Modeling gravitational wave signals from black hole binaries

The emerging field of gravitational wave astronomy is paving the way for the study of previously unobservable phenomena such as the merging of two black holes. This is achieved due to the ripples of gravitational energy that these events create, causing tiny vibrations in space-time that have only just become measurable.

Almost one hundred years after Einstein's theory of general relativity revealed space and time to be dynamical entities, gravitational research is about to take another giant leap. Some of the first ever gravitational wave detectors capable of accurately detecting signals from space will be coming online over the next few years, allowing a totally fresh perspective on the universe that will be comparable to the revolution brought about by radio astronomy.

A project from the University of the Balearic Islands, Spain, is based around this new field of gravitational wave astronomy, which aims to marry the theoretical physics behind black holes and general relativity with real observations from space. "Everything we know about the universe at present comes from different bands of electromagnetic waves, including optical, infrared and x-ray," says Professor Sascha Husa. "What these waves give us is an image of their source. What we are doing now uses the same principle but utilises gravitational waves instead, which will allow us to see objects that we have been unable to access so far, such as black holes and neutron stars.

"However, what these gravitational waves give you is not so much an image of the source, but rather a sound. They create vibrations in space-time, so with an event such as two black holes circling around one another, we will be able to observe the single wave train that this motion produces. We are basically hearing the ripples of gravitational energy that are sent throughout the universe, using incredibly sensitive state-of-the-art equipment."

Vibrations in space-time can be measured by the fact that they cause tiny fluctuations in the distance between two objects. The relative change in these distances is in the order of 10-22, and so it is only through a huge technological feat using very large laser interferometers that it is possible to measure this. "Before, the event rate of our instruments meant that we did not have sufficient sensitivity to study the field properly," says Husa. "However, they are now being upgraded and we should be beginning observations in 2015."

As a theoretical and computational physicist, one of Professor Husa's roles within the project is to make predictions for what wave trains will 'sound' like from different sources. For example, a binary black hole system will have a different mass and spin from other systems, and so it is up to Husa to use data from simulations to create analytical templates that can be used by those who analyse the data from the gravitational wave detectors, so that they can then identify binary systems and calculate their mass and spin.

"The templates that we create will allow our data analysts to sift through the noise produced by the

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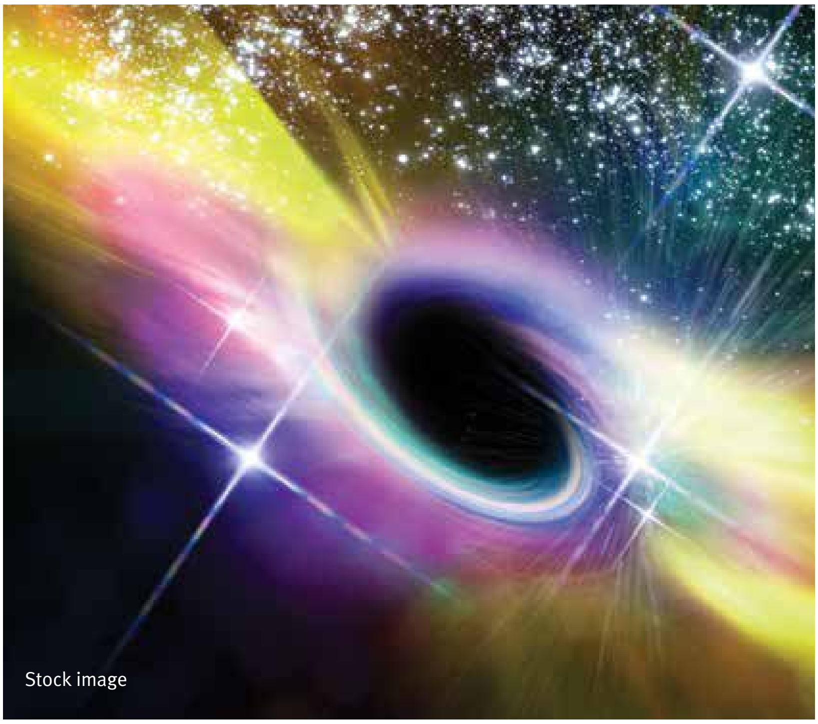
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universe and compare it to the templates, which will allow them to pinpoint where these binary black holes are and a little bit about their nature," explains Husa. "It is almost analogous to the music identification apps that are now available on smartphones. These apps are able to match the original audio waves of songs, the equivalent of our binary black hole templates, with songs playing in a noisy bar, and identify what it is."

For some sources, such as the slow inspiral of widely separated black holes, good analytical approximations for the gravitational waveforms are provided by perturbative post-Newtonian expansion techniques. For the last orbits and merger of two black holes, however, where the fields are particularly strong, and where one has the best chances of discovering entirely new physics, the Einstein equations have to be solved numerically.

Up until recently, it took the use of analytical perturbation theories to do this kind of work, but even this did not allow for the full picture to be shown. In 2005, however, there was a breakthrough that allowed researchers to carry out computer simulations of these types of events that gave measurable results. Since then, it has been a case of using these simulations to provide an improved picture of the wave-trains produced from the last orbits at the merger of two black holes.

These simulations are not cheap, however. A single simulation of a binary black hole can easily cost hundreds of thousands of CPU hours. "Without the top European supercomputers behind us it is not possible to carry out this sort of work," says Husa. "For a long time there have been large computational resources in the US but not in Europe, so having the resources provided by PRACE - we received 37 million core hours on SuperMUC hosted by GCS @ LRZ - gives us the chance to carry out this research which would not be possible on the national machines you have in most European countries."

This work with PRACE is part of a longer project which started in 2005, and it will be keeping these researchers busy for the foreseeable future. "We're hoping that in around 3 to 5 years we will have confirmed our first discovery of a binary black hole system, and will have been able to use our algorithms to calculate data about its spin and mass," says Husa.

"Having this sort of data will be a huge coup for astrophysics, as it will begin to answer questions about the history of stars, about what happens in clusters and globular clusters of stars, and about what happens when stars burn out, amongst other things."

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Project title: Modeling gravitational wave signals from black hole binaries
Project leader: Prof. Sasha Husa, University of the Balearic Islands, Spain
Project details: This project was awarded 37 million core hours on SuperMUC @ GCS@LRZ, Germany

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