Gravitational waves with the SKA

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Abstract

Through its sensitivity, sky and frequency coverage, the SKA will be able to detect gravitational waves – ripples in the fabric of spacetime – in the very low frequency band ($10^{-9} - 10^{-7}$ Hz). The SKA will find and monitor multiple millisecond pulsars to identify and characterize sources of gravitational radiation. About 50 years after the discovery of pulsars marked the beginning of a new era in fundamental physics, pulsars observed with the SKA have the potential to transform our understanding of gravitational physics and provide important clues about the early history of the Universe. In particular, the gravitational waves detected by the SKA will allow us to learn about galaxy formation and the origin and growth history of the most massive black holes in the Universe. At the same time, by analyzing the properties of the gravitational waves detected by the SKA we should be able to challenge the theory of General Relativity and constraint alternative theories of gravity, as well as to probe energies beyond the realm of the standard model of particle physics.

1 Introduction

Einstein's theory of General Relativity (GR) predicted the existence of gravitational radiation. Gravitational Waves (GWs) are ripples in the curvature of spacetime produced by accelerating masses such as black hole collisions or supernova explosions. These spacetime waves reach the Earth fairly unperturbed, thus carrying valuable information about the astrophysical sources that produce them. Their direct detection, beyond providing yet another confirmation of the predictions of GR, will stir up a new revolution in the way we observe the Universe, comparable to those resulting from radioastronomy or other windows of observation of the electromagnetic spectrum. So far, there exists compelling evidence of the existence of GWs through the timing measurements of relativistic binary pulsars [1, 2].

At present, multimessenger astronomy is becoming a reality, thanks to the wealth of information we are gaining from the Universe through complementary cosmic messengers such as photons, neutrinos, and cosmic rays. Within such an exciting context, Gravitational Wave Astronomy has an enormous potential to provide fundamental contributions [3]. The GW *window*, as a result of the weakness of the gravitational interaction, is not affected in cosmological terms by the electromagnetic decoupling limit, thus allowing the access to information from the very early Universe, in a range of energies highly superior to that currently achievable through other approaches. In astrophysical terms, this window can provide new and complementary information about compact binary systems (formed by white dwarfs and/or neutron stars and/or black holes) from which information is already available through their electromagnetic emission, either directly or from their environment (i.e. accretion disks or other distributions of matter/energy around such compact objects). In the case of gravitational radiation we can anticipate a significant impact on topics of research at the forefront of physics, such as galaxy formation history and the physics of very compact objects, aside from unexpected surprises difficult to foresee. In any event there is an enormous potential as gravitational radiation will allow us to probe regions very close to black hole horizons (where the gravitational potential is strongest) and speeds very close to the speed of light which, in turn, will allow us to carry out definitive tests about the structure of black holes and even about the validity of GR and/or alternative theories of gravity.

2 Gravitational wave detection and the role of the SKA

After pioneering efforts with resonant bar detectors, present-day research to detect gravitational radiation is based on laser-interferometric detectors. Among the various current instruments two deserve special mention, the Virgo detector [4] (originally a French-Italian collaboration joined by Poland, Hungary, and the Netherlands), a 3 km long laser interferometer, and the Laser Interferometer GW Observatory (LIGO) [5] in the USA, which comprises two observatories in Hanford, WA and Livingston, LA with 4 km long arms. The formidable accuracy necessary to unmistakably detect GWs results in an unprecedented technological challenge on issues as diverse as laser stability, the suspension system of the test masses, the design of the lenses and mirrors, the seismic isolation, etc. The advanced LIGO detectors will start operating as early as mid 2015. They will be followed by advanced Virgo and the Kamioka Gravitational Wave Detector (KAGRA) [6], formerly the Large Scale Cryogenic Gravitational Wave Telescope (LCGT). KAGRA is a Japanese GW laser interferometer that will be located underground in the Kamioka mine and will use cryogenic technology for the first time. Furthermore, there are plans to place one of the LIGO detectors in India, which will greatly enhance the capabilities of sky localization of the GW sources once all of the detectors operate as a single network. The panorama of ground-based detectors should also include a mention to the proposed Einstein Telescope, a third-generation GW detector in Europe, whose design study has already been undertaken by the European Commission [7]. The main astrophysical and cosmological sources for such ground-based detectors are compact binary coalescences and mergers, supernova core collapse, lumpy spinning stars, and stochastic cosmological backgrounds of diverse origin. The observations will provide key information to understand the formation and evolution of stellar-mass compact objects, the composition and equation of state of neutron stars, etc.

