Parameter estimation of spinning binaries using MCMC

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Introduction

Binary systems consisting of stellar-mass (∼1M⊙−100M⊙) compact objects are amongst the most promising gravitational-wave sources for ground-based laser interferometers. If at least one of the binary members is a black hole, our current astrophysical understanding suggests that the black hole should be spinning at least modestly [1]. Spins strongly affect the gravitational waveforms by introducing phase and amplitude modulations, caused by the coupling of the angular momenta. For parameter estimation on an inspiral signal, it is therefore of vital importance to take into account the effects of spins.

Building on a non-spinning binary inspiral parameter-estimation code [2], we have extended this code to extract the source parameters of spinning binary inspirals. The algorithm is based on a Markov-chain Monte-Carlo (MCMC) technique [3] to compute the posterior probability density functions (posterior PDFs) of the source parameters.

The waveform

In this first stage of our study, we model the gravitational-wave signal at the restricted 1.5PN approximation [4] and the effect of spins is included in the limit of simple precession [5]. These simplifications allow us to calculate the waveforms analytically, thereby greatly reducing the computation time. Here we present results for a fiducial binary system of a 10 M⊙, spinning black hole and a 1.4 M⊙ non-spinning neutron star. The waveform is described by a twelve-dimensional parameter vector, where the parameters are: chirp mass Mchirp, symmetric mass ratio η, spin magnitude a, the constant angle between spin and orbital angular momentum θ, geocentric time (t₀), phase (φ) and precession phase (ω) at coalescence, distance d, position in the sky (RA and Dec.), and orientation of the total angular momentum vector (θ₀, φ₀).

Results

We are carrying out a thorough exploration of the parameter space for spinning binary systems. Here we present the results for a fiducial source characterised by a spin parameter of α = 0.8, θ = 55° and d = 13 Mpc (the SNR is ∼ 20 at each detector). We show the marginalised PDFs of selected parameters, for observations carried out with the LIGO interferometer at Hanford only (Fig. 2) and with both LIGO 4-km interferometers at Hanford and Livingston (Fig. 3).

The most striking result is that due to the additional modulations induced by the spins, even with one detector one can fully resolve the physical and geometrical parameters of the binary, including the source location in the sky, although the uncertainties are fairly large. As expected, the accuracy of the measurements increases substantially when instruments are added to the network. As an example, we show in Fig. 4 the error box in the sky.

Conclusions and future work

- The binary geometrical parameters are resolvable even in observations with one detector (though the uncertainties are large).
- The quality of astronomy improves (as expected) with the number of detectors, and we are already exploring the effect of including VIRGO into the network along with LIGO.
- We are modifying the proposal distributions used in the MCMC to take into account correlations between parameters and make the code substantially more efficient.
- We will carry out a systematic investigation of the parameter space, starting our chains from offset values.
- We plan to include more realistic waveforms and test the code on injections into real interferometer data.

References