Snowmass2021 - Letter of Interest

LIGO Voyager: A Gravitational-wave Probe of Cosmology and Dark Matter

Thematic Areas: (check all that apply □/■)

■ (IF1) Quantum Sensors
■ (IF9) Cross-cutting and Systems Integration
□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics

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Abstract: The detection of gravitational waves from compact binary mergers by LIGO has opened the era of gravitational wave astronomy, revealing a previously hidden side of the cosmos. To maximize the reach of the existing LIGO observatory facilities, we propose a new instrument able to detect gravitational waves at distances $5\times$ further away than possible with Advanced LIGO, yielding a $100\times$ increase in the event rate for binary mergers. Observations with this new instrument will make possible dramatic steps toward understanding the physics of the nearby universe, the nature of the black hole horizon, as well as observing the universe out to cosmological distances ($z > 5$).

The first detection of gravitational waves (GW) from the object GW150914[1] by the Advanced LIGO (aLIGO) detectors inaugurated a new field of study: gravitational wave astronomy. The subsequent detection of a binary neutron star merger[2] has highlighted the possibilities of this new field. GW detectors provide a probe of physics in a new regime:

Binary mergers at cosmological distances will be observable with LIGO Voyager. For NS–NS binaries, the maximum redshift at which mergers can be detected approaches $z \approx 0.5$, rising to $z \approx 7$ for BH–BH binaries with $30\,\mathrm{M}_\odot$ components. Hundreds or thousands of detections will allow us to precisely characterize the long-sought NS equation of state (EOS)[3] and NS and BH mass and spin distributions in merging binaries.

The evidence for **the existence of intermediate-mass black holes** (IMBHs) in the $10^2 - 10^4\,\mathrm{M}_\odot$ mass range is still inconclusive at present. Attempts to look for electromagnetic signatures are hampered by the small dynamical footprint of low-mass IMBHs and the difficulty of associating phenomena such as ultraluminous x-ray sources specifically with IMBHs[4]. On the other hand, a handful of promising sources have been observed [5], and multiple formation scenarios have been proposed—though none without problems (see the introduction of[6] for a brief review). Thus, GW observations of compact objects in this mass range, which would be enabled by a future detector with good low-frequency sensitivity, could yield the first definitive proof of IMBH existence at the low end of the IMBH mass range [7]. Such measurements could also answer outstanding questions about the dynamics of globular clusters and about the formation history of today's massive black holes[8].

High precision probes of highly curved spacetime[9;10] will be enabled by the enhanced Voyager sensitivity. LIGO's first observations of GWs from binary black holes have already allowed made it possible to perform the first tests of general relativity (GR) in the highly relativistic strong-field regime[11]. LIGO Voyager instruments will allow us to significantly improve the precision of such tests – some of the binary black hole mergers will have a signal-to-noise ratio of hundreds.

GW memory may be left behind by most stellar collapse events, even those that do not result in an explosion. The typical growth timescale of the memory is of order $\gtrsim 0.1\,\mathrm{s}$, which makes it the only known low-frequency GW emission process in stellar collapse. Detecting the GW memory from a galactic event with aLIGO may be a difficult task even if the full projected low-frequency sensitivity is reached, but the baseline LIGO Voyager design would allow detection.

The LIGO Voyager design will provide a realistic chance of the detection, and characterization, of the gravitational wave (GW) signal associated with **postmerger oscillations following binary NS coalescence**. A search for these signals with data from LIGO Voyager would still require some level of optimism and a relatively nearby (i.e., $10 - 50\,\mathrm{Mpc}$) event, but, given the uncertainties in the expected rate of binary NS coalescence in the local Universe[12], the uncertainties in the numerical modeling of the postmerger signal and the science possible with the detection and accurate measurement of the dominant postmerger oscillation frequency ($\delta f \sim 10\,\mathrm{Hz}$), this constitutes an important high-frequency source for the next generation GW observatories.

The current LIGO detectors will approach the thermodynamic and quantum mechanical limits of their designs within a few years. Over the next several years, aLIGO will undergo a modest upgrade, designated "A+". The aim of this upgrade is chiefly to lower the quantum (shot) noise through the use of squeezed light, and also to reduce somewhat the thermal noise from the mirror coatings. This upgrade has the goal of enhancing the sensitivity by ~50%[13].

Voyager[14] represents a more substantial upgrade that will increase the range by a factor of $4 - 5$ over aLIGO, and the event rate by approximately 100 times, to roughly one detection per hour. Such a dramatic change in the sensitivity should increase the detection rate of binary neutron star mergers to about 10 per day and the rate of binary black hole mergers to around 30 per day. This upgraded instrument would be able to detect binary black holes out to a redshift of 8.

The path to Voyager requires reducing several noise sources, including:

1. quantum radiation pressure and shot noise,
2. mirror thermal noise,
3. mirror suspension thermal noise,
4. Newtonian gravity noise

All of these noise sources are addressed by the Voyager design, with the goal of commissioning and observational runs within a decade. The most significant design changes can be traced to the need to reduce the quantum noise in tandem with the mirror thermal noise.

- Quantum noise will be reduced by increasing the optical power stored in the interferometers. In Advanced LIGO, the stored power is limited by thermally induced wavefront distortion effects in the fused silica test masses. These effects will be alleviated by choosing a test mass material with a high thermal conductivity, such as silicon.
- The test mass temperature will be lowered to 123 K, to mitigate thermo-elastic noise. This species of thermal noise is especially problematic in test masses that are good thermal conductors. Fortunately, in silicon at 123 K, the thermal expansion coefficient crosses zero, which eliminates thermo-elastic noise. (Other plausible material candidates, such as sapphire, require cooling to near 20 K to be free of this noise.)
- The thermal noise of the mirror coating will be reduced by switching to low dissipation amorphous silicon based coatings, and by reducing the temperature.

Put together this cryogenic interferometer design exploits the full physical limits of the existing LIGO facilities, and will enable a qualitatively brighter vision of the dark side of the universe.

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