Extreme recoils: impact on the detection of gravitational waves from massive black hole binaries.

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ABSTRACT

Recent numerical simulations of coalescences of highly spinning massive black hole binaries (MBHBs) suggest that the remnant can suffer a recoil velocity of the order of few thousands km/s. We study here, by means of dedicated simulations of black holes build–up, how such extreme recoils could affect the cosmological coalescence rate of MBHBs, placing a robust lower limit for the predicted number of gravitational wave (GW) sources detectable by future space–borne missions (such as LISA). We consider two main routes for black hole formation: one where seeds are light remnants of Population III stars (\(\simeq 10^2 \, M_\odot\)), and one where seeds are much heavier (\(\gtrsim 10^4 \, M_\odot\)), formed via the direct gas collapse in primordial nuclear disks. We find that extreme recoil velocities do not compromise the efficient MBHB detection by LISA. If seeds are already massive and/or relatively rare, the detection rate is reduced by only \(\sim 15\%\). The number of detections drops substantially (by \(\sim 60\%\)) if seeds are instead light and abundant, but in this case the number of predicted coalescences is so high that at least \(\sim 10\) sources in a three year observation are guaranteed.

Key words: black hole physics – cosmology: theory – gravitational waves

1 INTRODUCTION

Massive black hole (MBH) binaries (MBHBs) are among the primary candidate sources of gravitational waves (GWs) at mHz frequencies, the range probed by the space-based Laser Interferometer Space Antenna (LISA, Bender et al. 1998). Today, MBHs are ubiquitous in the nuclei of nearby galaxies (see, e.g., Magorrian et al. 1998). If MBHs were also common in the past, and if their host galaxies experienced multiple mergers during their lifetime, as dictated by popular cold dark matter hierarchical cosmologies, then MBHBs inevitably formed in large numbers during cosmic history. Provided MBHBs do not “stall”, their inspiral driven by radiation reaction follows the merger of galaxies and protogalactic structures at high redshifts. MBHBs coalescing in less than a Hubble time would give origin to the loudest GW signals in the Universe, and a low–frequency detector like LISA will be sensitive to GWs from binaries with total masses in the range \(10^3–10^7 \, M_\odot\) out to \(z \simeq 20\) (Hughes 2002).

The formation and evolution of MBHs has been investigated recently by several groups in the framework of hierarchical clustering cosmology (e.g. Menou, Haiman & Narayan 2001, Volonteri Haardt & Madau 2003, Kouhiappas, Bullock & Dekel 2004). The inferred LISA detection rate, ranging from a few to a few hundred per year, were derived in a number of papers (Jaffe & Backer 2003, Wyithe & Loeb 2003, Sesana et al. 2004, Sesana et al. 2005, Enoki et al. 2004, Rhook & Wyithe 2005). More recently Sesana Volonteri & Haardt (2007) investigated the imprint of massive black hole formation models on the expected MBHB coalescence rate, finding that at least \(\sim 10\) (considering a model that marginally reproduces the observational constrains and that can be taken as a robust lower bound) sources should be safely regarded as observable by LISA, assuming a 3 year lifetime mission.