Current ground-based detectors operate in the high-frequency band (from 10 Hz to a few kHz) and are strongly limited in the low frequency band. The gravity gradient (Newtonian) noise turns impossible for them to operate below 1 Hz. Since below 1 Hz there are many different interesting sources of gravitational radiation, plans to build a GW observatory in space were naturally put forward during the last decades. In 2013, the European Space Agency (ESA) selected the science theme proposed by the eLISA Consortium in the white paper *The Gravitational Universe* [8] for its future large-class mission L3. The L3 mission will carry out a scientific program based on low-frequency Gravitational Wave Astronomy. The mission concept proposed in the white paper is eLISA, an all-sky monitor formed by a constellation of three spacecrafts in heliocentric orbits, each spacecraft separated from one another by a 1 million km baseline. Their relative positions will be monitored using high-precision laser interferometry (at the picometer level) using concepts and technology completely different to those of ground-based GW detectors. Since the core of these technologies can not be tested on ground, ESA developed a technology-demonstrator mission for a future GW space-based observatory, called LISA Pathfinder [9]. LISA Pathfinder is at the final stages of integration and tests and its launch is planned for September 2015. A space-based GW observatory like eLISA will be observing in the low-frequency band of the GW spectrum (from 0.01 mHz to 1 Hz), a band inaccessible to ground-based detectors, and will detect GWs from ultracompact stellar binary systems in our galaxy (which includes the so-called *verification binaries*, guaranteed known GW sources), collisions of (super)massive black hole binaries (within the mass range $10^{4-7}\,M_{\odot}$), capture of stellar-mass compact objects by (super)massive black holes in the centres of quiescent galaxies, and cosmological GW backgrounds of diverse physical origin.

In parallel to the design of GW detectors based on laser interferometry, there exists two completely different methodologies to detect (directly or indirectly) gravitational radiation. The first one is the search for B-modes originated by GWs of primordial origin in the Cosmic Microwave Background (CMB). These GWs are in the ultralow frequency range ($10^{-18} - 10^{-13}$ Hz) and they are the target of ground-based detectors like BICEP2 and space-based detectors like the ESA Planck mission (see [10, 11] for details). The second type of methodology, the one of interest for the SKA, is based on the use of an array of radiotelescopes for the accurate timing of a set of millisecond pulsars with known periods, a technique known as Pulsar Timing Arrays (PTAs) [12]. In this approach, when a GW passes across the region between the pulsars and the Earth it will perturb the local spacetime geometry producing minuscule but measurable changes on the times of arrival (ToAs) of the pulses (the effect being proportional to the amplitude of the characteristic strain of the GW [13]). Figure 1 illustrates this physical process. The differences between the predicted and measured ToAs are the so-called "timing residuals". Part of the residuals (irregular pulsar rotation, variability in the interstellar medium, etc.) are typically different between pulsars, while residuals due to GWs have a particularly simple functional form that only depends on the pulsar-Earth-gravitational wave angle [14]. PTA projects aim at extracting common signals present within the timing residuals for multiple pulsars in order to detect GWs and other correlated signals (e.g. fluctuations in atomic time standards or unmodelled effects in the Solar system ephemeris). With the appropriate technology (allowing timing precisions $< 100\,\mathrm{ns}$), a large enough number of pulsars (> 20) and a sufficiently long observational timing (about 10 years), the presence of GWs in the very low frequency range ($10^{-9} - 10^{-7}\,\mathrm{Hz}$) could be detected. It should be noted that a limit in the precision of the pulsar timing may exist due to various effects such as pulse jitter on short time scales (i.e. the intrinsic variability in the shape of individual pulses from a given pulsar), intrinsic pulsar timing noise on longer time scales (see [16] for an analysis of timing irregularities for 366 pulsars) and effects from the interstellar medium such as scattering [17].

