocity distributions. These studies considered only binaries containing neutron stars. We used an assumption (Bulik et al., 1999a; Bulik et al., 1999b) that all supernovae lead to the formation of a $1.4\,M_\odot$ neutron star. However, mergers of binaries containing a black hole are now more favored for GRBs. One reason for this is energetics, GRB990123 had an equivalent isotropic energy release of 10^{54} ergs. The energetic requirements go down when considering that the relativistic outflow from the central fireball is not isotropic but beamed. On the other hand not all kinetic energy in the outflow can be converted into gamma rays, and therefore the energetic requirement for the GRB central engine will go up. Therefore it is important to investigate the distribution around galaxies of binaries containing black holes.

In this paper we extend the results of Bulik et al. (1999a), to include the case of compact object binaries containing black holes. In Sect. 2 we describe the model for population synthesis and galactic potential used in this paper, in Sect. 3 we present the results, and we summarize this work in Sect. 4.

2. The model

2.1. Population synthesis code

We use the population synthesis code described in detail in Belczyński & Bulik (1999). Within this model we assume that the distribution of the masses of the primary stars is

$$\Psi(M) \propto M^{-1.5},$$

with $10\,M_\odot < M < 50\,M_\odot$. The lower limit of our primary mass was chosen to ensure that the star will explode as a supernova (M_{SN}). The value of M_{SN} depends crucially on core mass star forms after its main sequence life. Different stellar models predict different core masses and thus different values of M_{SN}. Standard stellar models predict the limiting mass of ZAMS star to become supernova larger than 9 $M_\odot$. However these models face problems when explaining some observational properties of single stars, such as the width of the main sequence band. More advanced models including convective core overshooting, result in lower M_{SN}= 6–8 $M_\odot$, and they are generally able to reproduce observations. Effects of stellar rotation, if they were included in the stellar models, could probably explain the observations without the need for overshooting, and they would also lower M_{SN}. However, even the most sophisticated present stellar models are still far from being perfect and their uncertainties do not allow us to precisely and with certainty set the value of M_{SN}. Our $M_{SN} = 10\,M_\odot$ might seem high but we want to ensure that all our primaries will undergo a supernova explosion. Change of M_{SN} to a lower value would increase the number of NS-NS binaries as compared to the number of BH binaries. This would not change our results as in this paper we work only on the distribution of a given class of mergers around its host galaxy.

The distribution of the mass ratio q (secondary to primary mass) is

$$\Phi(q) \propto \mathrm{const}$$

with $0 < q < 1$. The distribution of the initial binary eccentricity e is $\Xi(e) = 2e$ with $0 < e < 1$, and the distribution of the initial semi-major axis a used in population synthesis codes is flat in the logarithm, i.e. $\Gamma(a) \propto a^{-1}$ with the maximum $a_{max} = 10^5 R_\odot$.

Very little is known observationally about the kicks newly born black holes receive. While studies of pulsars indicate that substantial kicks are possible for newly born neutron stars, we believe that black hole kicks are smaller. The physical reason could be just that black holes are more massive, and also that asymmetric neutrino emission may not take place when a black hole is formed. Lipunov et al. (1997) use a Gaussian parameterization of the kick velocity and assume that for black holes it is proportional to the mass lost in the explosion. Fryer et al. (1999) show results for several cases, using the same functional form of the kick distribution for black holes and neutron star and assuming that black hole kicks are ten times smaller than those for neutron stars.

We parameterize the distribution of the kick velocity a newly born compact object receives in a supernova explosion by a three dimensional Gaussian with the width σ_v, and consider several values of this parameter. Such a choice allows us to compare the distributions of binaries containing black holes vs the double neutron stars that could be formed with different kick velocities.

For a detailed description of the population synthesis code we refer the reader to Belczynski & Bulik (1999). There is only one modification to the code, i.e. in the choice of the mass of a compact object formed in a supernova explosion. This is described in the next subsection.

