

RESEARCH PLAN: PATRICK BRADY

My current interests include gravitational-wave data analysis and astronomy using ground and space-based detectors, numerical relativity including simulation of binary coalescence, and the dynamics of gravitational collapse both from the point of view of cosmic censorship and as a possible source of gravitational waves. Over the next five years, I plan to play a lead role in LIGO and Advanced LIGO data analysis, to initiate a research program in astrophysics and data analysis related to the Laser Interferometer Space Antenna (LISA), and to expand my research into areas of astrophysics relevant to gravitational-wave astronomy.

Earth-based gravitational-wave detectors

The Laser Interferometer Gravitational-wave Observatory (LIGO) consists of observatories in Louisiana and Washington. It has an ambitious goal: the first detection of gravitational waves from astrophysical sources. Such waves, which are ripples in the fabric of spacetime itself, were predicted by Einstein in 1916 but have never been directly observed. The detection of gravitational waves will open a new frontier in astronomy, allowing direct observation of black holes, and bringing with it new information about neutron stars, nuclear matter and the origin of the Universe (if gravitational waves left behind from the first fraction of a second after the beginning of the Universe can be detected). The construction of LIGO is complete and the detectors are currently operating with strain sensitivity 10^{-21} at 100Hz for a band of about 100Hz.

I am co-chair (with Gabriela Gonzalez) of the working group charged to search for binary inspiral events in the Universe using data from three LIGO interferometers and the GEO600 interferometer in Europe. With post-docs and students at UWM, I have focused my efforts on developing the tools and techniques to search for signals from compact binary coalescences. We have played an important role in all of the activities which are ongoing within the group. In particular, we took the lead on the S1/S2 binary neutron star searches [1]. Duncan Brown (now a post-doc at Caltech) took the lead on the S2 search for primordial black holes [2]. Under my guidance, Eirini Messaritaki took the lead on the S2 binary black hole search, and Stephen Fairhurst took the lead on the S2 LIGO-TAMA joint analysis [4] and on the joint LIGO-VIRGO inspiral work. At the same time as performing these searches, we led the development of a robust detection pipeline for gravitational waves from compact binary inspiral which uses data from all three LIGO detectors plus the British-German GEO600 project. This pipeline is at the heart of LIGO searches for gravitational waves from binary black holes, binary neutron stars, and primordial black holes.

As we enter the era of gravitational-wave astronomy, my research will focus more on information extraction and interpretation of gravitational-wave observations. Here I summarize some specific activities my group will work on over the next few years.

Science from compact binary coalescence: In the near term, my postdocs and students will develop the tools and methods to: 1) Estimate the rate of compact binary coalescence in the Universe. This will take the form of an upper limit in the near term. With a detection, however, we will determine rate estimates. 2) Measure the masses and spins of the merging objects with the

goal to develop a catalog of binaries which might be used to constrain binary population models. 3) Measure the inclination, polarization, sky location, and distance as allowed by the use of multiple observatories, higher harmonic content and/or spin modulation. 4) Better combine information from the inspiral, merger and ringdown phases of binary black hole coalescence to optimize detection and provide data for comparison with numerical simulations which are in progress. 5) Probe the disruption of neutron stars during binary merger. 6) Test alternative theories of gravity such as scalar-tensor theories which can result in modified phasing of the gravitational waves from binary inspiral.

Joint electromagnetic-gravitational-wave observing campaigns: Recent detections of short, hard γ -ray bursts [5, 6, 7, 8] provide tentative evidence that binary neutron star (or neutron star/black hole) systems are the progenitors of these explosions. They also remind us of the potential scientific pay-off of combined electromagnetic and gravitational observing campaigns. Preliminary estimates suggest that current LIGO sensitivity could provide marginally interesting constraints on the higher mass systems if there is a γ -ray burst closer than 200 Mpc. To date, the closest bursts are at $z \simeq 0.15$ which is just beyond the LIGO reach. Nevertheless, I am working with Alex Dietz at Louisiana State University to search the current LIGO data around the times of confirmed short, hard γ -ray bursts; ultimately, this analysis will constrain the progenitor systems.

Searching for burst waves: The ability to identify gravitational-wave burst signals holds great promise for serendipitous discoveries. At UWM, Saikat Ray-Majumder (my Ph.D. student), Kipp Cannon (a postdoc at UWM) and I have developed an excess-power search for gravitational wave bursts. While the method is quite general and runs online during the current science run, we have been tailoring this search to the merger phase of compact binary coalescence. Binary black holes may be among the strongest sources of gravitational waves that may be detectable by the current generation of detectors. We have developed a pipeline to combine information from the inspiral and burst searches to improve our ability to detect these sources. We will add the ability to compare the results of a search with predictions from numerical relativity and other approximation schemes. Our goal is the extraction of information which can inform our understanding of strong-field gravitation around black holes.

Worldwide gravitational-wave detector network: Stephen Fairhurst and I have played a leading role in multi-project searches for gravitational waves from compact binary systems. Over the next decade, it is plausible that a worldwide gravitational-wave detector network may be operating. Such a network will afford the best possible scientific payoff from gravitational wave observations by combining the data sets to extract better source position information and information about the polarizations of gravitational waves. We will continue to explore the best ways to undertake joint observing runs by carrying out multi-project searches; we will also develop a set of tools to extract the information from detected waves.

