Astrophysical Sources of Low-Frequency Gravitational Waves

Marek Biesiada[1]

1. Department of Astrophysics and Cosmology, Institute of Physics University of Silesia, 75 Pułku Piechoty 1, 41–500 Chorzów, Poland

The first successful detection of gravitational waves (GWs) by ground-based interferometer LIGO announced in 2016, has opened up a new window on the Universe allowing to register catastrophic events involving big masses and strong space-time curvatures. This detection gave also a new boost to the idea of building a space-borne detector (LISA) – sensitive to much lower frequencies (1 mHz – 1 Hz) than ground-based detectors could ever be. Pulsar timing arrays (PTA) are currently searching of GWs at even lower frequencies (1 nHz – 0.01 mHz). In this contribution, I review astrophysical sources of GWs which we expect to register with LISA and PTA.

1 Introduction

Gravitational waves (GWs) are the transverse waves of spatial strain, generated by time variations of the mass quadrupole moment of the source and traveling at the speed of light. Their existence has been predicted by Albert Einstein in 1916 soon after he formulated the General Relativity (Einstein, 1916). The first solid, although indirect, observational evidence for the existence of gravitational waves was provided after discovery of the binary pulsar (NS-NS system) PSR 1913+16 by Hulse & Taylor (1975) and its subsequent follow-up by Taylor & Weisberg (1982). However, an ultimate dream of detecting GWs in the laboratory remained elusive for the long time, being incredibly demanding from the technological point of view. Eventually this dream came true with the announcement of the first direct detection of gravitational waves (GW150914) by the advanced LIGO detector (Abbott et al., 2016b). This great achievement definitely proved that technological barriers have been overcome and consequently it was followed by another detections (Abbott et al., 2016a, 2017a,b,c; The LIGO Scientific Collaboration et al., 2017). Signals came from coalescing black hole binary systems in all cases, besides GW170817 which was the first NS-NS coalescence ever detected and accompanied by successfully identified electromagnetic (EM) counterpart. This way a new window on the Universe has been opened, and with the GW170817 detection – multimessenger astronomy acquired a new dimension.[1]

2 Gravitational waves - properties and spectrum

To begin with, it is good to compare GWs with EM waves which are basic carriers of information about Universe.

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[1] Detection of the GW170817 signal from NS-NS coalescence was announced a few weeks after this talk was delivered.

- EM waves are oscillations of electric and magnetic fields that propagate through spacetime. GWs are oscillations of spacetime itself.
- EM radiation typically arises from the incoherent superposition of waves produced by many emitters (atoms, electrons in plasma etc.). This radiation directly probes the thermodynamic state of a system or an environment. GWs are coherent superpositions arising from the bulk dynamics of huge masses. These waves directly probe the dynamical state of a system.
- EM waves interact strongly with matter - they can be easily scattered or absorbed in the medium. GWs do not interact strongly with matter, hence they travel from the source undisturbed. This is a consequence of the relative strength of the electromagnetic and gravitational interactions. The weak interaction strength of GWs is both good and bad. Good - because GWs make possible to probe events inaccessible to telescopes like merger of black holes or collapse of a stellar core. Bad - because it makes their detection very demanding, necessitating a great deal of effort.
- The direct observable in EM domain is the energy flux, which falls of with the distance as $1/r^2$. For gravitational radiation, the direct observable is the waveform h, a quantity that falls off with distance as $1/r$. This implies that with GWs we can look farther into the Universe more easily than with EM waves.
- EM radiation typically has a wavelength smaller than the size of the emitting system, and so can be used to form an image of the source. By contrast, the wavelength of gravitational radiation is typically comparable to or larger than the size of the radiating source. GWs cannot be used to form an image of the source.
- In most cases, EM astronomy is based on deep imaging of small fields of view. On the contrary, gravitational-wave detectors have nearly $4\pi\,\mathrm{sr}$ sensitivity to events over the sky. In consequence, their ability to localize a source is poor, but it means that any source on the sky will be detectable, not just sources towards which the detector is pointed.
- EM spectrum comprises frequencies $f \sim 10^7$ Hz, and 20 orders of magnitude upward. Gravitational wave spectrum extends from $f \sim 10^4$ Hz, and 20 orders of magnitude downward.