2.2. *Compact object formation in a Sn explosion*

In general, supernovae from massive stars should lead to formation of more massive objects, perhaps black holes, and supernovae from less massive stars to lighter compact objects like neutron stars. The boundary between these two possibilities and the mass of a compact object formed in an explosion is not clear. Lipunov et al. (1997) assumed that a neutron star with a mass $1.4\,M_\odot$ is formed for progenitors with core masses below $35\,M_\odot$ at the time of explosion. For larger masses black holes are formed with the mass $k_{bh} \times 35\,M_\odot$ where the parameter k_{bh} varies between 0.1 and 1 (Lipunov, 1997). Tout et al. (1997) used a different formula: neutron stars are born with masses equal to $M_{Ch} + M_{pro}/50$, where $M_{Ch} = 1.4\,M_\odot$ is the Chandrasekhar mass, and M_{pro} is the progenitor mass at the time of collapse, and the assumption that objects above $1.8\,M_\odot$ are black holes. Fryer (1999) presented numerical simulations of core collapse in massive stars, and found that neutron stars are formed for progenitors with initial masses below $22\,M_\odot$, and black holes for masses above this value. In a population synthesis code Fryer et al (1999) assume simply a compact object with a mass $\frac{1}{3}M_p$, where M_p is the progenitor mass at the time of collapse. On the other hand Ergma and van den Heuvel (1998) analyze the population of known X-ray binaries and argue that the initial mass of the progenitor is not the sole parameter determining the mass of a compact object formed in a supernova explosion, but probably other factors like rotation or the magnetic field may play an important role.

Given such a range of uncertainties we use the following prescription for the compact object mass (either neutron star or black hole): the compact object mass is equal to half of the mass of the final helium core of progenitor star. This approach gives higher masses of compact objects as compared to the prescriptions discussed above. However, simulations of core collapse during supernova explosions (Fryer, 1999) show that the compact object might accrete back some of the material firstly ejected in explosion for a fraction of the range of stellar masses we are concerned with in our work. Although the predictions of how much mass is accreted in a given case are still uncertain and can not be easily parameterized, we believe that some enhancement of compact object mass is reasonable.

Standard equations of state for neutron stars give the maximum mass of a neutron star to be between 1.9 and 2.6 $M_\odot$, although rotation may increase it by about another 0.2 $M_\odot$. We have used a value of 2.4 $M_\odot$ as the maximum neutron star mass in our previous work (Bulik et al., 1999a). However, there are equations of state for neutron stars which allow masses as high as 3 $M_\odot$ or even up to 3.2 $M_\odot$ if rotation is included (Cook et al., 1994). Thus in this work we assume that the maximum neutron star mass is 3.0 $M_\odot$. This number was not crucial in the previous paper, as we treated both groups, namely double neutron stars and black hole neutron stars binaries together and in Bulik et al. (1999a) we assumed that all supernovae lead to formation of a $1.4\,M_\odot$ neutron star. In the present study this number plays an important role and as we are mostly interested in black hole binaries we want to be sure that we do not include any neutron stars as black holes in the present calculations. Thus we use 3.0 $M_\odot$ as the upper limit on neutron star mass and consequently the dividing line between neutron stars and black holes.

2.3. Gravitational potentials

We follow the approach we have used in our previous paper (Bulik et al., 1999a), and consider two extreme cases: propagation in a potential of a massive galaxy like the Milky Way, and propagation in empty space (corresponding to e.g. a globular cluster origin). The potential of a massive galaxy consists of three components: bulge, disk, and halo. To model the bulge and disk potentials we use the potential model proposed by Miyamoto & Nagai (1975):

$$\Phi(R,z) = \frac{GM_i}{\sqrt{R^2 + (a_i + \sqrt{z^2 + b_i^2})^2}} \qquad (1)$$

where the index i refers to either bulge or disk, a_i and b_i are the parameters, M is the mass, and $R = \sqrt{x^2 + y^2}$. The dark matter halo potential is spherically symmetric

$$\Phi(r) = -\frac{GM_h}{r_c}\left[\frac{1}{2}\ln\left(1 + \frac{r^2}{r_c^2}\right) + \frac{r_c}{r}\mathrm{atan}\left(\frac{r}{r_c}\right)\right]$$

