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WHITE PAPER ON GRAVITATIONAL-WAVE ASTRONOMY

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ABSTRACT

This white paper describes the current status of gravitational-wave detectors and the promises of gravitational-wave astronomy. It next describes the role that Canada can play in these exciting developments. A vigourous Canadian participation can be ensured with a minimum of resources by integrating a number of researchers within our Departments of Physics and Astronomy, whether or not they currently have a presence in this field. Such a move is not only strongly motivated by sound scientific reasons, it can be fully supported by a large pool of talented researchers who are awaiting an opportunity to return to Canada.

Subject headings:

1. GRAVITATIONAL-WAVE ASTRONOMY

It is exceedingly likely that gravitational waves will be directly detected for the first time during the coming decade. As gravitational-wave detections become routine, a new observational window onto the universe will open; this will be the dawning of the age of *gravitational wave astronomy*.

This new form of astronomy will advance physics and conventional astronomy in a variety of different ways. First, it will provide an independent way to probe the deep reaches of our cosmos and complement observations in the electromagnetic band. Second, it will constitute a unique way to study systems that are not radiating electromagnetically, or not doing so along our line of sight. Gravitational waves propagate essentially unscattered from their source, and they carry pristine information about the processes that produced them. Current and planned detectors, both on Earth and in space, will be sensitive in different frequency bands, and to different sources.

The (currently operational) ground-based detectors LIGO and VIRGO are sensitive to gravitational waves with frequencies between approximately 40 Hz and a few kHz. The planned space-based detector LISA will be sensitive in a low-frequency band that goes from approximately 10^{-4} Hz to 10^{-1} Hz.

Among the most promising sources of gravitational waves for ground-based detectors are **inspiraling compact binaries** consisting of neutron stars and/or black holes that are just about to undergo their final merger. In their mature phase the detectors are expected to observe somewhere between a few to about one hundred events per year. (The rates are uncertain because of the limited astrophysical knowledge that we possess about compact binaries; the measured rates will shed a welcome light on the relevant astrophysical processes that are responsible for their formation.) This will be the first detection of stellar-mass black hole–black hole binaries, and black hole–neutron star binaries. The mass and spin of the each object will be precisely determined, and this will constrain formation scenarios for stellar-mass black holes, as well as providing insight into their accretion history. Black-hole binaries are very clean systems, and this will permit the performance of well-controlled tests of general relativity in the highly dynamical, nonlinear, and radiative regime. The measurement of the tidal disruption of a neutron star by its companion black hole will reveal the internal structure of the neutron star and constrain the equation of state of matter at supernuclear densities. Coincident observations of compact binary inspirals and gamma-ray bursts will shed light onto the progenitors of such systems. The science reach of gravitational-wave astronomy is vast.

An interesting source of **continuous gravitational waves** is a deformed neutron star undergoing rapid rotation. Neutron stars with an ellipticity as small as 10^{-6} are detectable in the current version of the LIGO detector, to a distance of 500pc; the search is deeper if it can be complemented with epherimides data from radio observations, and neutron starts with even smaller ellipticities could thus be detected.

Gravitational wave bursts, generated for instance by core-collapse supernovae or cosmic strings, represent a third category of sources. Core-collapse supernovae originating from within the local group of galaxies could be observed by LIGO and VIRGO. These waves are generated by non-spherical processes in the proto-neutron star and travel essentially unaffected through the outer layers of the collapsing star. Detection of such waves will provide insights into the explosion mechanism of core-collapse supernovae, and may allow us to distinguish between different scenarios of shock-revival. Searches for cosmic-string signals will give rise to bounds on the density and tension of these objects.

Advanced versions of ground-based detectors will be sufficiently sensitive to discover **intermediate mass black holes**, should they exist. Such detections will shed light onto the dynamics of globular clusters, where these black holes are expected to form. The **Advanced LIGO detectors** have been funded by the U.S. National Science Foundation. Development is underway, and installation of the new optical and seismic isolation systems will start in 2011. The goal of Advanced LIGO is a ten-fold increase in sensitivity, and a seismic wall that is lowered to 10 Hz (from 40 Hz in the initial LIGO) by 2015.

Plans are also underway for the third generation of gravitational-wave detectors, which will have much higher sensitivities than LIGO and VIRGO. Examples are the Einstein Telescope (in Europe) and LCGT (in Japan), which will measure signals at frequencies as low as approximately 1 Hz. The **space-based LISA mission** will search for gravitational waves at mHz frequencies. The primary sources of gravitational waves for LISA are supermassive black hole binaries, the capture of solar-mass compact objects by massive black holes, and galactic white-dwarf binaries on tight orbits. Observations will provide key insights into the formation and population of supermassive black holes, help understand the processes involved in active galactic nuclei, probe deeply into the fundamental nature of gravitation, and so on. Furthermore, LISA's superb sensitivity will allow it to reach to high redshifts and thus allow, together with electromagnetic counterparts, to carry out cosmological studies.