GWs emitted during the final plunge of the binary, carry away a net linear momentum, causing a recoil of the MBHB center of mass in the opposite direction (Redmount & Rees 1989). This GW recoil could have interesting astrophysical effects, since many coalescence remnants can be ejected from their host galaxies and dark matter halos (e.g. Madau et al. 2004, Merritt et al. 2004, Micic Abel & Sigurdsson 2006). This justifies the increasing effort to obtain accurate estimates of the recoil velocity. In the case of non spinning black holes, the latest analytical (e.g. Favata Hughes & Holz 2004, Blanchet Qusailah & Will 2005, Damour & Gopakumar 2006) and numerical (Baker et al. 2006, Gonzalez et al. 2007) approaches are now both converging to maximum recoil velocities \(v_r\) in the range 100-250 km/s for binaries with mass ratio \(q = m_2/m_1 \sim 0.4\) (\(m_2 < m_1\) are the masses of the two binary members). The expected values are only slightly higher if the binary is eccentric; Sopuerta Yunes and Laguna (2007) found \(v_r \propto (1 + e)\).
On the other hand, recent relativistic numerical simulations of spinning black hole binaries (Herrmann et al. 2007, Schnittman & Buonanno 2007) suggest that $v_r$ increases linearly with the black hole spin parameter $a$, where $0 \leq a \leq 1$, and in the case of highly spinning black holes ($a > 0.8$) the magnitude of the kick suffered by the remnant could be of the order of a few thousand km/s (Tichy & Marronetti 2007). Campanelli et al. (2007) report values of $v_r$ as high as $\sim 4000$ km/s for equal mass binaries, if both spins lie in the binary orbital plane. Such a kick is sufficient to eject the remnant not only from a dwarf galaxy, where the escape velocity is $\sim 300$ km/s, but even from the center of a giant elliptical, for which the escape velocity can reach $2000$ km/s.

Though it is likely that MBHs acquire high spins (e.g. Volonteri et al. 2005) during their accretion history, the impact of the resulting recoil on the MBH assembly has never been studied in details so far. If extreme recoil is indeed the rule, the ejection of a large fraction of MBHs formed through the coalescence of a binary systems can cause a significant drop in the number of expected coalescing events on the way of MBH assembly. Volonteri (2007) recently showed that current assembly models are able to reproduce the majority of observed constraints even if the extreme recoil prescription by Campanelli et al. (2007) is taken into account. However, high kick velocities could seriously affect the expected number counts predicted for LISA, since the ejection of remnants by their host halos would avoid subsequent MBH assembly.

In this letter we estimate a robust lower limit for the predicted number of LISA sources. We use the Montecarlo realizations of the merger history performed by Volonteri (2007) to show that even in the worse (for GW observations) case scenario in which during each merger the two MBH spins are counter-aligned in the MBHB orbital plane and extreme recoil is at work, current MBH assembly models predict that at least ten sources will be detectable by LISA. In practice, the lower limit of the expected number of LISA sources does not substantially drop with respect to models employing non-spinning MBH recoil prescriptions (e.g. Volonteri Haardt & Madau 2003).

2 MODELS OF BLACK HOLE FORMATION

In the hierarchical assembly framework, MBHs form growing through mergers and accretion from seed black holes at high redshift. There are two main scenarios for MBH assembly, namely the light seed and the heavy seed models. In the light seed models, seed MBHs typically form with masses $m_{\text{seed}} \sim \text{few} \times 10^4 M_\odot$, in halos collapsing at $z \approx 20$, and are thought to be the end-product of the first generation of stars (Madau & Rees 2001). In the heavy seed models, black hole seeds form already massive ($10^5 - 10^6 M_\odot$) from the low angular momentum tail of gas in protogalaxies at high redshifts. The angular momentum distribution of the gas in early-forming halos can be determined by means of cosmological N-body simulations (Bullock et al. 2001); halos with low spin parameters are prone to global dynamical instabilities, leading to the formation of a massive seed black hole (Koushiappas et al. 2004, Begelman Volonteri & Rees 2006, Lodato & Natarajan 2006).

We focus here on the two specific models discussed in Volonteri (2007) that are representative of these two classes of MBH assembly scenarios: the VHM and the BVRlf models. In the VHM model, representative of the light seed scenarios, (Sesana et al. 2007 for details) seed MBHs form with masses $m_{\text{seed}} \sim \text{few} \times 10^4 M_\odot$, in halos collapsing at $z = 20$ from rare $3.5-\sigma$ peaks of the primordial density field. In the BVRlf model, representative of the heavy seed scenarios, (Sesana et al. 2007 for details), black hole seeds form in halos subject to runaway gravitational instabilities, via the so-called “bars within bars” mechanism (Shlosman, Frank & Begelman 1989). MBH seed formation is assumed to be efficient only in metal free halos with virial temperatures $T_{\text{vir}} \gtrsim 10^4$K, leading to a population of massive seed black holes with $m_{\text{seed}} \sim \text{few} \times 10^4 M_\odot$.