where r_c is the core radius. The halo potential corresponds to a mass distribution $\rho = \rho_c/[1 + (r/r_c)^2]$, and we introduce a cutoff radius $r_{cut} = 100\,\mathrm{kpc}$ beyond which the halo density falls to zero, in order to make the halo mass finite and the halo gravitational potential is $\Phi(r) \propto r^{-1}$ when $r > r_{cut}$. We use the following values of the parameters derived for the Milky Way (we assume that the Milky Way is a good example of a massive galaxy; the bulge potential ($i = 1$): $a_1 = 0\,\mathrm{kpc}$, $b_1 = 0.277\,\mathrm{kpc}$, $M_1 = 1.12 \times 10^{10}\,M_\odot$; the disk potential ($i = 2$): $a_2 = 4.2\,\mathrm{kpc}$, $b_2 = 0.198\,\mathrm{kpc}$, $M_2 = 8.78 \times 10^{10}\,M_\odot$; the halo potential: $r_c = 6.0\,\mathrm{kpc}$, and $M_h = 5.0 \times 10^{10}\,M_\odot$ (Paczyński, 1990; Blaes and Rajagopal, 1991). The distribution of stellar initial positions in the model galaxy is a double exponential $P(R,z) = R\exp(-R/R_{exp})\exp(-z/z_{exp})$, with $R_{exp} = 4.5\,\mathrm{kpc}$, $z_{exp} = 75\,\mathrm{pc}$, and we cut the distribution at $R_{max} = 20\,\mathrm{kpc}$ (Bulik et al., 1998). The initial velocity of a binary is assumed to be equal to the local rotation velocity in the galactic disk. After each supernova explosion we add the velocity the system received, which is calculated in the population synthesis code. We follow the trajectories of the binaries until they merge.

3. Results

In order to see the general properties of the population of compact object binaries we consider the case with no kick velocities $\sigma_v = 0\,\mathrm{km\,s^{-1}}$. In Fig. 1 we present the density of binaries as a function of their masses. The population in Fig. 1 has three components, which come from different regimes of initial binary mass ratio, which to some degree sets the subsequent binary evolution, as discussed earlier by Bethe & Brown (1998). The main component are the binaries which originate from systems with small mass ratios $q < 0.88$, the binaries along the line $M_1 \approx M_2$ originally had nearly equal masses $q > 0.95$ and the population of systems for which $M_2 > M_1$ originates from binaries with intermediate mass ratios $0.88 < q < 0.95$. The detailed description of evolution in each of these regimes can be found in Belczyński & Bulik (1999).

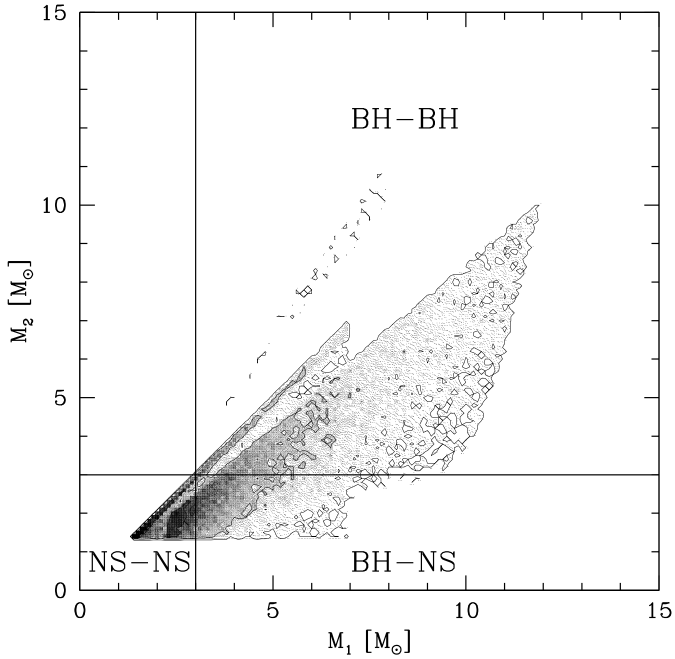

Fig. 1. The population of the compact object binaries in the space spanned by their masses. The three regions correspond to different initial mass ratios: the binaries with M_1 reaching up to $10\,M_\odot$ and $M_2 < M_1$, originate from systems with the initial mass ratio $q < 0.88$, and the binaries along the line $M_1 \approx M_2$ originally had nearly equal masses $q > 0.95$. The sparse population of systems for which $M_2 > M_1$ originates from binaries with $0.88 < q < 0.95$.

