Probing Distant Massive Black Holes with LISA

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Abstract. Idealized models are used to illustrate the potential of the Laser Interferometer Space Antenna (LISA) as a probe of the largely unknown population of cosmologically-distant Massive Black Holes (MBHs) and as a tool to measure their masses with unprecedented accuracy. The models suggest that LISA will most efficiently probe a MBH population of lower mass than the one found in bright quasars and nearby galactic nuclei. The mass spectrum of these MBHs could constrain formation scenarios for high-redshift, low-mass galaxies.

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1. Introduction

One of the major goals of the LISA experiment is the detection of the gravitational wave signal from massive black hole (MBH) coalescences at cosmological distances (see http://lisa.jpl.nasa.gov/). Despite remarkable progress in recent years, the characteristics of the population of distant MBHs remains largely unknown. In the future, LISA should open the “gravitational window” and offer us an usually sharp view of this population. Idealized models of the MBH population and its evolution with cosmic time are valuable in that they help define the various ingredients important for the interpretation of the future LISA data. In this contribution, I describe a class of such models and highlight some of their most important characteristics.

2. The population of massive black holes

Recent years have seen tremendous progress in the characterization of MBHs residing at the centers of nearby galactic nuclei (Kormendy & Richstone 1995). Dynamical evidence for the presence of MBHs in galactic spheroidal components has been found in nearly all studied local massive galaxies (Magorrian et al. 1998). A tight correlation between the inferred BH mass and the spheroid stellar velocity dispersion has also been established (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002).

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Figure 1. Event rates (per year, per unit redshift) of MBH mergers in models with BHs in all (100%, a) or only 3% (b) of potential host galaxies at $z = 5$. Very efficient MBH binary coalescence is assumed. In (b), two models are shown depending on whether rare MBHs preferentially populate massive $z = 5$ galaxies (dashed) or populate them randomly (dotted). These rates are likely overestimated, as explained in the text. [From Menou et al. 2001.]

Much less is known about the cosmologically-distant population of MBHs, however. Studies of the optical quasar luminosity function show that, at redshifts $z \sim 2 - 3$ (corresponding to the peak of quasar activity), quasars and associated MBHs are present in about 0.1% of bright galaxies at that epoch (Richstone et al. 1998). Recently, more direct X-ray studies with Chandra revealed that $\sim 10\%$ of all bulge-dominated, optically-luminous galaxies at $z \lesssim 2 - 3$ show central hard X-ray activity, which is presumably associated with accretion onto a MBH (Mushotzky et al. 2000, Barger et al. 2001).

These useful constraints, at $z \lesssim 3$, are consistent with the idea that MBHs may be even rarer at higher redshifts. Several formation scenarios for MBHs postulate that it is indeed the case (see, e.g., Eisenstein & Loeb 1995; Volonteri et al. 2002). A rare population of MBHs would result in reduced event rates for LISA: of all the successive galaxy mergers occurring in standard hierarchical structure formation scenarios, only those involving a pair of MBHs can potentially lead to a merger event detectable by LISA. As we shall see below, this property can be inverted, in principle, so that the rate of events detected by LISA would become a sensitive probe of the population of distant MBHs.

3. Event rate models and uncertainties

The consequences of a rare population of MBHs at high redshifts have been further investigated by Menou et al. (2001; see also Volonteri et al. 2002). A standard ”merger tree” was used to describe the merger history of dark matter halos and associated galaxies in the $\Lambda$CDM concordance cosmology ($\Omega_0 = 0.3$, $\Omega_b = 0.04$, $\Omega_\Lambda = 0.7$, $h_{100} = 0.65$). Given the local constraint that nearly all galaxies more massive than
Probing Distant Massive Black Holes with LISA

Figure 2. (a) Distribution of time between successive mergers of galaxies containing MBHs, integrated from $z = 5$ to 0, in models with BHs in 100% (solid) and only the 30% most massive (dashed) potential host galaxies at $z = 5$. (b) Shows the contribution to the total distribution (solid) of mergers in the redshift range $z = 3.5$–3 (dotted) and $z = 1$–0.5 (dashed) for the model with BHs in 100% of potential host galaxies at $z = 5$. Normalization is for a fixed comoving volume of $\sim 1.7 \times 10^4 \text{Mpc}^3$.

$\sim 10^{11} M_\odot$ (baryon + dark matter) must harbor a central MBH, as shown by dynamical studies for a large enough sample of nearby galaxies with masses $\gtrsim 10^{11} M_\odot$ (Magorrian et al. 1998), models with rare MBHs showed that at least a few % of all galaxies susceptible to harbor a MBH must do so at $z = 5$ (the tree’s initial redshift). It was found that this local constraint on the extent of the MBH population is more stringent for the models than the other two based on optical quasar and X-ray studies (simply because relatively few galactic mergers occur at $z < 2$–3). Additional details can be found in Menou et al. (2001).

Specifically, Menou et al. (2001) explored three models in which MBHs populate 100%, the 3% most massive or a random (mass-independent) 3% of all potential host galaxies at $z = 5$. The MBH merger event rates corresponding to these three models are shown in Fig. 1a and 1b. The model with a maximal population of MBHs (Fig. 1a) predicts rates about two orders of magnitude larger than the models with a MBH population about as rare as allowed by the local constraint (Fig. 1b).

