Research Statement

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The topics of my research to date have been the dynamical evolution of binary supermassive black holes (BSBHs) in galactic nuclei, and the implications of that evolution for the production and detection of gravitational waves (GWs). My computational approach is unique in combining small-N scattering experiments, the Fokker-Planck equation, and full N-body simulations.

Evolution of a BSBH in a rotating stellar nucleus

According to the current paradigm, galaxies can grow in size through mergers with other galaxies. Many galaxies are also known to contain a supermassive black hole (SBH) at their center. Taken together, these two hypotheses imply the formation of binary SBHs. The evolution of a massive binary can be broken down into three stages [1]:

1. The two SBHs are far enough apart that they move independently in the potential of the merger remnant. Both SBHs sink toward the center of the potential due to dynamical friction against the stars.

2. When they are close enough together, the two SBHs form a bound pair. Their two-body orbit continues to shrink due to exchange of energy and angular momentum with nearby matter – stars or gas.

3. If the binary separation manages to shrink to a small fraction of a parsec, emission of gravitational waves brings the two SBHs even closer together, resulting ultimately in coalescence.

My research is focused on the last two of these three phases. Only interactions of the massive binary with stars are considered; gaseous torques are ignored. To calculate the effect of stellar interactions on a BSBH I used numerical scattering experiments [2, 3]. The new feature of my model compared with previous studies is that it allows the galactic nucleus to rotate. It turns out that – in a galactic nucleus with significant rotation – a BSBH evolves in a qualitatively different way than in a nonrotating nucleus: the orbital plane of the binary tends to align with the nuclear symmetry plane, and the binary's eccentricity also evolves in an orientation-dependent manner: it decreases for corotating BSBHs and increases for counterrotating ones, sometimes resulting in eccentricities of 0.9 or more (Fig. 1, left). This work is described in Paper I [4].

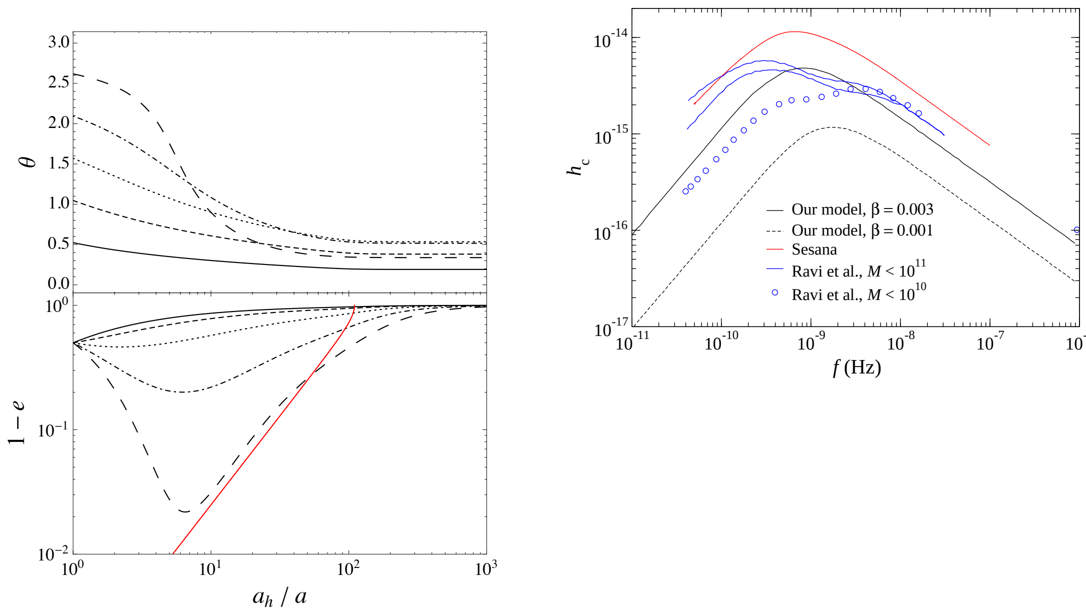

Figure 1: Left (from Paper I): evolution of orbital inclination θ and eccentricity e of an equal-mass binary in a moderately rotating nucleus; binary mass is $10^8\mathcal{M}_\odot$ and initial eccentricity is 0.5. Horizontal axis is binary semimajor axis in units of the "hard binary separation" a_h. Different line styles correspond to different initial θ. Right (from Paper II): predicted GW strain in the assumption of circular BSBHs. Black: our model assuming the "triaxial" (efficient) hardening law. Red and blue: models from [6] and [7], respectively.