When considering higher kick velocities, the basic shape of the diagram of Fig. 1 does not change substantially. We draw lines corresponding to $M_1 = 3M_\odot$ and $M_2 = 3M_\odot$, the upper limit on the maximal mass of a neutron star. We predict a large population of compact object binaries that contain a black hole. While we do not expect to see double black hole binaries, it is puzzling that no black hole neutron star binaries are known among binary pulsars. This could be explained by the fact that so far we know only a few such objects. There could also be a gap in the compact object mass distribution, and if such a gap really exists than the number of BH-NS binaries would be smaller than our simulations predict. Such a gap – jump between neutron star and black hole masses – was reported by Bailyn et al. (1998) on the basis of an observed sample of compact object masses. However, theoretical simulations of core collapse supernovae connected with evolutionary predictions for single and binary stars show no gaps in compact object mass distribution (Fryer and Kalogera, 1999).

The properties of the population of compact object binaries can be found from Fig. 2 where we plot the distribution of

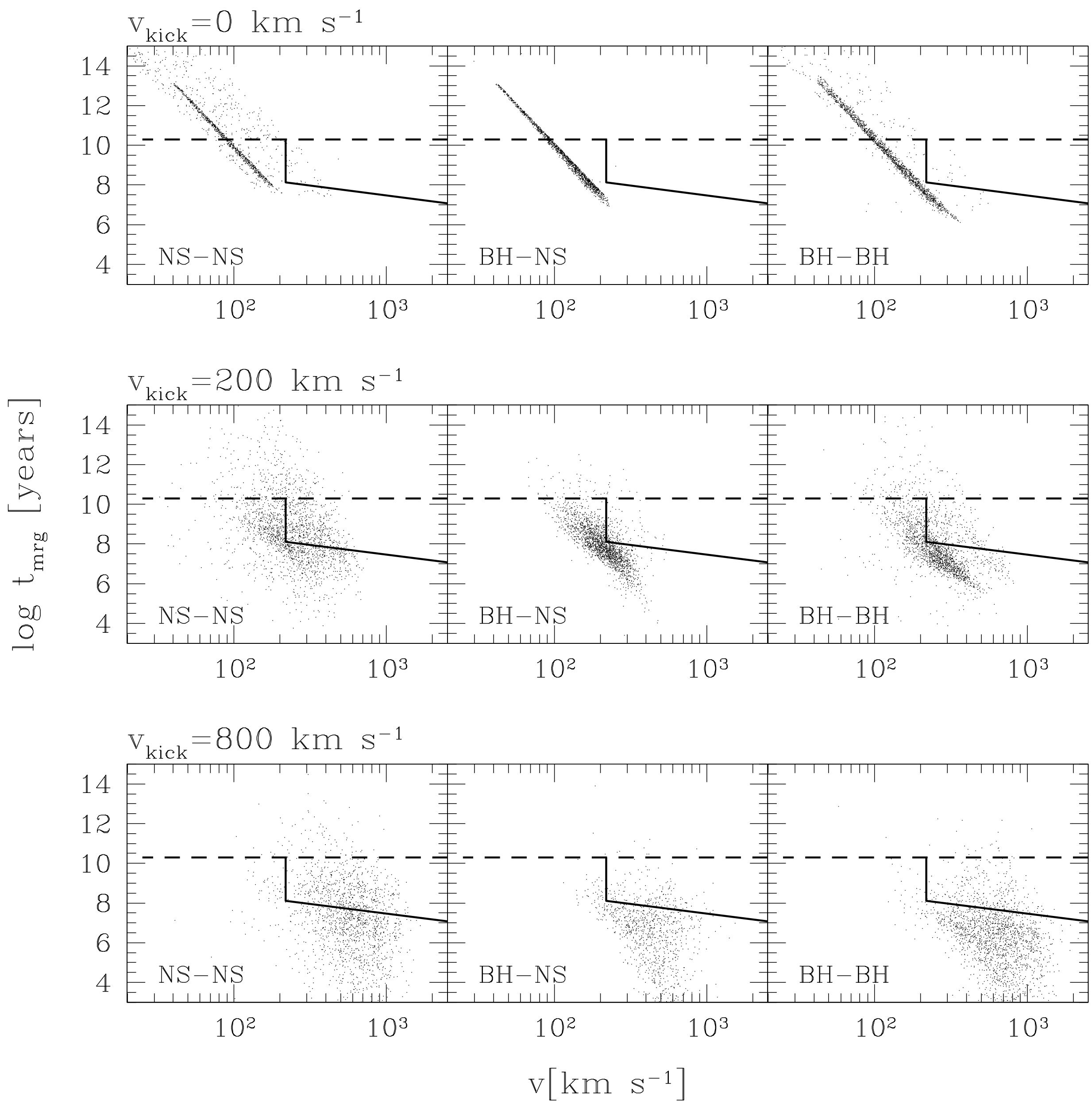

Fig. 2. The distributions of binaries in the plane spanned by the center of mass velocity v and merger time t_{mrg}. In each panel we also plot the following lines: the horizontal dashed line corresponding to the Hubble time (15Myrs); two solid lines: the vertical corresponding to $v = 200\,\mathrm{km\,s^{-1}}$ - a lower limit on the typical