Ground-based gravitational wave detectors—and LIGO in particular—have so far fully satisfied their expectations. Initial LIGO finished its target science run in fall 2007, collecting a full year of coincident data at design sensitivity. Analysis of this data will soon be completed, and will result in the establishment of several astrophysically relevant upper bounds, ranging from limits on the ellipticity of pulsars to limits on the energy density of stochastic gravitational waves.

Gravitational-wave observations complement and are complemented by a wide variety of electromagnetic observations. For example, X-ray observations of neutron stars and accretion disks around black holes will naturally be merged with gravitational-wave measurements to probe the nature of these objects and test the laws of strong-field gravity. Another example is cosmology, in which studies of the primordial density fluctuations in the microwave band can be combined with searches of stochastic gravitational waves; such searches have already been able to place limits on the energy density of gravitational waves that are comparable to bounds from nuclear synthesis, with significant improvements expected with second-generation detectors. With Canada's outstanding presence in X-ray astronomy and cosmology, gravitational-wave astronomy is an obvious point of convergence and mutual reinforcement.

2. CANADIAN PARTICIPATION

Canada does not formally participate in the experimental effort to measure gravitational waves, and its involvement in theoretical support has been limited to a very small number of individuals. This number, fortunately, has been increasing of late, and Canada is now poised to magnify its participation in gravitational-wave science. We argue that we can achieve maximum impact at minimal costs by increasing the number of theoretical astrophysicists working in support of gravitational-wave research.

This theoretical effort will be an integral part of the new gravitational-wave astronomy; it will complement in an essential way the experimental effort that goes into the construction and operation of the detectors. Analysis of the data, confrontation with theory, and extraction of source information all require an accurate knowledge of possible waveforms produced by relevant gravitating systems. This knowledge is obtained by constructing an accurate theoretical model of the source, and the methods to achieve this are numerous and diverse. They range, for example, from the full-scale numerical integration of the Einstein field equations to simulate the orbital motion and final merger of two black holes, to the exploitation of approximation schemes (based, for example, on an assumed small mass ratio or slow orbital velocities) to describe the system with analytical methods. They include the detailed modeling of the structure of neutron stars, how these stars deform under tidal forces, and the description of magneto-hydrodynamical phenomena above the surface.

Canada has had a small presence in the field of gravitational-wave source modeling since the nineteen nineties (with Choptuik at UBC and Poisson in Guelph), and this presence has doubled with the recent hire of Lehner at the University of Guelph/Perimeter Institute and Pfeiffer at CITA. We now have the critical mass required to attract a much larger community of researchers with interests in source modeling and data analysis. Such an integrated recruitment effort should be shared and pursued by many Canadian Universities, and we foresee a keen interest from the Canadian Astronomical Society.

Researchers working in the modeling of sources of gravitational waves must integrate many different areas of physics and astrophysics. They must be versed in general relativity and understand aspects of alternative theories so as to imagine new ways of testing the theory. They must know the astronomical universe, so as to identify the most promising and likely sources of gravitational waves. They must master many tools of theoretical physics and astrophysics, to be able to include all the processes that are relevant to a given source. And they must be fluent with techniques of Bayesian statistics to apply their models to the analysis of real gravitational-wave data. The sum total of these attributes ensure that a source modeler will integrate exceptionally well within any Department of Physics and Astronomy. The individual will communicate meaningfully with relativists and other theoretical physicists (such as high-energy physicists), interact positively with astronomers and theoretical astrophysicists, and establish links even outside the Department (in the Department of Statistics, for example). The individual will be part of an exciting endeavour to explore a new portion of the Universe, and will be in high demand for public lectures and outreach activities. A gravitational-wave researcher will thus make an extremely positive addition to any Department, whether or not is has an existing presence in gravitational physics.

In spite of the small (but growing) Canadian presence in gravitational-wave science, there is a large number of Canadian students who have pursued a career in this field. This is a testament to the excellent tradition of research in gravitational physics that Canada has enjoyed in the last fifty years, thanks to the pioneering efforts of Werner Israel, Bill Unruh, and others. These students, however, tend to leave Canada to attend graduate school in the United States or Europe, where they stay to the completion of one or two post-doctoral fellowships. Some of these have found academic employment outside of Canada, and have been prevented from returning (in spite of a strong desire to do so) by the absence of local opportunities. There is currently a large and talented diaspora of Canadian post-doctoral researchers who are waiting for an opportunity to return. A concerted effort to boost Canadian research in gravitational-wave science can rely on this eager population of young researchers.

Our recommendation is that Canada should magnify its effort in this field, so as to reap the benefits of an exciting new science. Such a move is motivated both by sound scientific reasons and the fact that it can be supported by a strong pool of talented researchers. A strong presence in gravitational-wave astronomy will complement and enhance other areas of astronomy and astrophysics in which Canada plays a leadership role. This goal can be achieved by creating a number of faculty positions in the field of gravitational-wave science and supporting these researchers with sufficient resources. These include financial support for graduate students and post-doctoral fellows, as well as access to high-performance computing. All this represents a modest investment that will rapidly translate into a new area of leadership for Canadian astronomy and astrophysics.