Currently there exist three PTA consortia carrying out such kind of observations, one in Australia (the Parkes Pulsar Timing Array, PPTA [18]), one in Europe (the European Pulsar Timing Array, EPTA [19]) and one in the USA (the North American Nanohertz Observatory for GWs, NANOGrav [20]). All three Consortia have well established pulsar timing programmes on at least 20 millisecond pulsars with time baselines of 10 years or more [14]. Since 2008, the three PTAs have joined efforts in an international collaboration called the International Pulsar Timing Array (IPTA [21]). The sensitivity of the instruments has gradually improved through advances on instrumentation, software, and observing cadence and data span, to render increasingly accessible the PTA frequency range where suitable sources of gravitational radiation are expected to exist. We note that PTAs reach peak sensitivities at frequencies of $10^{-9} - 10^{-7}\,\mathrm{Hz}$ [14], therefore representing a unique complementary approach to that followed by GW observatories based on laser interferometry, either ground-based or in space. In Figure 2 we plot the sensitivity curves of the main GW projects that we have mentioned. As we can see, the SKA constitutes a significant improvement with respect to current PTA projects. We can also see in this figure the complementarity of PTAs, space-based GW observatories, and ground-based GW detectors, not only in frequency but also in the type of GW sources. Since the intersection of GW sources among all projects is essentially empty, the associated science to be extracted from each class of experiments is also quite different and complementary.

Likewise, owing to the frequency range where radiotelescopes are most sensitive, PTAs will be able to detect a unique class of GW sources out of reach for laser interferometers. The most likely source expected in their frequency band is the stochastic background of GWs produced by the superposition of a large amount of GWs from coalescing supermassive black hole binaries (with masses above $10^8 M_\odot$) in the far Universe at redshift $z \sim 1$ [22, 23]. In addition, cosmic strings [24] and inflation [25] are also prime candidates. To put bounds on these GW backgrounds it is assumed that their spectrum follows a power law defined by a characteristic (dimensionless) amplitude h_c and a spectral index α ($-2/3$ for supermassive black hole binaries without environmental interactions, $-7/6$ for high emission modes from cosmic string cusps, and -1 for slow-roll inflation). The most stringent limit on h_c, from PPTA data [26], is 2.4×10^{-15} at a reference frequency of yr^{-1}. With the current bounds