escape velocity from a galaxy, and the line corresponding to a constant value of $v \times t_{merge} = 30$ kpc. The panels correspond to the kick velocity distributions width of 0km s^{-1}, 200km s^{-1}, and 800km s^{-1} from top to bottom respectively. In each panel we present the distribution of NS-NS, BH-NS and BH-BH separately.

different types of objects in the plane: v - the center of mass velocity, and t_{mrg} - time to merge. In the the top panel, corresponding to the case of no kick velocities, $\sigma_v = 0\,\mathrm{km\,s^{-1}}$, a correlation between v and t_{mrg} is apparent. The center of mass velocities in this case are due to mass ejection from the system (Blaauw, 1960), and is of the same order of magnitude as the orbital velocity. The lifetime due to gravitational wave energy loss has been calculated by Peters (1964), and it scales like $t_{mrg} \propto a^4$, where a is the orbital separation. The orbital separation is inversely proportional to the square of the orbital velocity, hence $t_{mrg} \propto v^{-8}$, which explains the trend in the top panel of Fig. 2. With increasing the kick velocity only very tight and eccentric systems survive and their lifetime becomes shorter. The typical center of mass velocity is now determined by both the orbital velocity at the time of supernova explosion, and the kick velocity. This moves the center of the distribution towards shorter merger times and higher velocities with increasing the kick velocity. The distributions become wider and the correlation between v and t_{mrg} vanishes for the case of high kick velocities.