The subsequent MBH evolution relies only on a few simple assumptions. Nuclear activity is triggered by halo mergers: in each major merger the more massive hole accretes gas until its mass scales with the fifth power of the circular velocity of the host halo, normalized to reproduce the observed local correlation between MBH mass and velocity dispersion ($m_{\text{BH}} - \sigma$ relation). MBHB coalescence is assumed to occur efficiently following halo mergers.

For both the VHM and the BVRlf models, we consider two cases that bound the effect of recoil in the assembly of MBHs and, as a consequence, LISA events: (i) no gravitational recoil takes place and (ii) maximal gravitational recoil is associated to every MBHB merger, using the model by Volonteri (2007), which is based on the estimates reported by Campanelli et al. (2007). For the latter we use the merger tree realizations presented in Volonteri (2007). The model takes into account consistently for the cosmic evolution of the mass ratio distribution of merging binaries and of their spin parameters (see discussion in Volonteri 2007). In each single merger, the mass ratio and the MBH spin magnitudes are therefore fixed by the merger hierarchy; the spin orientations are instead chosen so as to maximize the recoil. MBH spins are assumed to initially lie in the binary orbital plane, counter-aligned one to each other. The recoil velocity is then evaluated according to equation 1 of Campanelli et al. (2007), that in this case simplifies as:

\[
\vec{v}_r(q, a_1) = A q^4 (1 - q) \left[ 1 + B \frac{q}{(1 + q)^2} \right] \hat{e}_\parallel + K \cos(\Theta - \Theta_0) \frac{q^2}{(1 + q)^5} (a_2 + qa_1) \hat{e}_\perp. \tag{1}
\]

Here $A = 1.2 \times 10^4$ km/s, $B = -0.93$, $K = 6 \times 10^4$ km/s, $a_1$ and $a_2$ are the magnitudes of the spin parameters of the two holes, $\hat{e}_\parallel$ is a unit vector in the binary orbital plane and $\hat{e}_\perp$ defines the direction perpendicular to the orbital plane. The component of $\vec{v}_r$ along the $\hat{e}_\perp$ direction depends sinusoidally upon the angle $\Theta$ between the MBH spins and their initial linear momenta. To get the maximum recoil we set $\Theta = \Theta_0 \approx 0.184$.

We would like to emphasize that the prescription that we have chosen for (ii), and whose main features we have just summarized is the least favourable for gravitational wave observations and (probably) unlikely to occur in these extreme circumstances during MBH assembly (Bogdanovic Reynolds & Miller 2007).
3 GRAVITATIONAL WAVE SIGNAL

Full discussion of the GW signal produced by an inspiraling MBHB can be found in Sesana et al. 2005, along with all the relevant references. Here we just recall that a MBH binary at (comoving) distance \( r(z) \) with chirp mass \( M = m_1^{5/3}m_2^{5/3}/(m_1 + m_2)^{1/3} \) generates a GW signal with a characteristic strain given by (Sesana et al. 2005):

\[
h_c = \frac{1}{3^{1/2} \pi^{2/3}} \frac{G^{5/6}M^{5/6}}{c^3 r(z)} \left( f_c \right)^{-1/6}.
\] (2)

An inspiraling binary is then detected if the signal-to-noise ratio \((S/N)\) integrated over the observation is larger than a given detection threshold, where the optimal \( S/N \) is given by (Flanagan & Hughes 1998)

\[
S/N = \sqrt{\int d \ln f \left[ \frac{h_c(f)}{h_{\text{rms}}(f)} \right]^2}.
\] (3)