It is useful to categorize gravitational-wave sources (and the methods for detecting their waves) by the frequency band in which they radiate. Broadly speaking, we may break the gravitational-wave spectrum into following bands (the method of detection is indicated along each frequency band):

- extremely low frequency (ELF), $10^{-18} < f \leq 10^{-14}$ Hz; polarization of cosmic microwave background (CMB),
- ultra low frequency band (ULF), $10^{-14} < f \leq 3 \times 10^{-9}$ Hz; quasar astrometry,
- very low frequency band (VLF), $10^{-9} < f \leq 10^{-7}$ Hz; pulsar timing arrays (PTA),

- low frequency band (LF), $10^{-7} < f \leq 1$ Hz; space-borne detectors LISA,
- middle frequency band (MF), $0.1 < f \leq 10$ Hz; space-borne detectors as Deci-Hertz Interferometer Gravitational Wave Observatory (DECIGO), and Big Bang Observer (BBO),
- high frequency band (HF), $10 < f \leq 10^5$ Hz; ground-based interferometric detectors AdLIGO/Virgo, KAGRA, Einstein Telescope (will be sensitive down to 1 Hz).

HF band – the one whose exploration just started – requires long-baseline GWs-interferometry to achieve strain sensitivity of at least $h \sim 10^{-21}$ necessary to detect astrophysical GWs sources. The basic mode of operation is that of the Michelson interferometer, where laser light injected into the interferometer is split into two beams propagating along orthogonal arms, and then reflects off end test-mass optics and recombines at the beam-splitter to interfere at a photodiode. The detectors are locked on a dark fringe in order to improve resolution. The influence of an impinging GW is by stretching and compressing the proper-length of the arms, inducing a phase-shift in the recombined laser beams. Sensitivity of interferometric detector is limited at high frequencies by the photon shot-noise. Limitation at the lowest frequencies comes from seismic waves on the surface of the Earth. It can be minimised by monitoring seismic activity to subtract its signals, or moving the detector underground, but below 1 Hz there is no other choice except to place the detector in space.

The detection at LF band necessitates space-based laser interferometers. The canonical design for a mission in this band is the Laser Interferometer Space Antenna (LISA). This mission calls for an arrangement of three identical satellites in a 5 Mkm arm-length triangular configuration, trailing the Earth's orbit by 20°, and forming 2 optical links along each arm.

In VLF band band pulsars are used to detect GWs. Extraordinary timing stability of their pulsed emission enables them to act as standard clocks in space with which to infer the perturbing influence of passing nHz GWs. This idea has led to the establishment of three major PTA consortia. The first, known as Parkes Pulsar Timing Array (PPTA)[2] was created in Australia. Second – the North American Nanohertz Observatory for Gravitational waves (NANOGrav)[3] – a collaboration between the National Radio Astronomy Observatories (NRAO) and several US universities, using the Arecibo and Green Bank telescopes to perform multi-frequency observations. The third is the European Pulsar Timing Array (EPTA)[4] – a collaboration of European institutions, using the radiotelescopes at Jodrell Bank, Effelsberg, Westerbork, Nancy and Sardinia. These individual PTAs are separate entities with different strategies and techniques, but are ultimately bound together in the International Pulsar Timing Array (IPTA)[5].

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[2] http://www.atnf.csiro.au/research/

[3] http://nanograv.org/

[4] http: //www.epta.eu.org/

[5] http: //www.ipta4gw.org/

3 Sources of GWs - general remarks

Astrophysical example of time-varying quadrupole mass is a binary star with orbital period $P_{\rm orb}$. It is easy to calculate that the frequency of emitted GWs is $f_{\rm GW} = 2 f_{\rm orb}$. More compact binary emits stronger GWs. By GWs emission the system looses not only energy (circularizing the orbit[6]) but also its angular momentum (shrinking the orbit) until final coalescence. Let's make an intuitive assessment. For this purpose let M denote total mass of the system and R – the radius of an orbit. By the Kepler's third law: $f_{\rm orb} = \frac{1}{2\pi}\sqrt{\frac{GM}{R}}$. Since the Schwarzschild radius of a mass M, is $R = 2GM/c^2$, we get the bound on frequency of emitted GWs[7]: $f_{\rm GW} < \frac{1}{2\sqrt{2}\pi}\frac{c^3}{GM} \approx 10^4 \ {\rm Hz} \left(\frac{{\rm M}_\odot}{M}\right)$. Therefore, in the HF band accessible to ground-based detectors one would be able to see coalescences of systems as massive as $1000\,{\rm M}_\odot$ at most[8]. There is no way to see the coalescence of supermassive black holes (SMBH) with $M \sim 10^6 - 10^9 \ {\rm M}_\odot$ which reside in the centers of galaxies. Such events would be observed at frequencies $f_{\rm GW} \sim 10$ mHz – 10 μHz, i.e. in LF band.

4 Sources in LF band

4.1 Inspiralling SMBHs

Coalescing supermassive binary black hole systems will be measurable by LISA to extremely large distances. Even if such events are very rare, the observed volume is enormous, hence a considerable detection rate seems quite likely. One class of such binaries consists of systems in which the BHs are of roughly equal masses. These binaries can form following the mergers of galaxies (or pregalactic structures) containing a black hole in their cores.

