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LISA Gravitational Wave Capabilities and the Early Massive Black Hole Formation Process

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Abstract

It seems quite plausible that the growth of massive black holes in the nuclei of many moderate sized galaxies like the Milky Way, or in smaller pregalactic structures, was a fairly gradual process. Thus there would have been a time when an intermediate mass black hole was growing in the center by a combination of gas infall, tidal stripping of stars, and the occasional infall of a 10 solar mass black hole. There also is some possibility of a roughly 100 solar mass black hole falling in. The LISA mission could observe the latter events if the central black hole were about 10,000 solar masses in size, even at redshifts of roughly 3. A moderately improved LISA follow-on mission would be needed in order to detect the stellar mass black hole coalescences with a central intermediate mass black hole.

1.1 Introduction

The primary objective of the Laser Interferometer Space Antenna (LISA) mission is to detect and study in detail gravitational waves from sources involving massive black holes. Three particular types of sources are of major astrophysical interest, and will be described briefly in § 1.2. Then, information that can be obtained about these sources by LISA and by two possible follow-on missions will be discussed in § 1.3, with emphasis on the early massive black hole (MBH) formation process.

NASA and the European Space Agency plan to fly LISA as a joint mission, with a target launch date of 2011. The antenna consists of three identical spacecraft, with beams from frequency-stabilized lasers sent between them to measure changes in the distances between freely floating test masses inside the spacecraft [see e.g. Danzmann (1997), Danzmann et al. (1998), Folkner (1998), Hammesfahr (2001), Bender (2001), and Danzmann (2003)]. The spacecraft are servo-controlled using micronewton thrusters to keep them fixed in position with respect to the test masses to nanometer precision. Thus they serve as shields to avoid fluctuating forces on the test masses from solar radiation pressure and from the solar wind.

Each of the spacecraft is in an independent orbit around the Sun, with a one year period. They are five million kilometers apart, and form a nearly equilateral triangle with its center 50 million kilometers behind the Earth. 30 cm diameter telescopes are used to collimate the transmitted beams and receive them at the other end. It is surprising at first, but with 0.5 W of laser power transmitted, the shot noise in the received signals is low enough so that differential changes in the arm lengths can be measured to about a picometer precision in 100 s of measurements. This, plus care in minimizing disturbing forces on the test masses

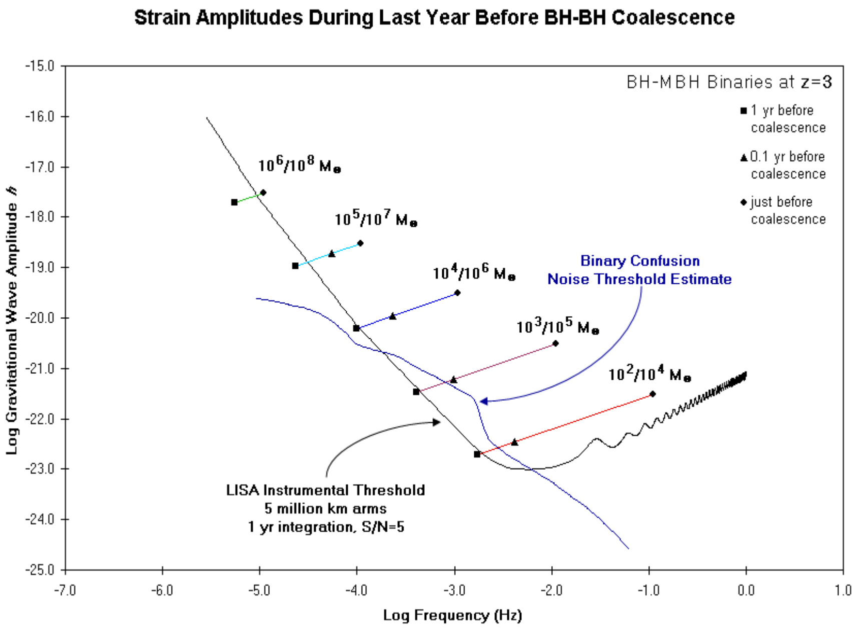

Fig. 1.1. Threshold sensitivity curve for LISA, extended to lower frequencies based on the suggested goal for the spurious acceleration level between 0.1 and 0.003 millihertz.

at the ends of the antenna arms, makes highly accurate measurements possible over a wide range of frequencies, from roughly 3 microhertz to 1 Hz. The highest sensitivity is achieved for 10 s to 1000 s periods.