Implications for gravitational wave detection

The detection of GWs from BSBHs is actively being pursued by a number of groups using pulsar timing arrays (PTAs). Several papers (e.g. [6, 7]) have made predictions for the shape and amplitude of the GW strain spectrum, $h_c(f)$, that would be produced by a cosmological population of BSBHs in merging galaxies. However, all of the current models are in tension with the upper limits on $h_c(f)$ from PTA observations [8]. This fact motivated me to construct a new model for the stochastic GW background in Paper II [5] where the model for BSBH evolution developed in Paper I is combined with a model for the cosmological evolution of the galaxy merger rate.

My work goes beyond previous studies in a few ways. First, as described above, rotation of galactic nuclei is included, which results in substantial changes to the binary's eccentricity. In most cases, eccentricity decreases, so that the binary emits most of its gravitational radiation while being almost circular. However, counterrotating BSBHs in slowly rotating galaxies can retain high eccentricities even in the late, GW-emitting stages of evolution.

I have also accounted, in an approximate way, for depletion of the binary's "loss-cone" by rescaling the diffusion coefficients according to the results of Vasiliev et al. [9], who derived expressions for the rate of loss-cone repopulation in galaxies with various geometries. The main result of this correction is a much longer evolution timescale in axisymmetric galaxies compared with triaxial ones, which leads to "stalling" of some of the BSBHs at large separations ("the final parsec problem") and reduces the overall GW background.

I also considered the possibility that SBH masses are systematically lower than usually assumed. A common parameterization [10, 11] sets SBH mass proportional to mass of the galactic bulge: $\beta = M_{\rm BH}/M_{\rm bulge} \approx 0.003$. However, there are reasons to suspect the ratio β is currently overestimated: there is disagreement in $M_{\rm BH}$ estimates between different methods as well as disagreement in bulge mass estimates between different papers (see §II.C in Paper II). I still assume $M_{\rm BH} = \beta M_{\rm bulge}$ but allow β to vary in the range $0.001 \ldots 0.003$. I found that $\beta = 0.001$ (the value reported in the early papers on $M_{\rm BH} - M_{\rm bulge}$ relation) implies values of $h_c(f)$ that are 2 – 3 times lower than the predictions of [6] or [7] and hence resolve the tension that currently exists between the theoretical treatments and the lack of a PTA detection (Fig. 1, right).

Future research plans

In my future research, I plan to expand on both of the projects described above. I will develop a more complete model for the dynamical evolution of BSBHs in stellar environments, and I will use this model as a basis for interpreting the PTA data and placing constraints on the BSBH population.

1. Constraining BSBH population parameters from pulsar timing array observations.

In Paper II, I developed a formalism for calculating the stochastic GW background spectrum $h_c(f)$, given a known distribution of BSBH parameters (total mass, mass ratio, initial orbital elements) and a galaxy merger rate. The shape of that spectrum can be characterized by three parameters: peak frequency, amplitude at high frequencies, and slope at low frequencies (the slope at high frequencies is $-2/3$ independent of model parameters). It is possible to place constraints on all of these parameters from PTA data [12]. This means we can place independent constraints on three different parameters of the model – for example, the following ones:

1. Black hole-bulge mass ratio β.
2. Galaxy merger timescale T, which, combined with the observed galaxy pair fraction, determines the galaxy merger rate.
3. The typical BSBH eccentricity at the moment it enters the GW-dominated regime $e_{\rm GW}$. Based on the results of Paper II, this parameter appears to be correlated with the shape of $h_c(f)$, unlike initial eccentricity, orbital inclination, or degree of nuclear rotation.

It is possible to constrain these parameters independently because they affect the shape of the GW background spectrum in different ways: T changes its amplitude, β affects both the amplitude at high frequencies and the peak frequency, and $e_{\rm GW}$ determines the slope at low frequencies. **Therefore, this project will be the first attempt to independently test two possible hypotheses for the lack of detection of nanohertz GWs: that either sbh masses or the galaxy merger rate is overestimated.**

2. A self-consistent model for evolution of binary SBHs in rotating and non-spherical nuclei.

In Paper I, I found that nuclear rotation qualitatively changes the dynamics of a BSBH, adding a new degree of freedom – inclination on the binary's angular momentum with respect to the nuclear rotation axis. This is in agreement with previous simulations [13, 14]. Another N-body study [15] found that non-sphericity of the stellar nucleus has a similar effect: it also causes a binary's orbital orientation to evolve in a certain direction, rather than as a random walk. In order to better understand this phenomenon, I plan to simulate BSBH dynamics in galaxies that are both nonspherical and rotating, as one would expect in galaxies that form via mergers. For this purpose, I will adapt a Monte-Carlo technique used in [9] that properly accounts for dynamical relaxation even when the number of particles in a simulation is much lower than in a real galaxy. **This study will be first the model of BSBH dynamics to properly include not only a realistic relaxation rate in non-spherical galaxies, but rotation as well.** It will also allow me to explore the change in galaxy rotation profile due to the effects of stellar ejections by a BSBH and, ultimately, further refine my model of the GW background spectrum.

References

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