Although these merger rates are very encouraging for LISA, they are likely overestimated. First, LISA will be sensitive to a finite range of BH masses, so that some of the events counted in Fig. 1 will be missed. Second, the orbital dynamics of two MBHs following the merger of their host galaxies is rather uncertain. The inefficiency of dynamical friction or subsequent nuclear stellar ejections at bringing MBHs together (Begelman et al. 1980; Quinlan & Hernquist 1997; Milosavljevic & Merritt 2001; Yu 2002) may imply that some of the galactic mergers counted in Fig. 1 are not actually followed by prompt mergers of the resident MBHs.

Fig. 2 compares the time between successive mergers of galaxies containing MBHs in models with BHs populating 100% (solid line) or only the 30% most massive (dashed
Figure 3. Mass distributions of merging BHs in the redshift range $z = 5-4.5$ (solid) and $z = 0.5-0$ (dashed), for the models with BHs in 100% (a) and only the 30% most massive (b) potential host galaxies at $z = 5$. Normalization is for a fixed comoving volume of $\sim 1.7 \times 10^4 \text{ Mpc}^3$.

Figure 3. Mass distributions of merging BHs in the redshift range $z = 5-4.5$ (solid) and $z = 0.5-0$ (dashed), for the models with BHs in 100% (a) and only the 30% most massive (b) potential host galaxies at $z = 5$. Normalization is for a fixed comoving volume of $\sim 1.7 \times 10^4 \text{ Mpc}^3$.

In both models, a large number of successive galactic mergers occur on timescales $\lesssim 10^9 \text{ yrs}$, leaving only that much time for a MBH binary formed from a previous galactic merger to coalesce. If a pre-existing MBH binary is unable to merge before a third MBH makes its way to the galactic center, a three-body interaction would result, leading typically to the slingshot ejection of the least massive BH (Saslaw et al. 1964).

It is also worth noting that the present models assume that all the galaxies described by the merger tree (with virial temperatures in excess of $10^4 \text{ K}$; see below) can potentially harbor a MBH. There is circumstantial evidence, however, that bulge-less galaxies may not harbor such MBHs (Gebhardt et al. 2001; Merritt et al. 2001; but see Filippenko & Sargent 1989 for a possible counter-example). Accounting for this would further reduce the event rates, in proportion to the size of bulge-less galaxies (which may be significant at the low-luminosity end; Bingelli et al. 1988).

4. Precision mass measurements

LISA will not only be able to detect MBH coalescences, but it will also constrain, and in some cases measure, the masses of the MBHs involved. To illustrate the potential of LISA for precision mass measurements, we use the same two models as described in the previous section (with BHs in 100% and only the 30% most massive potential host galaxies at $z = 5$, respectively). At every redshift step in the merger tree, the MBHs are forced to follow the mass – velocity dispersion relation with scatter (Tremaine et al. 2002):

$$M_{\text{BH}} = (1.35 \pm 0.2) \times 10^8 M_\odot \left( \frac{\sigma_e}{200 \text{ kms}^{-1}} \right)^{4.02 \pm 0.32} \text{.}$$

(1)
where $\sigma_e$ is the stellar velocity dispersion of the spheroidal component, at the half-light (effective) radius. It is related to $\sigma_{DM}$, the dark matter halo velocity dispersion, via the relation $\sigma_e = \sigma_{DM}/\sqrt{(3/2)}$, which is derived through the Jeans equation for isotropic, spherical systems, with the extra assumptions of an isothermal density profile ($\rho \propto r^{-2}$) for the dark matter and a typical DeVaucouleurs density profile ($\rho \propto r^{-3}$) for the stellar spheroidal component. The dark matter halo velocity dispersion is obtained from the virial theorem and the assumption that halos have a universal density (evolving as $(1+z)^3$): $\sigma_{DM} \propto M_{\text{halo}}^{1/3}(1+z)^{1/6}$. It is assumed that every single galaxy described by the merger tree potentially harbors a MBH and no attempt is made to separate a bulge-less galactic population potentially unable to harbor such MBHs.

Although forcing the masses of MBHs to systematically follow Eq. (1) is arbitrary, it is partially justified by recent results indicating that this relation may already be in place by $z \sim 3$, at least at the high-mass end (Shields et al. 2002). Fig. 3a and 3b show the resulting mass distributions for merging BHs in the two models of interest, for two representative redshift windows. The larger number of events ($\times 4$ at $z = 5$, $\times 2$ at $z = 0$) and the broader mass spectrum in Fig. 3a (100% BHs) are evident, as compared to the model with BHs in only the 30% most massive galaxies at $z = 5$ (Fig. 3b).

