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Massive Black Holes, Gravitational Waves, and Pulsars

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Abstract

We discuss recent work on two topics. In a recent paper by Jaffe & Backer, we calculate the spectrum of the stochastic background of gravitational radiation from the coalescence of massive black holes throughout the low-redshift Universe. In the recent thesis work of Lommen the observational upper limit on the energy density in the stochastic background of gravitational radiation at nanoHertz frequencies is lowered by an order of magnitude. This limit places an observational bound on the very uncertain merger history of galaxies and subsequent coalescences of massive black holes.

1.1 Introduction

The evidence for massive black holes (MBHs) in the majority of spheroids at zero redshift is increasing, although the origin and mass evolution of MBHs is an outstanding mystery. The evidence for growth of galaxies by mergers is strong, although the merger rate and its evolution with redshift is uncertain. Begelman, Blandford & Rees (1980) wrote a seminal paper on physical processes involved during the merger of galaxies containing MBHs that is followed by the coalescence of the MBHs. Rajagopal & Romani (1995) used the framework in Begelman et al., along with the classic description of gravitational radiation from a point mass binary in Peters & Matthews (1963), to estimate the stochastic background* spectrum of gravitational radiation. In the first section below we provide a summary of Jaffe & Backer (2003) that updates the work of Rajagopal & Romani using new data on both MBH demographics and galaxy merger rate.

The driver for the calculations done in Rajagopal & Romani and in Jaffe & Backer is the potential detection of the gravitational wave background by precision pulsar timing experiments, as had been considered earlier by Sazhin (1978) and Detweiler (1979). Pulsars act as distant clocks, and their electromagnetic emissions to us are perturbed in the same manner as the laser light in gravitational wave interferometers such as LIGO or *LISA*. A mirror is not needed as the source is periodic. Kaspi, Taylor, & Ryba (1994) present precision timing of two millisecond pulsars over a period of seven years. This measurement is used to constrain the energy density in the gravitational wave background to less than 6×10^{-8} in units of the closure density. In the second section we summarize the Berkeley Ph.D. effort of Lommen (2001) that extends the Kaspi et al. experiment to 17 years and lowers the gravitational wave background energy density limit by an order of magnitude.

* Some would call this a *foreground* and reserve *background* for primordial waves.

Prospects for future work are discussed briefly in the final section.

1.2 MBH-MBH Coalescences in the Universe

The goal in Jaffe & Backer is a parameterized model of MBH-MBH coalescences in the Universe that can be adjusted as new data become available. There are five major ingredients, which we list in order of decreasing certainty:

- Binary MBH gravitational wave spectrum
- Cosmological parameters
- Evolution of the MBHs in a merging system
- MBH demographics vs. z
- Galaxy-galaxy merger rate vs. z

As stated in the introduction, the emission of gravitational radiation of a point mass binary in general relativity is a classic result. We use the Peters & Matthews (1963) formulation to derive the wave amplitude h, a dimensionless strain, as a function of MBH masses at a given frequency at the source, which appears redshifted in the frame of the observer. The emitted frequency is twice the orbital frequency for the assumed circular orbits, which, in turn, establishes both the luminosity and the lifetime of the binary system.

Standard cosmological parameters are used. Current uncertainties lead to small changes in the resultant gravitational wave background spectrum.

Begelman et al. (1980) present a framework for the evolution of a pair of galaxies with central MBHs after the galaxies become gravitationally bound. The galaxies merge into each other on an orbital time scale owing to dynamical friction. The process continues with the central cores and their MBHs sinking toward each other. In Begelman et al. and at this conference, the final fate of the MBH binary is questioned. In the simplest of spherical models dynamical friction halts when a loss cone of stars in the orbital plane develops. This may happen before the gravitational radiation time scale is sufficiently short to bring the MBHs to coalescence in a Hubble time. While there is an absence of observational evidence of stalled MBH binaries in subparsec orbits, measurements are very difficult or currently impossible, and so we must say that there is no significant evidence of absence. Figure 1.1 displays the evolution time scale as a function of MBH separation, following a figure in Begelman et al. (1980). In Jaffe & Backer (2003), we assume that nature is efficient in bringing the MBH binary from the galaxy merger separation quickly to the separation where gravitational wave decay of the orbit is rapid. That is, no Green's function is needed to convert between the galaxy-galaxy capture moment and the time of domination of evolution by gravitational wave emission.

