Supermassive black holes as sources for LISA

Martin G. Haehnelt

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK.

Abstract. I briefly discuss some issues relevant for the formation of supermassive black holes and give estimates of the event rates for the emission of gravitational waves by coalescing supermassive black hole binaries. I thereby use models which take into account recent improvements in our knowledge of galaxy and star formation in the high-redshift universe. Estimated event rates range from a few to a hundred per year. Typical events will occur at redshift three or larger in galaxies lying at the (very) faint end of the luminosity function at these redshifts.

INTRODUCTION

Supermassive black holes (SMBH’s) are amongst the prime targets for LISA and LISA will be primarily sensitive to events involving SMBH’s in the mass range $10^{4-6} M_\odot$ over a wide range range in redshift [1–3] (see also the contributions by Blandford and Sigurdsson these proceedings). The evidence for the existence of SMBH’s more massive than that has been steadily increasing over the last years. The two most convincing cases are currently our own galactic centre and NGC4258 [4–6]. In both cases the inferred deep potential wells and high mass densities leave little room for alternative explanations other than the presence of a SMBH [7].

Our best estimate of the overall mass density in black holes still comes from the integrated flux emitted by optically bright QSO’s which are generally believed to be predominantly powered by SMBH’s. From this a present-day black hole mass density of $\sim 1.5 \times 10^5 M_\odot \, Mpc^{-3}$ was inferred [8,9] which corresponds to about $5 \times 10^7 M_\odot$ per $L_*$ galaxy. This estimate has recently been complemented by an investigation of a large sample of black hole masses for nearby galaxies which gives a factor three to ten higher value suggesting that the mass of the typical black hole of a galaxy could be as high as 0.6% of the stellar mass contained in its bulge [10,11] (see also Richstone these proceedings for a discussion).

THE FORMATION OF SUPERMASSIVE BLACK HOLES

A variety of more or less detailed scenarios has been suggested for the formation of SMBH’s (see Rees 1984 [12] for a review). These scenarios involve one or several of the following basic processes leading to the concentration of mass,

- the dynamical evolution of a dense cluster of stellar objects,
- the build-up of a supermassive black hole by merging of supermassive black holes of smaller mass,
- and the viscous evolution and eventual collapse of a self-gravitating gaseous object (barred or non-barred disc, supermassive star).

While all these processes will occur the first two have serious difficulties when it comes to explain the existence of typical SMBH’s observed in optically bright QSO’s or nearby galaxies. I will briefly discuss the options one by one. The main problem with the “stellar route” to a SMBH is the rather long dynamical relaxation timescale $t_{rel} \sim 3 \times 10^{10} \, v_{300}^{-3} \, N_8^2 \, m_\star \, \log (N/2)^{-1} \, yr$, where $v_{300}$ is the 1D-velocity dispersion of the stellar cluster and $N_8$ is the number and $m_\star$ the mass of stellar objects. Typical masses of black holes powering high-redshift QSO’s are $\sim 10^{8-9} M_\odot$. As the stellar cluster from which these could form has to be even more massive the relaxation
FIGURE 1. Event rates for the emission of gravitational waves involving supermassive black holes above a certain mass as indicated on the plot. The four panels are for different variants of the cold-dark-matter cosmogony (see table 1 for parameters). One event per newly-formed dark matter halo is assumed. Dashed and solid curves are for two different QSO lifetimes used to calibrate the models as indicated in the upper left panel. The upper and lower curves are for $10^5 M_\odot$ and $10^6 M_\odot$, respectively.

timescale is prohibitively long. It is generally very difficult to concentrate the mass in an efficient manner once the gas has fragmented into stars.