Hughes (2002a) discusses the precision with which mass and redshift measurements can be achieved with LISA, for equal-mass BH binary mergers. Precisions of $\lesssim 30\%$ can be reached for at least two of the three redshifted mass combinations (chirp, reduced and total mass) in the approximate BH mass range $10^4 M_\odot/(1+z) - 10^6 M_\odot/(1+z)$, at redshifts $z \lesssim 10$ (with errors $\lesssim 30\%$ on the redshifts). Provided enough events are detected by LISA, it should therefore be possible to distinguish between the two models shown in Fig. 3 without difficulty.
Figure 5. Mass ratio distributions for merging BH binaries in the redshift range $z = 5-4.5$ (solid) and $z = 0.5-0$ (dashed), for the models with BHs in 100% (a) and only the 30% most massive (b) potential host galaxies at $z = 5$. Normalization is for a fixed comoving volume of $\sim 1.7 \times 10^4$ Mpc$^3$.

An even more exquisite precision can be achieved if one is willing to give up the distance/redshift information and focus on redshifted chirp masses ($M_{\text{chirp}} = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$): those can be determined with 1% accuracy or better for equal-mass BH binaries in the mass range $10^3$–$10^5$ $M_\odot$, at $z \lesssim 10$. Fig. 4 compares the distributions of redshifted chirp masses for the two models of interest, in the same two redshift windows as before. The distribution integrated over all redshifts is what LISA will be sensitive to, but Fig. 4 nicely illustrates how the distributions for the two models differ significantly. The tendency for large chirp mass values in the model with BHs in the 30% most massive potential host galaxies at $z = 5$ is clearly seen (the same is true for the distribution integrated over all redshifts). Provided LISA sees enough such events, it should be very easy to distinguish between the two models (based on redshifted chirp masses only).

These optimistic statements ignore the following complication: the quoted measurement errors strictly apply to equal-mass binaries (Hughes 2002a). As Fig. 5 shows, however, in both models, the majority of MBH binary mergers are of the unequal mass type (as expected in general). LISA measurement accuracies for equal-mass binaries are very encouraging in suggesting that LISA will be able to distinguish between various MBH population scenarios with exquisite precision. Preliminary calculations for unequal mass binaries (Hughes 2002b) are promising since they suggest that precisions comparable to those of the equal-mass case could still be achieved for (redshifted) chirp and reduced masses.
5. Characteristics of the MBH population probed by LISA

There are two noticeable characteristics of the population of merging MBHs according to the models presented in §3 and §4. First, Fig. 3 shows that the mass function of merging BHs rises steeply towards low masses. Combined with the LISA sensitivity window peaking around $10^5 M_\odot/(1+z)$, it implies that the large majority of the events seen by LISA should be mergers of BHs with masses $< 10^6 M_\odot$. This contrasts with the generally larger masses ($\sim 10^6 M_\odot$) inferred for MBHs in bright quasars and at the center of dynamically-studied nearby galactic nuclei. Although the population of MBHs probed by LISA would then not dominate the mass density of MBHs in the Universe (Yu & Tremaine 2002), it would better represent the total population in terms of its number density.

Second, this population of lower mass MBHs may allow us to probe some of the properties of their low-mass host galaxies. The cutoff at low masses in the mass function of merging BHs (see Fig. 3 and 4) reflects the assumption in the models that only galaxies above a certain (redshift-dependent) mass threshold can host a MBH. Indeed, studies of baryon cooling in nascent, metal-free (primordial) galaxies suggest that, in the absence of molecular hydrogen cooling (which is easily dissociated by a weak UV background), the gas must rely on atomic lines to cool within a Hubble time (e.g. Haiman et al. 2000; Loeb & Barkana 2001). The mass (baryon + dark matter) of galaxies forming stars (and “seeds” for the MBHs, presumably) must then be in excess of an equivalent virial temperature $\sim 10^4$ K:

$$M_{\text{min}}(z) \simeq 9 \times 10^7 M_\odot \left( \frac{T_{\text{vir}}}{10^4 K} \right)^{3/2} \left( \frac{1+z}{10} \right)^{-3/2}. \quad (2)$$

Once combined with the assumption that MBHs follow the mass - stellar (and dark matter halo) velocity dispersion relation given by Eq. (1) without scatter, this property translates into a minimum BH mass in the models of

$$M_{\text{BH, min}} \sim 3000 M_\odot \left( \frac{T_{\text{vir}}}{10^4 K} \right)^2, \quad (3)$$

nearly independent of redshift. Note that this limit involves an extrapolation of Eq. (1) to galaxies of much lower mass than those for which it has been observationally established.

Hughes (2002a) shows that, for equal-mass binaries, the redshifted chirp mass of a binary made of two $10^3 (10^4) M_\odot$ BHs can be determined out to $z \sim 10$ with a precision of 0.03% (0.07%) or better. This suggests that the location of the mass cutoff in Fig. 4 could be determined with high accuracy by LISA (even though it will be sensitive to the distribution integrated over all redshifts). Given the significant uncertainties in the physics of baryon cooling (and the relevance of other effects such as UV photo-evaporation and supernova blow-ups), the LISA sensitivity to the BH mass cutoff could potentially be turned into a test of low-mass galaxy cooling and formation models. Note also that arguments against the existence of a large population of MBHs with masses
\( \sim 10^6 M_\odot \) have been presented by Haehnelt et al. (1998) and Haiman et al. (1999). LISA should be able to efficiently test these claims as well.

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