We use the results in Merritt & Ferrarese (2001) to provide the MBH demographics in the local Universe. In our current work, we make no adjustment to the population as a function of redshift.

The final ingredient in our model is the galaxy-galaxy merger rate. We use the recent work of Patton et al. (2002). These authors estimate the fraction of bound pairs in a large (4184) field galaxy survey. The pair separation establishes the orbit time and hence the time scale for evolution of the orbit by dynamical friction (see Fig. 1.1). We explore two models of variation of the merger rate with redshift that are within current observational limits. We have approached the model from the viewpoint of observational data at zero redshift rather than the more theoretical approach that uses a merger tree starting at high redshift.

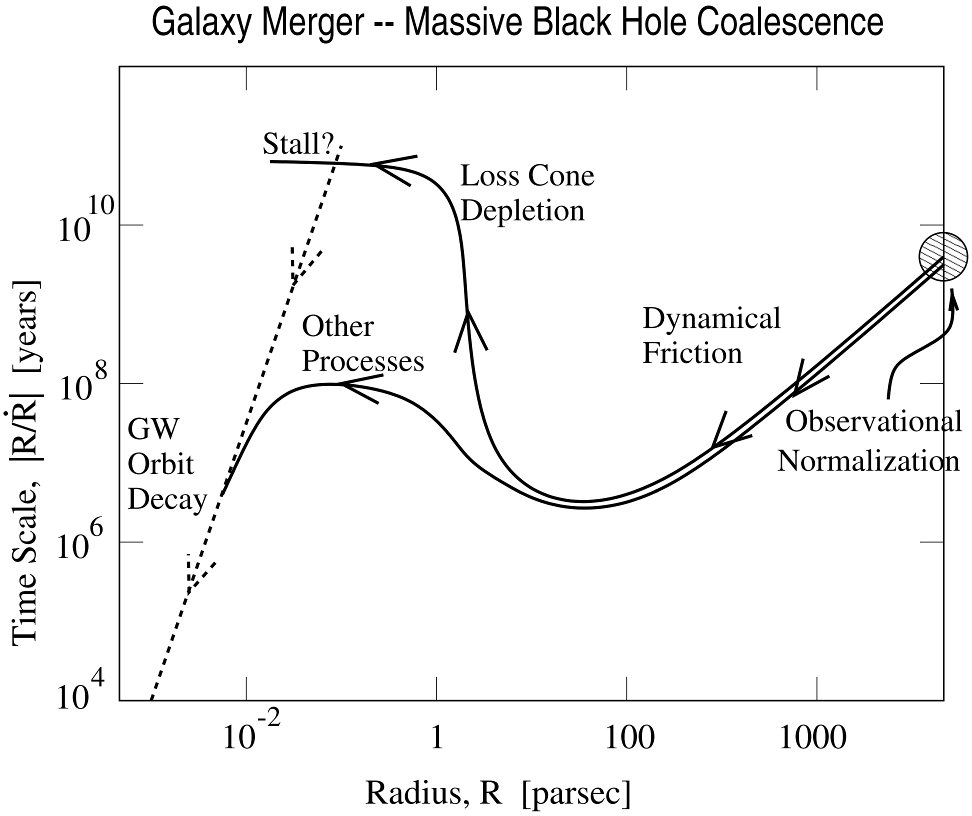

Fig. 1.1. Evolution of the separation of massive black holes during the galaxy-galaxy merger process. Dynamical friction brings them together until a loss cone forms, which slows decrease. Once sufficiently close, the loss of orbital energy and angular momentum to gravitational radiation leads to rapid coalescence.

Our results are summarized in a spectrum (Fig. 1.2) of the characteristic strain, $h_c(f)$, which is derived from the power spectral density spectrum of h by $h_c^2 \equiv f P_h$. This allows for ease of comparison with experimental measurement variances at any frequency, which is the topic of the next section. Both analytical and Monte Carlo results are presented. The most likely redshift for source contribution is ~ 1, and some million MBH binaries are contributing. The significant variance from a smooth spectrum in the Monte Carlo model indicates that a relatively small number dominate.