Here, \( f = f_c/(1+z) \) is the (observed) frequency emitted at time \( t = 0 \) of the observation, and the integral is performed over the frequency interval spanned by the shifting binary during the observational time. Finally, \( h_{\text{rms}} = \sqrt{5} h_c(f) \) is the effective rms noise of the instrument; \( h_c(f) \) is the one-sided noise spectral density, and the factor \( \sqrt{5} \) takes into account for the random directions and orientation of the wave; \( h_{\text{rms}} \) is obtained by adding in the instrumental noise contribution (given by e.g. the Larson’s online sensitivity curve generator [http://www.srl.caltech.edu/~shane/sensitivity], and the confusion noise from unresolved galactic (Nelemans et al. 2001) and extragalactic (Farmer & Phinney 2003) WD–WD binaries. Notice that extreme mass-ratio inspirals (EMRI) could also contribute to the confusion noise in the mHz frequency range (Barack & Cutler 2004).

4 RESULTS

4.1 Coalescence rates

Figure 1 shows the number of MBH binary coalescences per unit log \( M \) per unit observed year, \( dN/d\log M dt \), predicted by the two models that we have considered, for both cases where recoil is neglected and extreme recoil is taken into account. Each panel shows the rates for different redshift intervals. Note that when extreme recoil is included, the rate predicted by the BVRlf model at any redshift is only marginally affected, while the VHM model is more sensitive to the GW recoil: at \( z > 15 \), GW kicks do not affect the coalescence rate; on the contrary, at \( z < 15 \), the rate drops by a factor of \( \sim 3 \) for \( M \geq 10^3 M_\odot \), if extreme kicks are included in the evolution. This is related to the fraction of seeds that experience multiple coalescences during the MBH assembly history. We can schematically think of the assembly history as a sequence of coalescence rounds, as also recently suggested by Schnittman (2007). After each round extreme recoil depletes a large fraction of remnants, and the relative importance of each subsequent round drops accordingly. In the VHM model, about 65% of the remnants of the first round will undergo a second round of coalescences, so the second round has an important relative weight in the computation of the total rate. When extreme recoil is taken into account, a large fraction of the first round remnants is ejected from their hosting halos. We find that the effective fraction of remnants that can experience a second coalescence drops to \( \sim 30\% \). This is the reason why the number of coalescences involving light black holes \((M < 10^3 M_\odot)\) does not drop at any redshift, while the number of coalescences involving more massive binaries drops by a factor \( \approx 3 \). In the BVRlf scenario seeds are rarer, and the fraction of first coalescence remnants that participate to the second round is around 25%; switching on the extreme recoil has a significantly smaller impact on the global rate in this case. Moreover, in this model seeds are more massive and the bulk of merging events happens at lower redshift, where the hosting halo potential wells are deeper and consequently larger kicks are needed to eject the coalescence remnants. As a matter of fact, the seed abundance sets the mean number of major mergers that a seed is expected to undergo during the cosmic history, and this basically sets the ability of extreme kicks to reduce the coalescence rate.

4.2 LISA detection rate

We now discuss how the number of GW sources detectable by LISA is influenced by extreme GW recoils. To facilitate the comparison with our previous works, all the results shown here assume an observation time of 3 years, a sharp low-frequency wall at \( 10^{-4} \) Hz in the instrumental sensitivity (see Sesana et al. 2007), and a detection threshold \( S/N = 5 \) (see equation 3): the confusion noise includes only galactic and extragalactic white dwarfs and ignores a possible contribution from EMRIs (Barack & Cutler, 2004). At the end of this section, we will briefly discuss the impact of the former assumptions on the number of detectable sources. Figure 2 shows the redshift distribution of MBHBs detected by LISA. The effect of extreme GW recoils on the source
number counts drastically depends on the abundance and nature of the seeds, along the lines discussed in the previous section. In the VHM model, the number of detectable sources drops by a factor $\sim 60\%$, and the number of the potential \textit{LISA} detections is reduced from $\approx 140$, if the recoil is neglected, to $\approx 60$, if extreme recoil is included. Vice versa, the detection rate predicted by the BVRlf model is only weakly affected by the extreme recoil prescription, and it drops by about 15\% (from 40 to 34 events in 3 years of observation). Note that though the overall number of coalescences in the VHM model decreases only by about 25\% when extreme recoil is considered, the number of \textit{LISA} detections is reduced by a much larger factor. This is because if the seeds are light, \textit{LISA} can not detect the bulk of the first coalescences of light binaries happening at high redshift, that are responsible for the major contribution to the coalescence rate and are not affected by the recoil. \textit{LISA} can observe later events, involving more massive binaries, that are largely suppressed by the MBH depopulation due to extreme GW kicks. In the BVRlf model, on the other hand, seeds are more massive, and the second coalescence round is less important; in this case, the \textit{LISA} sensitivity is sufficient to observe almost all the first coalescences, and the number of detections is only mildly reduced. As the kicks affect the merger rate starting from the second round, its signature consists in a slight decrease of the mean chirp mass of the detected binaries, see figure 3.