Advanced LIGO: As we approach the Advanced LIGO upgrade of the interferometers in the LIGO facilities, I see two roles in which my group can make significant contributions. We can inform design decisions which may impact the science available with Advanced LIGO. We can also lead the development of the data analysis software and computing infrastructure for Advanced LIGO. I have chaired the LIGO Data Analysis Software Working Group since January 2004 when it was charged “to develop a long-term vision for LSC data analysis software, and to set policy on

software issues that strike the right balance among the many competing virtues of a data analysis system.” This group has been reasonably successful in developing and deploying a stable data analysis software environment. I envision the development of a robust and scalable data analysis environment for Advanced LIGO which will exploit the power of the internet and the Grid Computing paradigm. Furthermore, it is critical that this system can provide low-latency astronomical triggers with confidence; this is a dream I hold for Advanced LIGO observations.

Space-based gravitational-wave detectors

Space-based gravitational-wave detectors will be sensitive to gravitational waves with frequencies from 0.1 mHz to 0.1 Hz, including signals from collisions of massive black holes (masses a million times that of our sun), the capture of ordinary stars by massive black holes, and the emission of gravitational waves by the slow orbit of binary star systems in our Galaxy. The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA mission which will consist of three spacecraft in orbit about the Sun; by measuring the relative separation of these spacecraft, scientists will detect gravitational waves. This mission provides even more exciting opportunities for gravitational-wave astronomy during the next decade (we hope). I have initiated a program of research to address some of the questions which arise in LISA data analysis. Unlike earth-based detectors, space-based detectors are expected to have a plethora of signals all visible in the data at the same time. The data analysis challenge can therefore be thought of as a combined detection/measurement problem [9]. Preliminary investigations have been carried out, but many important open issues remain to be solved: what is the best method to deal with the white dwarf binaries? Do binary black hole merger signals significantly impact our ability to extract other, weaker, sources? Are there any calibration issues which could impact signal identification? I look forward to exploring these questions over the next year and to building a substantial research effort in the area of space-based gravitational-wave astronomy.

Theoretical issues in gravitation and astrophysics

Among the most exciting prospects for gravitational-wave astronomy is the ability to probe the gravitational field around black holes, neutron stars or in the early Universe. This will require us to confront theoretical models with observational data. I remain interested in basic problems in gravitation and astrophysics especially when they are relevant to gravitational-wave observations.

Extreme-mass-ratio inspiral: Neutron stars or white dwarfs spiraling into massive black holes will provide a superb laboratory for testing general relativity and alternative theories of gravity. These tests will rely on our ability to determine the gravitational waves from these systems. A great deal of progress has been made in this direction over the past decade, but some problems remain [11]. For example, it is still not clear if one needs to perform second order perturbation theory to determine the waves to sufficient accuracy for the most interesting science.

Numerical relativity: The existence of black holes is among the most fascinating predictions of

general relativity. Gravitational-wave astronomy promises to provide direct observation of strong gravitational fields around black holes while pairs of them are involved in violent relativistic interactions. Theoretical understanding of the late stages of inspiral and merger of black holes will be needed in order to extract physical information. This point of view has been expounded in Ref. [10] and remains true. With Luis Lehner and Frans Pretorius, I am planning to explore these issues using the numerical techniques which are currently available. Among the problems which I wish to address is the interpretation of results from simulations in a form which can be used in gravitational-wave astronomy. I have a new graduate student working with me on this subject. He has begun learning some numerical techniques which he will apply to a spherically symmetric collapse problem over the next 6 months; after that, we will move on to the much harder problems in higher dimensions.

Dynamics of gravitational collapse: In addition to my work on detection and sources of gravitational waves, I remain interested in more abstract issues in gravitation theory. I will continue the study of singularities and their formation in gravitational collapse. I believe numerical methods provide one of the best methods to examine broad, physically interesting parameter spaces of solutions involving singularities. The study of null singularities inside black holes, and the evolution of spacetime near to them remains difficult using analytic techniques. I would like to understand which features of spherical collapse survive when symmetries are relaxed; outside black holes it is well understood what happens at late times, but inside the story is not complete [12]. A numerical scheme based on characteristic evolution may be useful in this regard. There exist coordinate systems without caustics near to the Cauchy Horizon of Kerr black holes; these coordinates should be good enough to allow evolution near to the singularity that will form when the hole is perturbed.

Grid Computing Research

It appears likely that grid enabled software will be useful when pursuing computationally intensive projects like those described above. Over the past few years, I have become involved in two projects [13] which aim to exploit the power of grid-computing in large scale experimental projects. Moreover, the deployment of both inspiral and burst searches on the LIGO Data Grid have provided substantial insight into the practical issues which arise in the Grid computing model. These issues include data distribution, security, check-pointing, and a host of other computer science issues. Our group at UWM is one of four involved in the successful ITR2003 proposal [14] which has enabled the deployment of grid computing tools across the LIGO Data Grid. The power of grid computing for numerical and data intensive fundamental science makes this an extremely worthwhile direction to pursue. I also hope to learn how numerical relativity might benefit from the grid and to explore numerical algorithms that could exploit this new tool in our arsenal.

References

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