1.2.1 Observations of MBH-MBH Coalescence with LISA

We can extend the formalism from Jaffe & Backer (2003) for other uses. When the *LISA* satellite system is launched in the coming decade, we will be able to monitor the Universe of coalescing MBHs more directly, by observing individual events themselves: they are the brightest objects in the gravitational radiation sky.

As we show in Jaffe & Backer (2003), the nHz–μHz background observable with pulsar timing is sensitive to the most massive, nearby binaries. *LISA*, however, observes the final

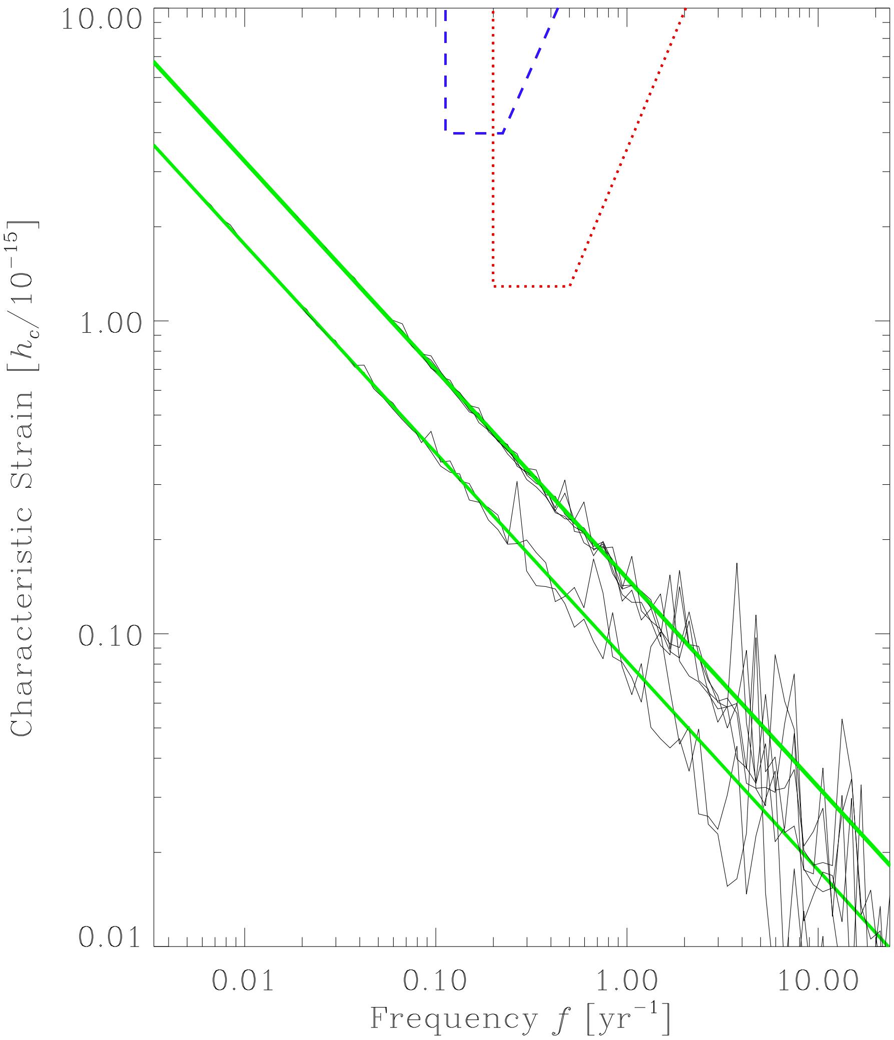

Fig. 1.2. Characteristic strain spectrum $h_c(f)$ for two models discussed in Jaffe & Backer (2003), along with Monte Carlo realizations. The upper thick curve and the associated realizations have strong evolution of merger rate with z, and the lower set of curves has no evolution. The maximum redshift is $z = 3$. The dashed line gives an estimate of the current best limits on the gravitational wave background from pulsar timing observations. The dotted line shows the expected limits from a pulsar timing array, after operation for ~ 8 years.