We emphasize here two aspects (i) at time it is not clear if \textit{LISA} will be able to shed light on the importance of recoil in MBH assembly, even in this extreme case, since the uncertainty introduced in the number counts is at most of a factor of $\sim 3$, comparable with uncertainties due to our ignorance in the MBH accretion history and in the detailed dynamics of MBHBs (see, e.g., discussion in Sesana et al. 2007); (ii) on the other hand, this fact confirm that MBHBs are \textit{LISA} safe targets; since extreme recoil effects increase
with the seed abundance, we expect the drop in the detections to be more significant for those scenarios that predict a larger number of sources. In figure 3 we show how different assumptions on the detection threshold, the instrumental noise below $10^{-4}$ and the confusion noise from EMRI affect the LISA detection rates. If seeds are massive, the results shown in figure 2 are hardly affected. If seeds are light, EMRI confusion noise and a more conservative detection threshold, say $S/N = 8$, can halve the number of sources detected by LISA. For both scenarios, extending the LISA sensitivity window below $10^{-4}$ has also minimal effect on the number of detections.

5 DISCUSSION

Here we have considered two specific MBH assembly models, representative of two different MBH seed formation scenarios. However our findings can be considered, at least qualitatively, valid in general. Given the size and the abundance of the seeds, our 'coalescence round' picture depends on the details of the models. For example in the VHM model we checked that by changing the accretion prescription (see Volonteri, Salvaterra & Haardt 2006) the total number of events would change by a factor of two (note that the accretion prescription considered in the models described in the previous section gives the minimum number of coalescences); however the relative weights of the different coalescence rounds do not change significantly. So we can safely conclude that a decrease $\geq 50\%$ in the expected LISA sources should be a general trend for all those models in which the MBH assembly starts from light seeds at high redshift. In this class of models the number of predicted coalescing events is so high ($\geq 100$ yr$^{-1}$) that at least a few tens of MBHBs should be guaranteed LISA sources. On the other hand, extreme recoils should not be an issue at all for LISA if the MBH seeds are massive and/or rare. We remark here that in the BVRHf model we assumed MBH seed formation to be efficient only in metal free halos with virial temperatures $T_{\rm vir} \geq 10^4K$, i.e. we have considered atomic hydrogen to be the only coolant. Assuming efficient molecular hydrogen gas cooling (e.g. Koushiappas, Bullock & Dekel 2004) the number of seed MBHBs increases by an order of magnitude (and being the seeds massive, LISA would be able to detect the first coalescence round), and the GW kick would not be an issue at all. Relying on this results, the estimate of $\sim 10$ detections in three years predicted by the BVRHf model described in Sesana et al. 2007 does not change under the assumption of extreme recoils (seeds are heavy and rare), and can be considered a robust LISA detection lower limit. To conclude, in Sesana et al. 2007 we explored different MBH assembly scenarios to quantify the imprint of the MBH seed prescription on the LISA data stream. Motivated by recent studies on extreme GW recoils, we have quantified in this letter their impact on the MBHB coalescence and on the LISA detection rate, confirming that the detection of at least $\sim 10$ coalescing binaries in a 3 year mission is a robust prediction even considering extreme GW recoils.

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