It is now well established that SMBHs are copious in the nuclei of nearby galaxies Ferrarese & Ford (2005), with observational relationships indicating a strong coupling between the evolution of the BH and the galactic host. The last decade has seen them identified as keystones in theoretical models of hierarchical galaxy formation, where massive galaxies form through continued accretion from cosmic web filaments and through galactic mergers. As such, the massive BHs we observe in active or nearby galaxies are the natural by product of initial proto-galaxies (with BH seeds) undergoing hierarchical clustering throughout cosmic time. The formation of massive BH binaries naturally follows the galactic mergers. After a galactic merger, the individual black holes spiral by dynamical friction into the core of the common merger remnant, eventually residing at the center of a stellar bulge. After the binary gets tighter via environmental couplings it enters the GW inspiral regime, where orbital evolution is dominated by the emission of GWs. Depending on the mass of the binary, GWs from these coalescences will be detectable to fairly large redshifts ($z \sim 5 - 10$), possibly probing an early epoch of the structure formation in the Universe.

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[6] In GWs community's jargon circular orbit is called Keplerian.

[7] This argument might be made a bit more rigorous invoking orbital frequency at the innermost stable circular orbit (ISCO) in Schwarzschild metric, which has unambiguous meaning for extreme mass ratio inspirals (EMRIs). Anyway, order of magnitude assessment is the same.

[8] This value corresponds to the so called intermediate mass black hole (IMBH) supposed to exist in the centers of globular clusters.

4.2 EMRIs

The most exciting LF sources are the Extreme Mass-Ratio Inspirals (EMRIs), where stellar mass compact remnants gradually spiral-in towards a much larger BH, and in so doing map out the geometry of the SMBH spacetime. This class consists of relatively small bodies (black holes with mass $\sim$ 10 $\mathrm{M}_{\odot}$, neutron stars, or white dwarfs) that are captured by larger black holes ($M \sim 10^5 - 10^7$ $\mathrm{M}_{\odot}$) which reside at the cores of many galaxies, including the Milky Way. Such systems are measurable to a distance of a few Gpc if the inspiraling body is a 10 $\mathrm{M}_{\odot}$ BH, and to a distance of a few hundred Mpc if the body is a NS or a white dwarf. LISA will measure the GWs that come from the last year or so of the smaller body's inspiral, probing the nature of the SMBH's gravitational field.

4.3 Periodic sources

LF periodic sources accessible to LISA come primarily from binary star systems in the Milky Way. These systems do not generate waves strong enough to back-react significantly on the system, so that their frequencies typically change very little or not at all over the course of LISA observations. Certain systems are well-known in advance to be sources of periodic waves for the LISA band (e.g. AN CVn, WZ Sge cataclysmic variables). These sources are understood well enough that they may be regarded as *calibrators.* Besides the known sources, it is expected that LISA will discover several thousands of binary systems that are too faint to detect with telescopes. Joint observations by LISA and other astronomical instruments are likely to be quite fruitful, helping to understand these systems much better than can be done with a single instrument alone. For example, it is typically difficult for telescopes to determine the inclination of a binary to the line of sight (a factor needed to help pin down the mass of the binary's members). GWs measure the inclination angle almost automatically, since this angle determines the relative magnitude of the GW polarizations h_{+} and $h_{\times}$. The remaining several million Galactic unresolved binaries will create a stochastic GWs foreground signal.

4.4 Stochastic sources

Ground-based detectors can measure a stochastic background by correlating the data streams of widely separated detectors. On the other hand, LISA can take advantage of a different trick: by combining its six data streams in an appropriate way, it can construct an observable that is completely insensitive to GWs, measuring noise only. This makes it possible to distinguish between a noise-like stochastic background and true instrumental noise, and thereby to learn about the characteristics of the background. Besides unresolved point sources, particularly interesting source of backgrounds is the dynamics of the early Universe. It is supposed to produce an all-sky gravitational-wave background, similar to the cosmic microwave background. Backgrounds can arise from amplification of primordial fluctuations in the universe's geometry, phase transitions as previously unified interactions separated, or the condensation of a brane from a higher dimensional space. These waves can actually spread over a wide range of frequency bands; waves from inflation in particular span all bands, from ultra low frequency to high frequency. The payoff from their detection would be tremendous – providing insight into the very beginning of the Universe, complementary to what we might ultimately learn from imprints in the CMB polarization patterns.

5 Concluding remarks.

We are very lucky that we lived this moment when an era of GWs astronomy commenced. In my talk I was merely able to touch a small portion of promises that the future will bring. Interested reader is encouraged to consult much extensive reviews e.g. Sathyaprakash & Schutz (2009).

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