Progress Report on Second Year of APRA02 Grant NAGW-12906, "Investigations into gravitational wave emission from compact body inspiral into massive black holes"

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1 Preamble

In contrast to year 1 (when much of the activity associated with this grant focused upon developing our group at MIT), year 2 was a period of very focused attention on research problems. We made significant progress developing relativistic waveforms for the extreme mass ratio inspiral problem; we have pushed forward a formalism our group developed for mapping the spacetimes of massive compact objects; and, in collaboration with the Caltech group, we began to develop a framework for addressing issues in LISA data analysis for extreme mass ratio systems. This grant was also used to support travel for Hughes and postdoc Joel Franklin, and to enable a slight expansion of the MIT astrophysics Beowulf cluster.

For brevity, we will use the following acronyms in this progress report:

- **CSR**: Center for Space Research (our host laboratory at MIT).
- **EMRI**: Extreme mass ratio inspiral. This is now the conventional name for gravitational waves from a small body captured by a massive black hole.
- **TB**: Teukolsky based. Describes calculations based on the "Teukolsky equation", i.e., the perturbed Einstein equations.

2 Personnel supported by this grant

- *Scott A. Hughes* (PI), 2 months summer support
- *Joel Franklin* (postdoc), 12 months support.

In last year's progress report, we indicated that graduate student Clayton Featherstone was likely to be supported by this grant. Unfortunately, Featherstone was very unhappy at MIT, and chose to withdraw. A second year graduate student, Ryan Lang, will begin work with our group in Spring 2005.

3 Computing Infrastructure

In year 1, quite a bit of funds (and time) went into the development of the CSR Beowulf cluster. This year, much less time and money went into developing this cluster; our only developmental work was to expand the number of usable nodes slightly. The cluster now supports 100 high-performance nodes, which has had a substantial impact on the research activities described below.

5 Non-EMRI research activity

Though the bulk of our research activities have focused upon analyses relevant to LISA measurements of EMRI gravitational waves, some time has been gone into other analyses. In the past year we have completed two projects relating to LISA measurements of massive black hole binary coalescences. The first is an analysis with Kristen Menou (Columbia University) of the accuracy with which LISA can determine the masses of such binaries. We find that there may exist a family of binaries in which the initial mass of the binary's black holes and the final mass of the merged remnant are determined well enough that the change in mass may be determined with high accuracy. This would constitute a robust probe of strong field gravity, possibly constraining the ultra-strong field final dynamics without requiring numerical relativity. Our second project is an analysis with Daniel Holz (Kavli Institute for Cosmological Physics, University of Chicago) of the possibility of using massive black hole coalescences as standard candles, complementing other cosmological standard candles such as Type Ia supernovae. Papers from both of these analyses have been accepted to the Astrophysical Journal, and should appear in early 2005.

A "spin off" application of our TB code has been an analysis of the recoil or "kick" that is imparted to the merged remnant of a binary black hole coalescence. Although not directly tied to LISA waveform generation and measurement (and hence not strictly related to the goals of this grant), this work is a good example of broader astrophysical applications from the codes we have developed. This work was done in collaboration with Marc Favata (student of Eanna Flanagan at Cornell) and Daniel Holz (postdoc at the Kavli Institute for Cosmological Physics at the University of Chicago), and has led to three publications (described below).

6 Publications

The following papers appeared in press during year 2 of this grant.

6.1 EMRI related research

Rotating black hole orbit functionals in the frequency domain, Steve Drasco and Scott A. Hughes, Physical Review D **69**, 044015 (2004); astro-ph/0308479.

Towards a formalism for mapping the spacetimes of massive compact objects: Bumpy black holes and their orbits, Nathan A. Collins and Scott A. Hughes, Physical Review D **69**, 124022 (2004); gr-qc/0402063.

In addition, the following two papers will be submitted for publication in early 2005:

Gravitational radiation reaction in the adiabatic limit, Scott A. Hughes, Steve Drasco, Eanna E. Flanagan, and Joel Franklin, to be submitted to Physical Review Letters.

Snapshots of generic extreme mass ratio inspirals, Steve Drasco and Scott A. Hughes, to be submitted to Physical Review D.

6.2 Non-EMRI research

How black holes get their kicks: Gravitational radiation recoil revisited, Marc Favata, Scott A. Hughes, and Daniel E. Holz, Astrophysical Journal Letters, **607**, L5 (2004); astro-ph/0402056.

Consequences of gravitational radiation recoil, David Merritt, Milos Milosavljevic, Marc Favata, Scott A. Hughes, and Daniel E. Holz, Astrophysical Journal Letters, **607**, L9 (2004); astro-ph/0402057.

How black holes get their kicks: Radiation recoil in binary black hole mergers, Scott A. Hughes, Marc Favata, and Daniel E. Holz, to appear in the proceedings of *Growing Black Holes: Accretion in a Cosmological Context*, edited by A. Merloni, S. Nayakshin, and R. Sunyaev, Springer-Verlag series of "ESO Astrophysics Symposia"; astro-ph/0408492.

Golden binaries for LISA: Robust probes of strong-field gravity, Scott A. Hughes and Kristen Menou, Astrophysical Journal, in press; astro-ph/0410148.

Using gravitational-wave 'standard sirens', Daniel E. Holz and Scott A. Hughes, Astrophysical Journal, in press.

7 Travel

The following travel was supported by this grant:

- Workshop on LISA data analysis, Albert Einstein Institut, Golm, Germany, March 2004 (airfare and meal costs).
- Travel by Joel Franklin to Cornell University, Ithaca NY, to collaborate with Hughes and Drasco, September 2004 (car rental and hotel costs). [Note: Hughes visited Cornell, with NSF funding, for 6 weeks in fall 2004.]
- Visit by Jonathan Gair to MIT, July 2004 (hotel and meal costs).
- LISA International Science Team meeting, Stanford Linear Accelerator, Palo Alto CA, December 2004 (airfare, hotel, car rental, and meal costs).