The “merging scenario” for the formation of SMBH’s has become increasingly attractive with the accumulating observational evidence for the hierarchical build-up of large galaxies predicted by CDM-like structure formation scenarios. In hierarchical cosmogonies typical present-day galaxies have formed by merging of about ten smaller galaxies between redshift three and now and each of these “progenitors” will have formed from even smaller sub-units at higher redshift. When these galaxies merge the putative black holes at their centre will generally merge as well [13]. If merging were indeed the dominant process for the build-up of the mass of SMBH’s the problem of the formation of present-day SMBH’s could be deferred to the problem of the formation of much smaller mass SMBH’s in galactic sub-units at very high redshift [16]. These would, however, have to form with the high efficiency inferred from the large black-hole mass to stellar-bulge mass ratio of present-day
galaxies in small protogalactic clumps with shallow potential wells. As argued by Haehnelt & Rees [14] and Haehnelt, Natarajan & Rees (HNR98) [15] the black-hole formation efficiency should be larger in the deeper potential wells of the larger galaxies forming around redshift three making this an unlikely but not impossible option.

This leaves the last option where most of the mass is accreted in gaseous form — the fastest and most efficient way to concentrate mass in SMBH’s. The typical timescale for the concentration of the mass will be $10^7 - 10^8$ yr, the dynamical time scale of the galactic nucleus. The viscosity is mainly due to gravitational instabilities inevitably present in a self-gravitating disc. There is no fundamental limit for the efficiency of this process but the concentration of the gas has to compete with the consumption of the gas by star formation which will occur on a similar timescale. Unfortunately the expected gradual build-up of the mass is not likely to produce gravitational waves efficiently [3]. It will, however, be accompanied by the frequent merging characteristic for hierarchical cosmogonies and probably also by the infall of SMBH’s of intermediate mass which may form via the stellar route in the central star cluster at the galactic nucleus. In the next section we will give estimates of the expected event rates and briefly discuss some of the uncertainties involved.

**EVENT RATES IN HIERARCHICAL STRUCTURE FORMATION SCENARIOS**

Structure in the universe is generally believed to originate from small density fluctuations of some sort of collisionless dark matter (DM). These fluctuations are assumed to be Gaussian distributed and can be specified by their spatial power spectrum. The dynamical evolution of the dark matter, the mass function of collapsed DM halos and their merging rates can be reliably predicted once the cosmological model is specified. The main difficulty in a comparison with astronomical data is to predict the distribution of gas and stars relative to that of the dark matter. Here we would like to know the space density and merging rate of SMBH’s to estimate the gravitational wave event rates due to coalescing SMBH binaries. Haehnelt & Rees and HNR98 have demonstrated that with simple relations between DM halo and black hole mass observed high-redshift galaxies and QSO’s can be explained reasonably well. The models proposed in HNR98 predict the “formation rate” of newly-formed DM halos and thus allow us to get a crude estimate of the formation rate of SMBH’s as function of their mass. However, these estimates depend on the uncertain lifetime of optically bright QSO’s as they are calibrated by a comparison with the QSO space density. The typical formation of a DM halo involves...
TABLE 1. The model parameters of the CDM variants explored: $\sigma_8$ is the rms linear overdensity in spheres of radius $8h^{-1}\text{Mpc}$ and $\Gamma$ is a shape parameter for CDM-like spectra. $h$ is the Hubble constant in units of the $100\text{km s}^{-1}\text{Mpc}^{-1}$ and $\Omega_0$ and $\Omega_\Lambda$ are the total energy density and that due to a cosmological constant, respectively.