coalescence events limited not so much by the power of the event, but by whether the frequency of the signal falls within the *LISA* band. Thus, we must determine the total event rate

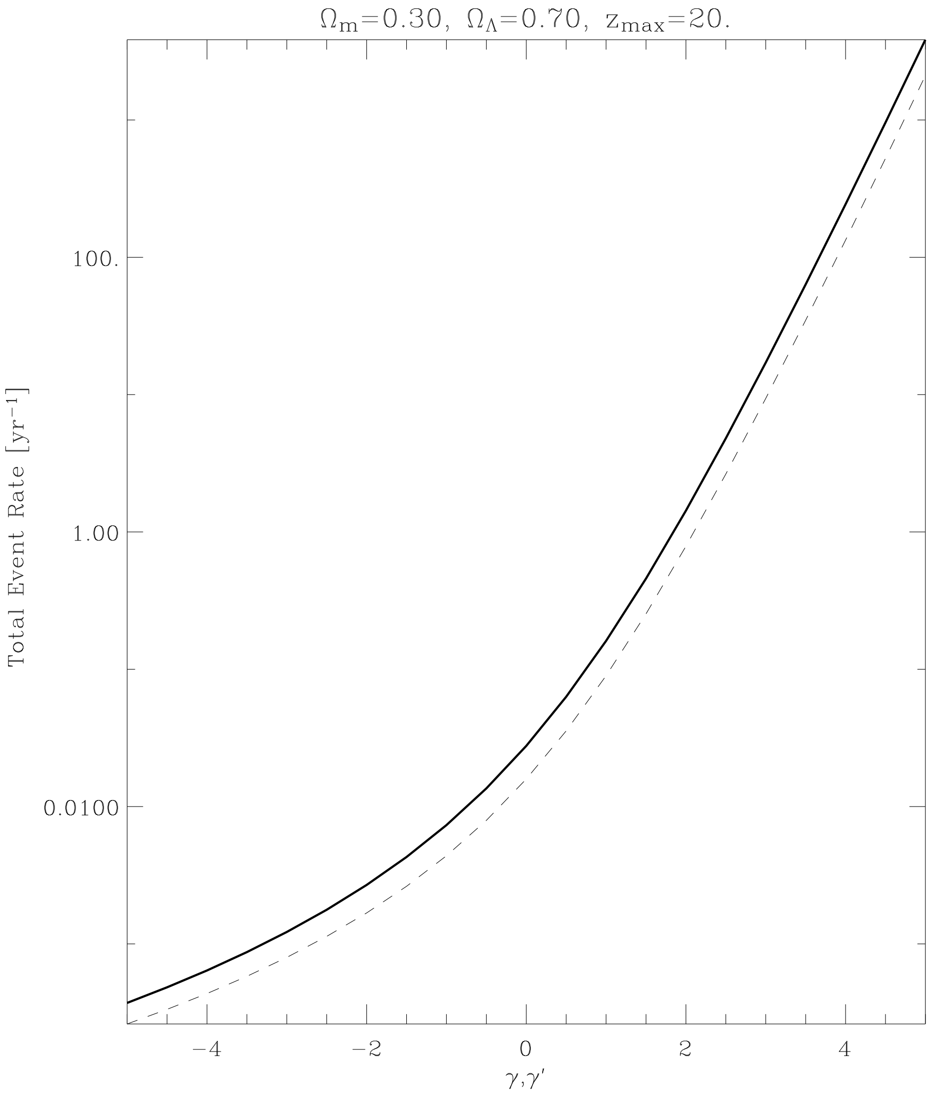

Fig. 1.3. The total MBH-MBH coalescence rate for the model of Jaffe & Backer (2003). The index γ gives the power-law index of the merger rate (which is also degenerate with the normalization of the MBH mass function). The solid (dotted) curve is for a merger rate parameterized as a power law in redshift (time).

(along the light cone) of MBH-MBH coalescences, and what fraction thereof is observable by *LISA*.