The recommended threshold sensitivity curve for LISA is shown in Fig. 1.1. The curve shown is for a signal-to-noise ratio of 5, which is needed for detection of most sources, and 1 year of observations. Above 0.1 millihertz (mHz), the baseline curve for the mission is given. At lower frequencies, a curve suggested as a practical goal for the mission (Bender 2003) is shown.

The other long curve gives an estimate of the corresponding sensitivity limitation due to unresolved binary stars. Below about 3 mHz, there are so many galactic binaries that they cannot be resolved from 1 yr of observations. At higher frequencies, most galactic binaries are separated enough in frequency so that they can be solved for, and subtracted out from the data. What remains then is the background due to extragalactic binaries, with the main contribution from close white dwarf binaries out to redshifts of 1 or more.

The central part of the confusion noise curve has been discussed by Hils and Bender (2000), based on binary gravitational wave spectral amplitude estimates of Hils et al. (1990). However, as discussed in Bender (2003), the curve has been extended down to 0.01 mHz, also using the spectral amplitude estimates from Hils et al. (1990). In addition, an extension of the extragalactic part of the curve to higher frequencies is included, based on roughly a factor two higher estimate than earlier for the ratio of the extragalactic to galactic spectral amplitudes. The ratio is now estimated to be about 0.2, based partly on including some allowance for higher star formation rates at earlier times (Kosenko & Postnov, 1998).

The short straight line segments shown in Fig. 1.1 represent the signal strength and the frequency as a function of time for massive black hole binaries with different combinations of masses. The segments shown are for the last year of observations before coalescence, for MBH-MBH binaries at a redshift of z = 3. The factor 100 difference in masses is chosen just for illustrative purposes. The signals as a function of time to coalescence will be the same for a different mass ratio but the same chirp mass, except for having a different final frequency.

1.2 Types of Sources

The first of the three main types of gravitational wave sources involving massive black holes, and the one that will be discussed most here, is a close black hole binary formed during the early growth of an intermediate mass black hole (IMBH). A number of scenarios have been considered for how IMBHs grow, either in dense galactic nuclei or in compact clusters. For example, one scenario (Lee 1995, 2001) is that roughly 10 $M_\odot$ black holes mixed with normal stars in a galactic nucleus will sink toward the center, and suffer quite frequent collisions with each other. After a small number of doublings of the BH binary mass, a runaway growth process is expected (Lee, 1993) where the largest BH grows more rapidly and gets most of the mass.

Another scenario (Portegies Zwart & McMillan 2002; Razio & Freitag 2004) is that a very massive star can form in a compact cluster through successive collisions of the most massive stars, with the normal evolution toward collapse delayed by the frequency of collisions. In such a case, an IMBH, defined here as having a mass between 100 and $10^5 M_\odot$, may be formed at some point. If the cluster was formed close to the galactic center, it might in some cases spiral in to the center, and the IMBH could serve as the seed for the later growth of a moderate size MBH, such as found locally in the Milky Way, M32, and M31.

The infall of gas clouds and the tidal stripping of stars are expected to play the major role in the feeding of the growing IMBH, even if it got started through collisions (see e.g. Freitag 2001). And rapid growth events may be triggered by mergers with other smaller structures. However, if the IMBH is massive enough, and something like a 100 $M_\odot$ BH should fall into the galactic center and form a binary even a couple of times during the IMBH growth, signals observable by LISA could be generated, as discussed later. Binaries formed during the infall of 10 $M_\odot$ BHs even at large redshifts could be observed by a future more sensitive mission, as discussed later.