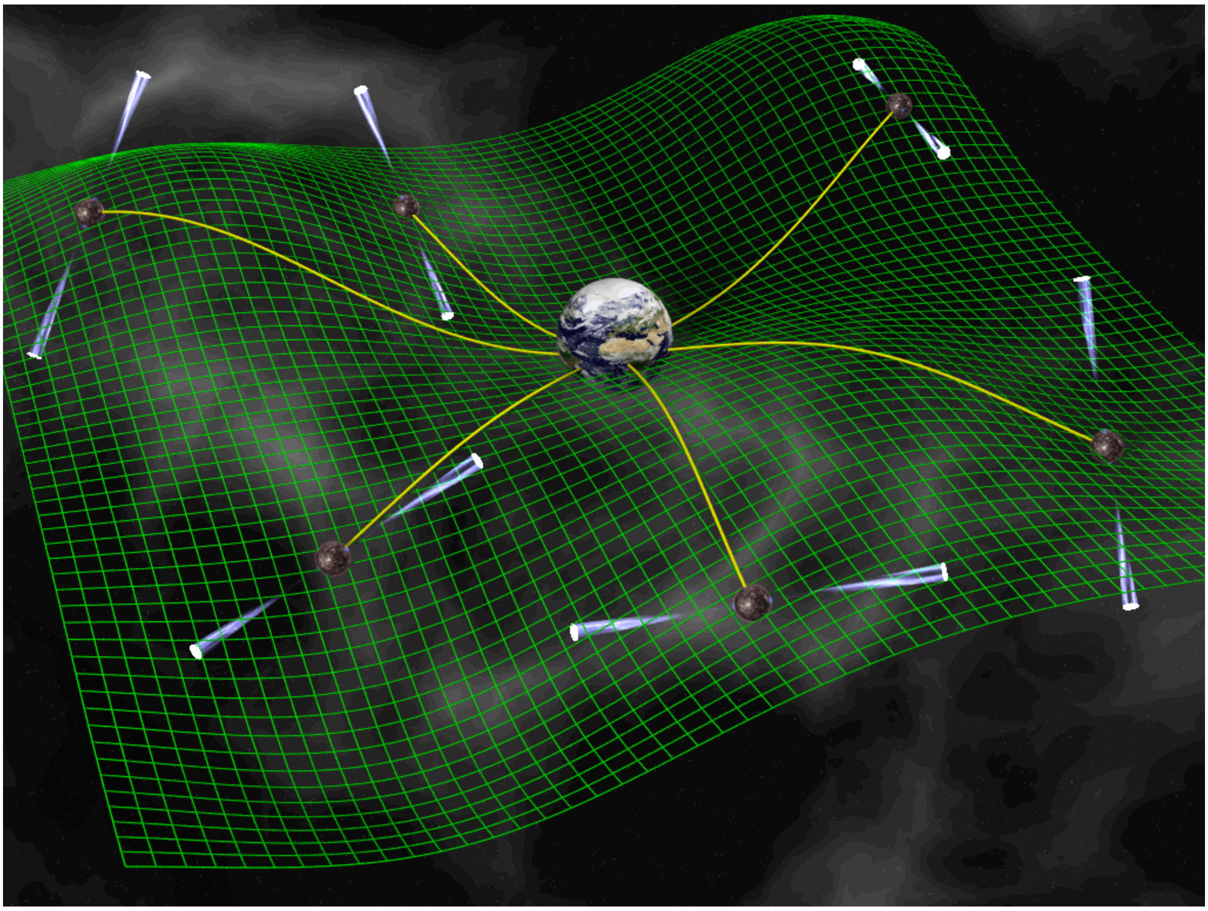

Figure 1: Artistic representation of the effect that GWs passing through our galaxy will produce in the arrival times of the pulses emitted by pulsars and received by radiotelescopes on Earth. Credit: Max Planck Institute for Radio Astronomy (D. Champion).

from PTA data, some extreme models for the coalescence rate of supermassive black holes as well as for the tension and loop size of cosmic strings have already been ruled out [14]. PTAs can also be used to search for individual supermassive black holes that produce continuous GWs, as the timing experiments are sensitive to sources emitting GWs with periods from a few weeks to around the total duration of the data set [14]. Finally, it has been argued that the merger of two supermassive black holes may produce permanent deformations in their surrounding spacetime that can be detectable as a memory event in the form of a "glitch" in the timing residuals [27, 28].

The SKA will no doubt constitute a major improvement of the ongoing efforts of the current PTAs. It is estimated that the SKA, as described in the baseline design document [29], will have a 50% probability of detecting a GW source after only five years of operation. However, as [14] note, this is a conservative estimate since the probability calculation does not

