Gravitational Waves in Astrometry and Pulsar Timing Arrays

Abstract: Gravitational waves are fluctuations in the fabric of spacetime and, in general relativity, they can be characterized by two polarizations states (commonly called the tensor E and B modes). A background of such gravitational waves can be detected through astrometric measurements and pulsar timing arrays, and the angular power spectra of these measurements for each polarization state is known. However, the capability of these experiments for localizing gravitational wave sources has not been studied in depth—this is of great importance since it will facilitate comparison with electromagnetic data. In addition, it is often assumed that a background of gravitational waves will conserve parity; however, this is not guaranteed since sources such as supermassive black hole mergers are known to produce circularly polarized gravitational waves that may give rise to chiral backgrounds. Thus, my intention is to determine how the locations of gravitational wave sources may be determined from astrometry and pulsar timing array data, as well as calculate the parity-breaking power spectra.

Proposal: The advent of gravitational wave astronomy has provided a new window onto the universe for astrophysicists. Traditional barriers that are opaque to electromagnetic radiation can be penetrated by gravitational waves, which thus provide a novel way to research black holes, early universe processes, and other phenomena that are otherwise difficult to study using light. While it is possible to detect gravitational waves by direct observation, the existing interferometers of LIGO and Virgo are not suitable for studying the polarization content of gravitational waves, since at least five detectors are required to isolate the polarization states. Pulsar timing arrays and astrometric measurements may provide better constraints on the polarization content of gravitational waves. Light interacting with a gravitational wave will have its trajectory altered and this causes the apparent position of light sources to be deflected and the arrival of light pulses to be delayed. Thus, it is possible to study a stochastic background of gravitational waves using astrometric missions such as Gaia by observing how the positions of a field of stars changes over time, as well as by timing millisecond pulsars against each other to measure correlated signatures in pulse arrival times.

The correlation functions and angular power spectra of such experiments have been calculated for each polarization state of gravitational waves by a variety of methods [1-3]. The power spectra will provide a starting point for analyzing a gravitational-wave background detected by astrometry or pulsar timing arrays; however, clearly there is more to a study of gravitational wave backgrounds than just the polarization content. I propose to investigate two key aspects of these gravitational wave experiments: their ability to localize sources and their ability to probe chiral gravitational waves. Neither issue has been studied in great depth—however, both projects will enhance experiments by facilitating comparison with non-gravitational-wave data and challenging the common, but possibly false, assumption that a background of gravitational waves will preserve parity.

First of all, after detecting a background of gravitational wave, is it possible to localize sources of the signals? In other words, will the signal exhibit any preferred directions? I propose to study whether a gravitational wave background will exhibit such an asymmetry using bipolar spherical harmonics [4, 5]. The coefficients of the bipolar spherical harmonics can be constructed from the same quantities used to calculate the power spectra and should be able to show whether the signal will have a dipole asymmetry. In addition, it is sometimes assumed that this stochastic background of gravitational waves will conserve parity. Then the energy densities in the left and right-handed circularly polarized states should be the same, which implies that cross-correlation of tensor-E and B modes and the redshift-B mode cross-correlation will be zero. However, sources such as supermassive black hole binaries are expected to to emit circularly polarized gravitational waves, and in this case the detected background would be chiral and the cross-correlations would not vanish. Therefore, I propose to calculate the parity-breaking power spectra, i.e. the E-B and redshift-B cross-correlations for a chiral gravitational wave background.

Since gravitational wave astronomy is a relatively new field, the results of these research projects will be useful for the development of pulsar timing arrays and astrometric surveys as gravitational wave detectors. The ability to locate gravitational wave sources from these experiments will be extremely useful, as it will allow us to compare measurements with electromagnetic data from the same region and therefore study gravitational-wave-emitting phenomena in greater depth. In addition, as stated earlier, for a chiral gravitational wave background, the EB and redshift-B cross-correlations will not vanish. Normally, if these functions were expect to be zero, then they could be used as null tests for systematic errors in these experiments; however, since we do expect some astronomical sources to emit chiral gravitational waves, subtracting these cross-correlations out of the data may result in the loss of real and important physics. Therefore, an expectation of what the cross-correlations should look like beforehand will be important for analyzing the data from astrometry and pulsar timing arrays, and that is what this project seeks to establish.

I would like to carry out this research at the California Institute of Technology, since this topic of research overlaps significantly with the work of Sterl Phinney and Yanbei Chen. I would also be happy to work with Daniel Holz at the University of Chicago or Franz Pretorius at Princeton University, since their research also focuses heavily on gravitational waves. The NSF fellowship will support me in my goals by allowing me to begin research in graduate school as soon as possible and spend as much time as I can developing the skills and knowledge necessary for my future career in physics research.

Timeline:

<u>Years 1-2</u>: Calculate the bipolar spherical harmonic coefficients from the redshifts and position deflection of stars. Use these to determine whether the gravitational wave signal will exhibit a preferred direction/dipole. Publish results on how to use astrometry and pulsar timing arrays to locate gravitational wave sources.

<u>Year 3</u>: Use the total-angular-momentum formalism to calculate the parity-breaking cross-correlation power spectra. Publish the functions and their derivations.

[1] L. G. Book and E. E. Flanagan, “Astrometric Effects of a Stochastic Gravitational Wave Background,” Phys. Rev. D 83, 024024 (2011) [arXiv:1009.4192 [astro-ph.CO]].

[2] L. O'Beirne and N. J. Cornish, “Constraining the Polarization Content of Gravitational Waves with Astrometry,” Phys. Rev. D 98, no. 2, 024020 (2018) [arXiv:1804.03146 [gr-qc]].

[3] D. P. Mihaylov, C. J. Moore, J. R. Gair, A. Lasenby and G. Gilmore, “Astrometric Effects of Gravitational Wave Backgrounds with non-Einsteinian Polarizations,” Phys. Rev. D 97, no. 12, 124058 (2018) [arXiv:1804.00660 [gr-qc]].

[4] A. Hajian and T. Souradeep, “Measuring statistical isotropy of the CMB anisotropy,” Astrophys. J. 597, L5 (2003) [astro-ph/0308001].

[5] L. G. Book, M. Kamionkowski and T. Souradeep, “Odd-Parity Bipolar Spherical Harmonics,” Phys. Rev. D 85, 023010 (2012) [arXiv:1109.2910 [astro-ph.CO]].