| MODEL | $\sigma_8$ | $h$ | $\Omega_0$ | $\Omega_\Lambda$ | $\Gamma$ |
|-------|------------|-----|-------------|------------------|--------|
| SCDM  | 0.67       | 0.5 | 1.0         | 0.0              | 0.5    |
| OCDM  | 0.85       | 0.7 | 0.5         | 0.0              | 0.21   |
| LCDM  | 0.91       | 0.7 | 0.3         | 0.7              | 0.21   |
| $\tau$CDM | 0.67   | 0.5 | 1.0         | 0.0              | 0.21   |

the merging of several DM halos and this formation should be accompanied by one or several merging events of SMBH’s. Figure 1 gives estimate of event rates and makes the rather conservative assumption that each newly-formed DM halo produces one gravitational wave event. The solid curves are for a lifetime of $1.5 \times 10^7\text{yr}$ and assume a non-linear relation between black hole and DM halo mass as discussed by HNR98. Typical event rates are one per year about the same as those obtained by Haehnelt (1994) [2] for similar assumptions. The four panels are for different cosmogonies which span the range of currently viable models. The relevant parameters are given in table 1. Obviously the numbers have to be convolved with the sensitivity curve of LISA. LISA should detect the coalescence of equal mass binaries of $10^5-10^6\text{M}_\odot$ out to maybe redshift ten. Even though at high redshift a sufficient signal-to-noise ratio will probably only be achieved for considerably less than a year. The coalescence of unequal mass SMBH binaries will only be detectable at significantly lower redshift. One should also keep in mind that little is known observationally about black holes of such small mass especially at high redshift and that the predictions rely on an extrapolation of the models from the typical black hole of mass $10^8\text{M}_\odot$ or larger observed around redshift three. Furthermore at low redshift (below $z \sim 2$) the numbers in Figure 1 are likely to underestimate the merging rate of SMBH’s as no attempt was made to model the late merging of galaxies in DM halos which formed at earlier times.

As demonstrated by the dashed curves event rates would be about a factor thirty higher if the lifetime of QSO’s were as short as $3 \times 10^5\text{yr}$. In this case a linear relation between DM halo mass and black hole mass is required [15]. The lifetime of the QSO’s will also affect the predicted host-galaxy luminosity and the clustering properties of the QSO’s. Constraints on both of these should be soon improved by the planned new large QSO surveys (2DF, SLOAN) and the uncertainty in the QSO lifetime reduced or even removed.

Figure 2 shows the predicted apparent brightness of typical host-galaxies at $z = 3$ as a function of black hole mass for the cosmological models in Fig. 1. The left panel is for the long lifetime and the right panel for the short lifetime. Note that especially for short QSO lifetimes most of the predicted coalescences should occur in extremely faint galaxies.

DISCUSSION

The existence of supermassive black holes in a major fraction of all galaxies seems firmly established. Most of the mass in these SMBH’s will have found its way beyond the event horizon in the gas-rich nuclei of the progenitors of present-day galaxies at high redshift. The emission of gravitational waves from coalescing supermassive binary black holes formed during the merger of such proto-galaxies should occur frequently enough to be detected during the lifetime of LISA. Typical events should occur in proto-galaxies at the (very) faint end of the luminosity function. The event rates are expected to increase with redshift with a rather broad peak at redshift three or larger and a slow decline at higher redshift The details of this decline are very uncertain and depend strongly on how efficiently small black holes form in shallow potential wells. The biggest uncertainty, however, is the number of detectable coalescences per newly-formed halo. Each new halo will be formed by the merging of a number of smaller halos each of which will contain one or more SMBH’s. How many coalescences occur will depend on whether the black hole binary formed in one merger has already coalesced when the next black hole sinks to the centre. Otherwise slingshot ejection is possible [13]. Furthermore the black holes will be embedded in a nuclear star cluster formed from gas on its way into the SMBH. These star cluster will not
contribute much to the total mass in SMBH’s. Nevertheless, they still could form with high velocity dispersion and black holes of 100 to $10^4 \text{M}_\odot$ might build up efficiently by the coalescence of stars [17]. At lower redshifts these would also be detectable by LISA when the coalesce with the central SMBH.

I finally conclude, that even a pessimist who assumes a rather long QSO lifetime and only one binary coalescence per newly-formed halo should expect a couple of SMBH binary coalescences during the lifetime of LISA while an optimist might expect to see up to several hundred of these exciting events.

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