There are observational indications of the existence of IMBHs, but the situation is still uncertain (van der Marel 2004). The one suggested scenario where gradual growth of IMBHs is avoided is the sudden collapse of a dense cloud of gas and dust or of a relativistic star cluster (see e.g. Gnedin 2001). In this case, a MBH with a mass of 10^5 $M_\odot$ or more could be formed suddenly, or result from the rapid evolution of a supermassive star formed from the collapse (New & Shapiro 2001). Whether a signal LISA could detect would be generated in such cases is not clear.

The second type of source is close MBH-MBH binaries formed after mergers of pregalactic structures or galaxies (see e.g.: Menou et al. 2000; Menou, 2003; Volonteri et al. 2003; Haehnelt 2003; Yu 2002, 2003; Milosavljevic, 2003). There are many questions, such as the following. At what stage did MBHs form in pregalactic structures? For what MBH masses would dynamical friction bring a MBH and its surrounding star cluster to the center of the merged galaxy fairly rapidly? Is there a hang-up for roughly 10^6 $M_\odot$ and more massive MBHs in spherically symmetric galactic nuclei because of scattering out most of the stars in the center? And, how often does a third MBH fall in and scatter out one or more of the MBHs in the binary? A number of the papers at the 1st Carnegie Centennial Symposium and at other recent meetings have addressed these questions, and it appears likely that LISA can provide unique information on them (see e.g. Bender 2003).

The third type of source is highly unequal mass binaries formed by a stellar mass BH or compact star from the central density cusp being scattered in close to a MBH in a galactic nucleus. Such binaries can give information about the conditions in the central density cusps and contribute to determining the mass function of MBHs in galactic nuclei. However, they also are expected to provide the most sensitive tests of the dynamical predictions of general relativity, through the accurate mapping of the metric very close to the MBH. A number of studies of the formation of such binaries have been done (Hils & Bender, 1995; Sigurdsson & Rees, 1997; Miralda-Escude & Gould 2000; Freitag 2001; Sigurdsson 2003), but the expected event rate is still fairly uncertain.

Since this paper is intended to concentrate mainly on what can be learned from gravitational waves about the formation and initial growth of IMBHs, only the first type of source discussed above will be considered in some detail in § 1.3.

1.3 Expected Information Obtainable From Gravitational Waves

It is assumed here that the growth of IMBHs through the mass range of roughly 10^3 to 10^5 $M_\odot$ is frequently fairly smooth, and involves collisions of stars and stellar mass BHs, as well as the infall of gas by various mechanisms. Then, as discussed earlier, an important question for LISA is how often a perhaps 100 $M_\odot$ BH may fall into the IMBH. Such a BH could come from a high mass tail of the initial mass function for Population III stars (Madau & Rees 2001), or possibly from some other process.

The expected signal during the last year for a 100 $M_\odot/10^4$ $M_\odot$ binary at z = 3 is shown in Fig. 1.1. By integrating the SNR over time, the total SNR is found to be greater than 5, and the same is true for z = 5. For LISA to see such signals, a rate of only a couple per year per L^* galaxy for events of this kind is required.

For the future, it is worth mentioning briefly what could be learned about the growth of intermediate mass black holes from a fairly modest high-frequency LISA follow-on mission (see also Bender 2001). Fig. 1.2 is the same as Fig. 1.1, except that an additional curve showing the instrumental threshold sensitivity for the assumed follow-on mission has been added. Four changes from the LISA mission parameters have been assumed. The main one is an improvement in the product of transmitted beam brightness and receiver area by a factor 1000. This can be accomplished, e.g., by going to 1 meter diameter telescopes and 10 W lasers. The corresponding reduction in the shot noise component of instrumental noise is a factor 30. The other sources of distance measurement noise, such as beam pointing jitter, also have to be reduced by a similar factor. In addition, 10 times lower spurious accelerations of the test masses and a reduction to 500,000 km arm lengths are assumed.

