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MASSIVE BLACK HOLES AND THE LASER INTERFEROMETER SPACE ANTENNA (LISA)

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The goals of the LISA mission include both astrophysical investigations and fundamental physics tests. The main astrophysical questions concern the space density, growth, mass function, and surroundings of massive black holes. Thus the crucial issue for the LISA mission is the likelihood of observing signals from such sources. Four possible sources of this kind are discussed briefly in this paper. It appears plausible, or even likely, that one or more of these types of sources can be detected and studied by LISA.

The Laser Interferometer Space Antenna (LISA) mission was proposed in 1993 by scientists from both Europe and the United States as a candidate for the third medium-sized mission (M3) of ESA. The proposal was for a joint ESA-NASA mission, but the brief ESA mission study that was carried out in 1993-1994 was for an ESA mission. LISA was not chosen for M3, but was considered and chosen in 1994 as the third new Cornerstone mission under the ESA Horizons 2000 Programme. Since the time scale for LISA as an ESA-led Cornerstone mission appears to be very long, there also has been interest recently in the US in the possibility of flying a NASA-led version of LISA on a considerably shorter time scale. A joint ESA-NASA mission would of course be even more attractive, if a way can be found in the future to accomplish this in a timely fashion.

The ESA Cornerstone version of LISA has been described by Danzmann,1 Thorne,2 and Danzmann et al.3 In that version, two spacecraft are located at each corner of a triangle 5 million km on a side, and located 50 million km behind the Earth in orbit around the Sun. In the NASA-led version, and probably in a planned revised version of the ESA Cornerstone mission, there will be only one spacecraft at each corner, with two separate optical assemblies pointing along the two arms of the triangle. The on-orbit mass of each spacecraft is about 200 kg. The sensitivity for one year of integration and a S/N ratio of 5 is $1 \times 10^{-23}$.

Most sources observable by LISA would be galactic binaries consisting of two compact stars. At least hundreds and probably thousands of individual sources of this kind are certain to be observable. At frequencies below about 3 millihertz, there will be so many such sources that most of them cannot be resolved. Their signals therefore will give a confusion noise level that prevents other weaker signals from being observed.

Supermassive black holes with masses larger than $10^8 M_\odot$ are now believed to exist in the centers of most large galaxies. However, much less is known about the abundance of massive black holes (MBHs) with masses between roughly $10^6 M_\odot$ and $10^7 M_\odot$, except for those believed to exist in our galaxy and in M32. If the fraction of smaller or medium sized elliptical and spiral galaxies containing such MBHs is substantial, there are several types of signals associated with them that LISA may well be able to observe (see e.g., Ref. 4 for some additional discussion). The essential assumption we have to make if we expect LISA to see such signals is that roughly $10^5$ to $10^6$ galaxies contain MBHs.

One important question is how the MBHs formed. If they grew from seed MBHs, and the seed MBHs were formed by stellar collisions in dense galactic nuclei, then coalescences of multiple seed MBHs in each such galaxy are likely to be observable by LISA. Quinlan and Shapiro5 have simulated the collisional formation of seed black holes with masses of up to roughly $10^6 M_\odot$, and find that typically a number of such seeds are formed. If tens of seeds survive and grow to roughly $500 M_\odot$ or larger before coalescing, then the resulting event rate could be substantial. LISA could observe the gravitational wave signals over the last year before coalescence out to a redshift of $z=5$.

On the other hand, Rees6 and Haehnelt and Rees7 have suggested that very large black holes are more likely to have formed by collapse of supermassive stars produced by rapid contraction of gas and dust clouds in galactic centers. If this is true for most $10^5$ or $10^6 M_\odot$ black holes as well as for supermassive black holes, then the issue becomes whether signals from the supermassive star collapse are likely to be observable. Although the collapse would be quite slow if the supermassive star is rotating slowly (see e.g., Rees6), fast rotation could lead to a bar instability and more efficient gravitational wave radiation at frequencies LISA is sensitive to.

Another promising source of signals for LISA is highly unequal mass binaries. The capture rate for compact stars or stellar mass black holes orbiting MBHs in galactic nuclei has been discussed by Hils and Bender,8 Sigurdson and Rees,9 and Sigurdson.10 For neutron stars or white dwarfs the expected capture rate is high, but often scattering by other stars near the MBH will make the duration of gravitational wave emission much less than a year, and such events difficult to observe. However, for 5 or $10 M_\odot$ black holes in the cusp surrounding the MBH, the fraction of captures giving observable signals will be a lot higher. An event rate of higher than once per year appears to be quite plausible, if our assumption on the total number of MBHs is correct.