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Spinning black-hole binaries: a bridge between astrophysics and relativity.

Context

Until 2015, almost all of the information we had collected about the Universe came to us in the form of photons. Gravitational waves (GWs) provide a qualitatively new way to observe the Universe that complements traditional electromagnetic observations. The weak coupling between gravity and matter, while making the experimental effort so challenging, also allows GWs to propagate without scattering or absorption. GWs, therefore, have an unobscured view through a unique window on the most energetic phenomena in the Universe, with a potential for discovery that could well reveal new frontiers for observational and theoretical physics.

Some of the strongest astrophysical sources of GWs are merging binary systems comprising black holes (BHs). In 2015, GWs were observed by the twin LIGO interferometers. This revolutionary achievement was not only the first direct detection of GWs, but also the first irrefutable observation of a binary BH system.

BHs in Einstein's theory of relativity are fully characterized by just two numbers: their masses and spins. Despite the simplicity of isolated BHs, the evolutionary dynamics of BH binaries is rich and complex. Relativistic spin-spin and spin-orbit couplings cause the BH spins and the orbital plane to precess about the direction of the total angular momentum. Spin precession is both a blessing and a curse for GW observations: by breaking symmetries, it encodes precious astrophysical information about the sources, but extracting that information requires more physically and computationally demanding calculations.

Breakthrough

Our team made theoretical breakthroughs in understanding binary BH spin precession, establishing fundamental links between the astrophysical binary BH formation channels and the complex GW signatures of precessing binaries observed in the LIGO/Virgo band.

The behaviour we observed in earlier projects using computationally expensive methods suggested that spin precession may be simpler than previously appreciated. We noticed the presence of hidden constants of motions which allowed for a vast simplification of the dynamics. We found analytic solutions to the spin precession equations at 2PN using effective-potentials methods. Just as the orbits found by Kepler have different shapes (ellipse, parabola, hyperbola) depending on the values of the conserved energy and angular momentum, we discovered that binary BH spins precess in three qualitatively different shapes depending on the values of the conserved quantities. These solutions provide a deeper understanding of binary BH spin precession, just like the orbits of Kepler are more illuminating than a brute force integration of Newtonâ€™s inverse-square law.

Results

Our new multi-timescale analysis has revolutionized the study of precessing binary BH systems in the post-Newtonian regime. The dynamics of precessing BHs has been studies for the past 50yr in an orbit-averaged fashion. Our new analytic solutions allowed us to develop a precession-averaged formulation. We can now calculate binary BH inspirals from arbitrarily large binary separations, bridging the gap between astrophysical binary BH formation and the GWs emitted near merger billions of years later at frequencies detectable by LIGO/Virgo.

At its heart, our analysis consists of a new, efficient, post-Newtonian framework. The public python module we developed, PRECESSION, is now a major tool in use by the GW community to evolve spinning BHs and was featured in 20+ publications to date.

This breakthrough allowed for an explosion of new predictions: we uncovered morphological transitions, discontinuous limits, maximal nutations, new resonant phenomena, and new instabilities. We exploited our findings to distinguish BH populations, while other groups used our solutions to build waveform models. Our approach is now at the backbone of state-of-the-art templates used in LIGO/Virgo parameter-estimation pipelines.

Our findings provides an essential ingredient to turn the full promise of GW astronomy into reality.

Code repository:

https://github.com/dgerosa/precession

Movie:

https://www.youtube.com/watch?v=H1xy8FzKNDY

Evolution of samples of BH binaries using both an old-fashioned, orbit-averaged integrator and our new precession-averaged approach. Our new solutions remain accurate till very close to merger while delivering an immense computational speed-up.

Case study

Client profile

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Product used

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