Obviously, the total MBH-MBH coalescence rate depends on the details of the MBH population and the galaxy merger rate as a function of redshift, as shown in Figure 1.3. We see that for various scenarios the rate can vary by several orders of magnitude, and could be as high as 1000 per year.

Hughes (2001) notes that the gravitational wave signal is dependent only on the combination of parameters $(1+z)M_c$, where z is the redshift of the coalescing pair, and $M_c^{5/3} = (M_1+M_2)^{-1/3}M_1M_2$ gives the "chirp mass" of the system. Hughes also shows that *LISA* can best measure the parameters of those binaries with $(1+z)M_c \sim 10^5 M_\odot$. In the Jaffe & Backer (2003) formalism, the mass of the MBH population does not change with time, and today the mean is considerably higher than this. In reality, of course, the population would likely have had a mean near $10^5 M_\odot/(1+z)$ at a redshift of several. Thus, if we calculate the fraction of pairs around this mass for the present-day population, we can consider this a rough lower bound on the total event rate from binaries, whose properties will be measured well by *LISA*. For the MBH mass function considered in Jaffe & Backer, we find about 10% of MBHs are within a factor of 20 of $10^5 M_\odot$, and so about 1% of pairs would be in that range. However, if the mass function at early times was peaked around this value, a considerably larger fraction of pairs would be detected.

A more realistic calculation (as in Menou et al. 2001) would explicitly take into account the evolution of the MBH mass function. However, since the mechanism for MBH growth is poorly understood (is it dominated by accretion or mergers? how are MBHs originally formed?), it is likely that the theoretical parameter space is as wide as the purely parametric models we have constructed here.

1.3 Gravitational Wave Detection and Pulsar Timing Experiments

Any precision measurement of length or time or energy can be used to detect gravitational radiation. Figure 1.4 presents a large-scale view of the stochastic gravitational wave background spectrum with limits from current and planned experiments. The cosmic microwave background anisotropy ($\delta T/T$) places a limit on a scale-free primordial spectrum at attoHertz frequencies. Pulsar measurements ($\delta t/t$) place a limit at nanoHertz frequencies, where the dominant source is likely to be from the MBH binary population in the Universe. The *LISA* and LIGO instruments will operate in the milliHertz and kiloHertz bands, respectively. *LISA* will be sensitive to individual MBH-MBH coalescence events, while pulsar timing will detect only the cacophony of all objects with just a small level of cosmic variance from one frequency to the next (Fig. 1.2).

Gravitational radiation perturbs the spatial part of the spacetime metric from unity by an amount given by the dimensionless strain, h. For electromagnetic radiation propagation through a gravitational radiation field the strain can be treated as a perturbation of the index of refraction from unity in 3-space. Propagation of an electromagnetic wave (and therefore a pulsar pulse) from a distant source in the Galaxy through integer cycles of a gravitational wave leaves no net effect. What *is* embedded in the pulsar arrival time is the result of propagation through fractional cycles of the gravitational wave—at the pulsar after emission and at the earth upon reception. The latter reception effect is correlated among a spatial array of pulsars, and therefore we can use a pulsar timing array as a gravitational wave telescope.

The dimensionless strain that we are sensitive to in pulsar timing is given by $h_c \approx R/(\sqrt{N}T/2\pi)$, where R is the characteristic residual from the timing model, N is the number of degrees of freedom, and T is the duration of the measurement. Given that R is independent of T in the best cases, the strain limit improves with duration. Sensitivity to low-frequency gravitational waves is limited by duration as well as by the need to fit for a neutron star rotation polynomial series in the timing model.

In her recent thesis work at Berkeley, A. Lommen (2001), along with collaborators E.