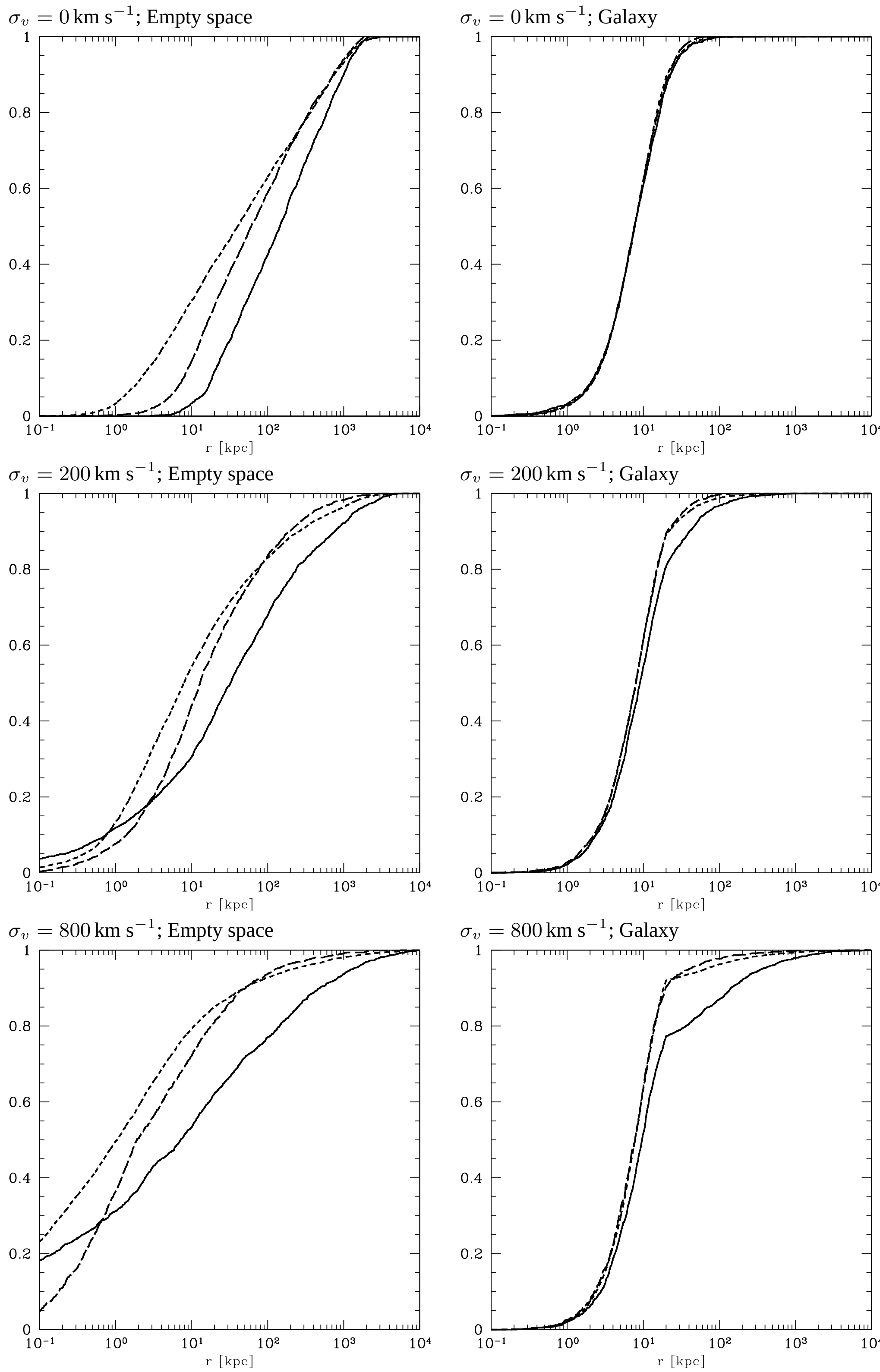

Fig. 3. Cumulative distribution of projected distances on the sky of compact object binary mergers. The left panels correspond to the case of propagation in the empty space, and the right panels to the propagation in the potential of a massive galaxy. The top panels show the case of no kick velocities $\sigma_v = 0\,\mathrm{km\,s^{-1}}$, the middle panels correspond to $\sigma_v = 200\,\mathrm{km\,s^{-1}}$, and the lower panels represent the case $\sigma_v = 800\,\mathrm{km\,s^{-1}}$. In each panel the solid line, long dashed and short dashed lines represent the distributions of NS-NS, BH-NS, and BH-BH binaries, respectively.