Also added in Fig. 1.2 is the signal strength during the last year for a binary at z = 3 containing a 10 $M_\odot$ stellar mass BH and a 1000 $M_\odot$ BH. This signal would be observable by the follow-on mission, but not by LISA. A major benefit of the added sensitivity would

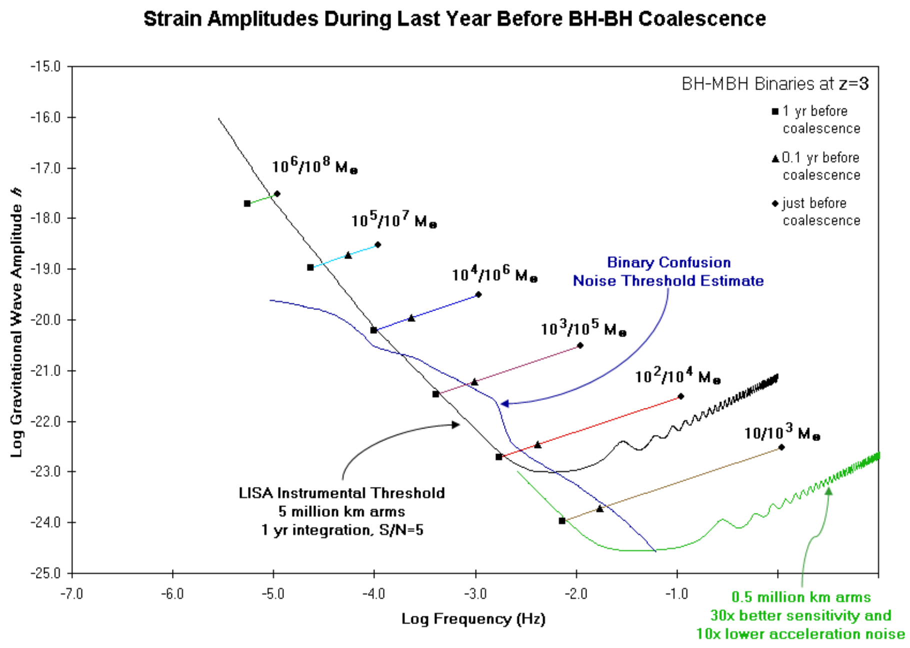

Fig. 1.2. Same as Fig. 1.1, but including a threshold sensitivity curve for a possible moderately improved high-frequency LISA follow-on mission.

be much improved information on the early growth phase of IMBHs, since the frequency of stellar mass BHs falling in seems likely to be considerably higher than for 100 $M_{\odot}$ BHs.

For highly unequal mass BH binaries, such as 10 and 10^5 or 10^6 $M_{\odot}$ BHs, the improvement in sensitivity with the high-frequency follow-on mission unfortunately is not likely to be large. The limited improvement is mainly because of the estimated confusion noise level from extragalactic close white dwarf binaries. The current estimate is about a factor two higher than earlier estimates, as mentioned above.

For completeness, it is worth mentioning that a strong case also can be made for a LISA follow-on mission aimed at improved sensitivity at lower frequencies. This is discussed elsewhere by Bender (2001, 2003). A moderate low-frequency mission might have, e.g., 15 million km arm lengths and a factor 10 lower spurious accelerations of the test masses than LISA. Fig. 1.3 is similar to Fig.1.1, but with a threshold sensitivity curve for the assumed low-frequency follow-on mission added. The signal strengths for MBH binaries are shown in this case for z = 1 and for up to 100 years before coalescence. The main advantage of such a mission would be to permit detection of MBH-MBH binaries resulting from mergers of pregalactic structures or galaxies up to about 30 years before coalescence. This hopefully would provide considerably more detailed information on galaxy formation. A more ambitious low-frequency mission with roughly 1 AU arm lengths also would be possible.