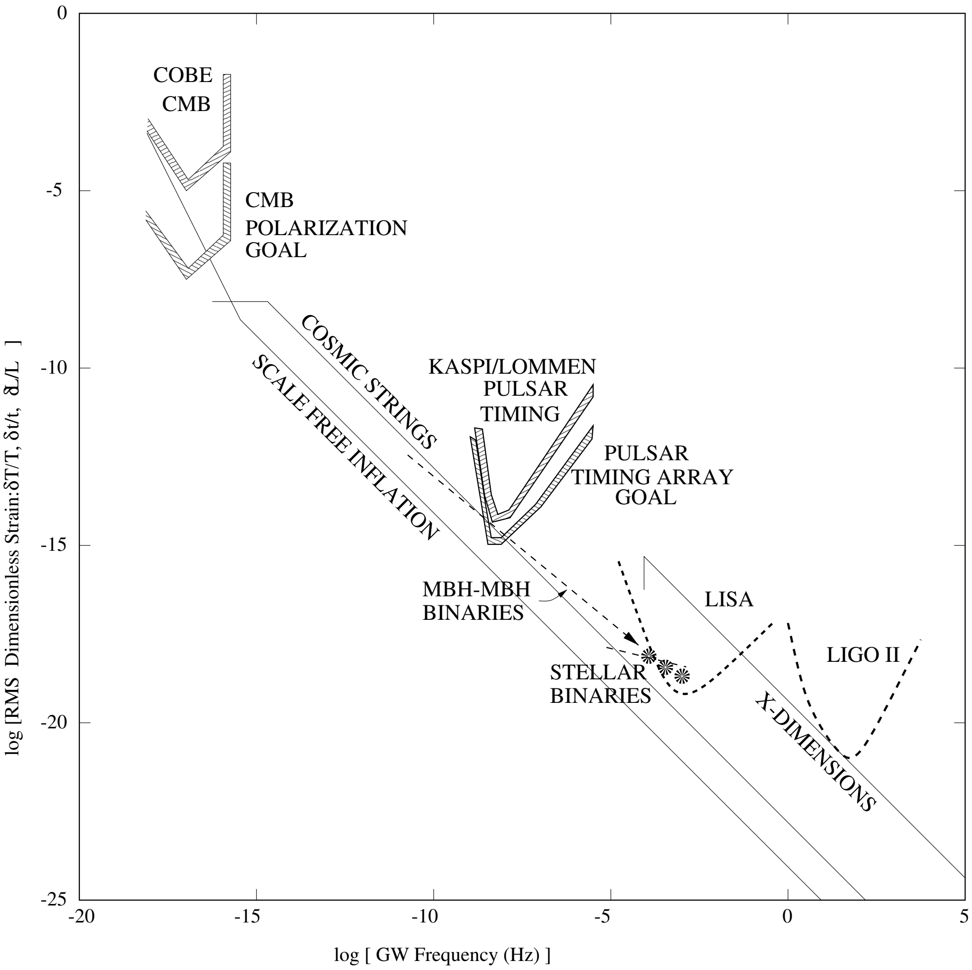

Fig. 1.4. Characteristic strain spectrum covering all observable bands.

Splaver and D. Nice at Princeton, initiated a precision timing program at the Arecibo Observatory following the upgrade completion in 1996. The *best* star for long-term precision is the 5-millisecond pulsar B1855+09. We have tied this new experiment to the earlier Arecibo experiment presented in Kaspi et al. (1994) using lower sensitivity measurements at other telescopes. The resulting limits in Figure 1.2 follow roughly from $R \approx 2\ \mu$s, $N \approx 200$, and $T \approx 17$ yr. Our current limit in h_c is a factor of $\sim$5 above the MBH-MBH model with strong evolution of the merger rate with redshift. We are in the process of defining more quantitatively the parameter space excluded by the measurements, but it seems at this time that the pulsar measurements are not highly restrictive.

1.4 Conclusion

The Jaffe & Backer model of MBH-MBH coalescences provides a revised estimate of the stochastic background of gravitational radiation at nanoHertz frequencies along with a new estimate of the cosmic variance in the spectrum. This model can be improved as new information becomes available. Furthermore, the model can be improved by linking evolutionary components of the model to early-Universe constraints on the growth of structure.

New precision pulsar timing measurements have lowered the bound on the energy density in a stochastic background of gravitational radiation. This constrains extreme models of galaxy-galaxy merger history. Continuing measurements will employ a pulsar timing array that will allow us to detect, rather than simply constrain, the spectrum.

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