Similarly to our previous work (Bulik et al., 1999a) we present the distribution of compact object mergers projected distances on the sky for two cases: (i) propagation in the potential of a massive galaxy like the Milky Way, and (ii) propagation in empty space, corresponding to a small galaxy. The results of cases (i) and (ii) are shown in the right and left panels of Fig. 3, respectively. Generally for the same width of the kick velocity distribution, the spatial distribution of more massive binaries is tighter around the origin for the case (ii). This is due to the fact that the merger time for the more massive objects is typically smaller, see also Fig. 2. The median projected distance for the BH-BH binaries is about ten times smaller than that for the NS-NS binaries. Increasing the kick velocity leads to two effects: decrease of the lifetime of a compact object binary and increase of its center of mass velocity. The decrease of the lifetime, however, is more important in determining the spatial distribution of these objects. The median distance to the merger decreases significantly with increasing the kick velocity, however, a long tail of the distribution extending to large distances remains.

In the case(i) (propagation in the potential of a massive Galaxy) the increase of the width of the kick velocity distribution leads to division of the population into two groups: the bound and the escaping binaries. The spatial distribution of bound binaries follows that of the stellar matter in galaxy. This division is responsible for the breaks in the cumulative plots in the right panels of Fig. 3. There is a small difference between the populations of different types of compact object binaries, regardless of the kick velocity. With increasing the kick velocity the fraction of unbound binaries becomes larger. This fraction also depends on the type of binary, the escaping fraction of binaries containing black holes is smaller than that of the NS-NS binaries. For the case of the highest kick velocity distribution width considered here, $\sigma_v = 800\,\mathrm{km\,s^{-1}}$ less than 10 percent of black hole neutron star binaries become unbound in comparison to almost 30 percent of the double neutron star systems.

4. Discussion

We have presented an extension of our previous work (Bulik et al., 1999a) where we analyzed the distribution of neutron star binaries around galaxies. Here we have modified the code to produce binaries which are heavier, e.g. contain black holes. The class defined as NS-NS binaries in this paper is broader than the binaries in Bulik et al. (1999a), since it includes objects with masses up to $3\,M_\odot$, while the heaviest compact objects in our previous paper had a mass of $2.4\,M_\odot$, and the bulk of them were $1.4\,M_\odot$ neutron stars. The trend, which we also noted before, that heavier binaries tend to stick closer to the host galaxies is evident when comparing the distribution around a massive galaxy for the NS-NS class shown in this paper with the distributions shown in Bulik et al. (1999a). For the highest kick velocity distribution width considered here, $\sigma_v = 800\,\mathrm{km\,s^{-1}}$, the fraction of escaping NS-NS binaries is $\approx 25\%$ here, in comparison to almost 40% in Bulik et al. (1999a).

When interpreting the results of Fig. 3 one has to remember that for reasons stated above the kick velocity probably decreases with increasing mass of the compact object. Thus, the distribution of NS-NS binaries lies somewhere between the case $\sigma_v = 200\,\mathrm{km\,s^{-1}}$ and $\sigma_v = 800\,\mathrm{km\,s^{-1}}$ (the middle and the lower panel in Fig. 3, and the distribution of BH-NS binaries may be somewhere between the cases $\sigma_v = 0\,\mathrm{km\,s^{-1}}$ and $\sigma_v = 200\,\mathrm{km\,s^{-1}}$. We find that BH-NS binaries (and also BH-BH systems) will merge within the host galaxies provided that they are massive. In the case of smaller galaxies, the BH-NS mergers will take place typically a few times closer to the host galaxy than the NS-NS mergers. However, there is still a long tail of the distribution, with a significant fraction extending to large distances.

We have shown that the distances from the host galaxies where compact object binaries merge, decrease with increasing mass of the binary. The reasons for such behavior are twofold. First, the lifetimes of heavier binaries are smaller, because of the increased gravitational wave energy loss. Second, the width of the kick velocity distribution in a supernova explosion is probably smaller when black holes are formed, which leads to smaller center of mass velocities. We conclude that BH-NS binary mergers are more likely progenitors of gamma-ray bursts than the NS-NS binaries. Their distribution closely follows that of the matter in massive galaxies, and also allows us to explain the extreme energetics of some bursts. However, this conclusion is so far based on a small sample of well observed GRB afterglows for long and hard bursts.

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