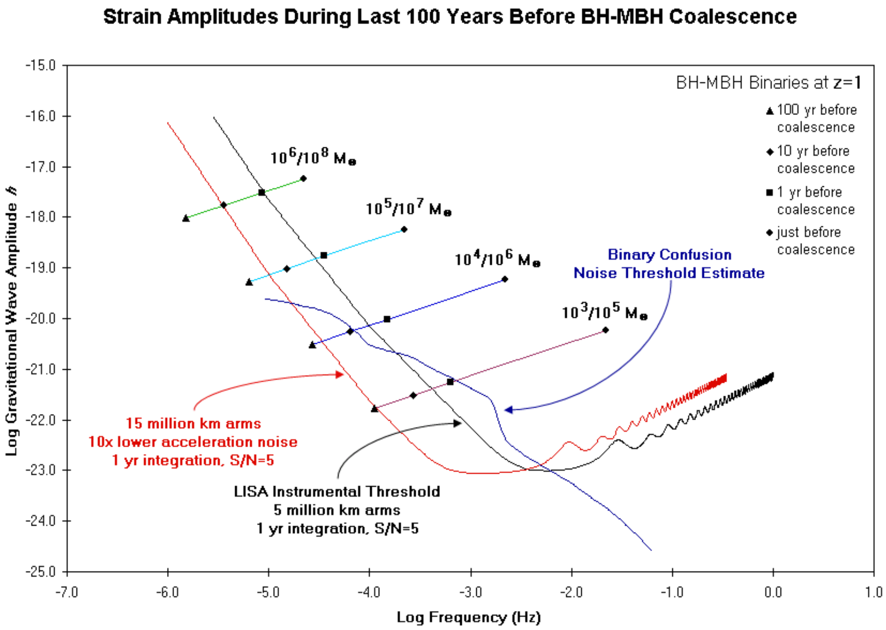

Fig. 1.3. Same as Fig. 1.1, but including a threshold sensitivity curve for a possible moderately improved low-frequency LISA follow-on mission.

Acknowledgments

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References

Bender, P. L. 2001, Chapt. 10 in Gravitational Waves, ed. I. Ciufolini, V. Gorini, V. Moschella, & P. Fre (Bristol, UK: Inst. of Phys. Publishing), 115

Bender, P. L. 2003, Class. Quantum Grav, 20, in press

Danzmann, K. 1997, Class. Quantum Grav, 14, 1399

Danzmann, K., et al. 1998, LISA-Laser Interferometer Space Antenna, Pre-Phase-A Report, 2nd edn (Garching, Germany: Max-Planck-Institut fur Quantenoptik)

Danzmann, K. V. 2003, Class. Quantum Grav, 20, in press

Folkner, W. M. 1998, in Laser Interferometer Space Antenna, AIP Conf. Proceedings 456, ed. W. M. Folkner (Woodbury, NY: Amer. Inst. Phys.), 11

Freitag, M. 2001, Class. Quantum Grav, 18, 4033

Gnedin, O. Y. 2001, Class. Quantum Grav, 18, 3983

Hammesfahr, A. 2001, Class. Quantum Grav, 18, 4045

Haehnelt, M. G. 2003, Class. Quantum Grav, 20, in press

Hils, D. & Bender, P. L. 1995, ApJ, 445, L7

Hils, D. & Bender, P. L. 2000, ApJ, 537, 334

Hils, D., Bender, P. L., & Webbink, R. F. 1990, ApJ, 360, 75

Kosenko, D. I., & Postnov, K. A. 1998, Astron. & Astrophys. 336, 786
Lee, M. H. 1993, ApJ, 418, 147
Lee, H. M. 1995, MNRAS, 272, 605
Lee, H. M. 2001, Class. Quantum Grav, 18, 3977
Madau, P. & Rees, M. J. 2001, ApJ, 551, L27
Menou, K. 2003, Class. Quantum Grav, 20, in press
Menou, K., Haiman, Z., & Narayanan, V. K. 2000, ApJ, 558, 535
Milosavljevic, M. 2003, Class. Quantum Grav, 20, in press
Miralda-Escude, J. & Gould, A. 2000, ApJ, 545, 847
New, K. C. B. & Shapiro, S. L. 2001, Class. Quantum Grav, 18, 3965
Portegies Zwart, S. F. & McMillan, S. L. W. 2002, ApJ, 577, 899
Razio, F., & Freitag, M. 2004, in Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), in press
Sigurdsson, S. & Rees, M. J. 1997, MNRAS, 284, 318
van der Marel, R. 2004, in Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), in press
Volonteri, M., Haardt, F., & Madau, P. 2003, ApJ, 593, 661
Yu, Q. 2002, MNRAS, 331, 935
Yu, Q. 2003, Class. Quantum Grav, 20, in press