Promise and progress of millihertz gravitational-wave astronomy

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Abstract

Extending the new field of gravitational wave (GW) astronomy into the millihertz band with a space-based GW observatory is a high-priority objective of international astronomy community. This paper summarizes the astrophysical promise and the technological groundwork for such an observatory, concretely focusing on the prospects for the proposed Laser Interferometer Space Antenna (LISA) mission concept.

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1 Introduction

Just over a century ago Einstein first described our current theory of gravity, general relativity, and quickly recognized that his theory might imply the existence of gravitational waves. It wasn't until decades later that scientists began to realize that observing GWs could be a practical possibility and may provide especially detailed information about strong-gravity systems inaccessible to electromagnetic astronomy.

Last year the Laser Interferometric Gravitational wave Observatory (LIGO) opened this new field of GW astronomy by announcing the first direct GW observations, simultaneously providing direct observations of a binary black hole systems and revealing a number of relatively large stellar black holes. This should be just the beginning of many years of exciting astronomical observations in the roughly 10-1000 Hz band.

An important upcoming step for the nascent field of GW astronomy is extending the GW window into the promising millihertz band, from roughly 0.01 to 1000 mHz, via a space-based observatory. These observations should expose a great and distinct wealth of astronomical information.

2 Gravitational waves: a new probe of the universe

Gravitational dynamics are described in general relativity by Einstein's equations, which relate the spacetime curvature tensor to the stress energy tensor describing forces, motion and distribution of matter. Energy and momentum conservation prevents monopole and dipole variation so GWs can only be generated by the time variation of quadropole or higher moments. Where the motion of objects is small compared to the speed of light, GW emissions are tiny, typically scaling with $(v/c)^5$.

Spacetime geometry is mathematically encoded in the metric tensor field $\mathbf{g}$, which may be treated by linear perturbations for the propagation of GWs far from sources. In this limit with suitable (gauge) choice of coordinates $\mathbf{x} = \{t, x, y, z\}$, metric perturbations are governed by a simple linear wave equation, a solution for waves propagating in the z direction can be written as

$$\mathbf{g} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 + h_+(\mathbf{x}) & h_\times(\mathbf{x}) & 0 \\ 0 & h_\times(\mathbf{x}) & 1 - h_+(\mathbf{x}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (1)$$

Here $h_{+,\times}(\mathbf{x})$ are the two GW polarization modes. A great distance r from a the source, the solution is can be written $h_{+,\times}(\mathbf{x}) = \hat{h}_{+,\times}(t - z)/r$, where the functions $\hat{h}_{+,\times}(t_{\rm ret})$ encode infomation about the source and its motion.

The special features of GWs as a new messenger of astronomical information include:

- **Clean strong-gravity sources.** Where GWs are measurable, gravity often dominates other forces. Assuming we understand gravity, the simple parameters describing the emission physics may be inferred from observation with unusual precision. To achieve the required velocities, significant GWs can only be emitted by the highest density astronomical objects such as black holes, neutron stars, and white dwarfs.

- **Clean propagation.** Because of their weak coupling to matter, the universe should be mainly transparent to GWs, this enables observation of otherwise obscure sources.

- **Coherent emission and detection.** Unlike light, GW wavelenghts are larger than the size of the source yielding a monolithic coherent signal with an amplitude falling off as $1/r$. The signals must also measured by amplitude, not power, with the same scaling. This makes it relatively easy to observe signals from great cosmological scale distances by GWs.

3 Millihertz GW astronomy

At a given mass, GW emissions are strongest and most likely to be detectable higher frequencies (higher v/c). Then they carry vast energies away from their sources, implying a short lifetime that scales with mass. There is an exact time scaling of GW signals with overall source mass. LIGO band GW astronomy is limited to the rare and short-lived last moments of stellar scale systems ranging up to a few hunderd solar masses. The millihertz band provides a sweet spot between rare events with the strongest gravity and more numerous slightly weaker-gravity systems.

Opening the millihertz band [1], exposes the giant signals from mergers of massive black holes up to from $\sim 10^4$ to $\sim 10^8$ solar masses. The signals are so loud that we are likely limited by rate not signal strength even for distant events occurring at the earliest likely cosmological times. These observations will show how these massive black holes at galactic centers form and merge over the epoch of galactic formation and assembly into the large galaxies we see today. Over several years we might expect hundreds of these events.

At the other extreme, millihertz GW observations should also reveal a much larger population of nearby lower velocity binaries. These would include the LIGO binaries, years before merger, as well as somewhat lower density sources including white dwarf binaries in the Milkyway. Such an observatory might individually pick out more than 10,000 of these objects, while a millions more would aggregate into a stochastic foreground signal.

Another expected class of millihertz sources bridges these regimes involving stellar scale objects falling into massive black holes in the relatively recent history of the universe. These events can reveal presently obscurred details about stellar remnant populations in the deep hearts of galaxies while also providing precision information about the the spacetime geometry near massive black holes.

4 The LISA concept

Astrophysically plausible GWs yield extremely small relative motion ($\lesssim 10^{-21}$ fractional displacement) in free-falling objects. Observing them requires overcoming two main technical challenges: 1) isolating the objects from any other forces which may cause motion at this level, and 2) measuring the motion. Terrestrial motion seems to preclude surmounting the former of these challenges on the ground. Fortunately they are each facilitated by a space-based instrument where large empty space is easy to come by and ambient forces are much quieter.

The LISA concept includes three spacecraft each following internally isolated free-floating test masses on elliptical solar orbits forming nearly rigid triangle a few million kilometers across. Changes in separation between the testmasses is measured by laser interferometry.

The international science community has honed this concept though many years of science studies and technology development, with a key acheivement being the successful demonstration, last year, of key novel technologies in space by the European Space Agency's LISA Pathfinder mission. Building on this success, ESA, with NASA as a junior partner, now plans to launch a millihertz-band gravitational-wave observatory in the early 2030s.

References

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