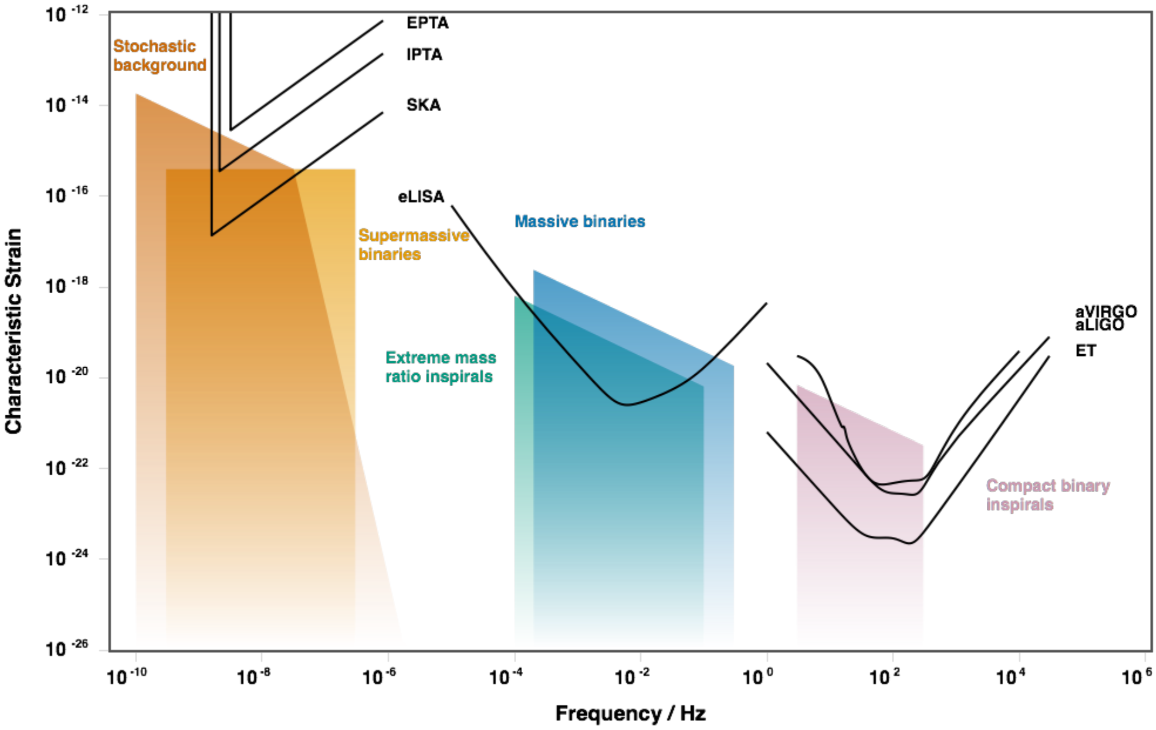

Figure 2: Sensitivity curves of PTA projects (EPTA, IPTA, and SKA), a space-based GW mission concept (eLISA), and ground-based GW detectors (LIGO and Virgo). These GW observatories represent the three more promising frequency bands: The very-low frequency band (PTAs), the low-frequency band (space-based detectors), and the high-frequency band (ground-based detectors). These sensitivity curves have been generated using the online tool described in [15].

include the pre-existing IPTA data sets. While the full IPTA reaches a nominal upper bound in the characteristic GW amplitude of $h_c \sim 4 \times 10^{-15}$ at 5×10^{-9} Hz, the SKA is expected to reach levels of $h_c \sim 10^{-16} - 10^{-17}$ at a reference frequency of yr^{-1} [14]. Although current PTA experiments may succeed in detecting GWs by the time the SKA1 is commissioned, it is the SKA2 that will make Gravitational Wave Astronomy at nHz frequencies a reality. It is expected that the SKA will detect many more millisecond pulsars than is currently possible (or that are currently usable due to the different limiting noise processes mentioned before), and will allow to time them to very high precision ($< 100\,\mathrm{ns}$) every 10-20 days, making them very sensitive to the small space-time perturbations of GWs. Even if a red noise signal had already been identified by the existing PTAs, the SKA data sets could be used in conjunction with the longer PTA data sets to improve the sensitivity to GWs [30]. In the best case scenario where a GW detection had already taken place, the increased sensitivity of the SKA data sets could not only provide an independent confirmation of the detection but could also confirm the nature of the signal by distinguishing between the different spectral indices for the various sources. Finally, we briefly comment that information from Very Long Baseline Interferometry (VLBI) can significantly benefit GW searches by providing independent measurements of parameters that can be held fixed in the pulsar timing model [14].

3 Conclusion

To conclude, it is very likely that the SKA1 or the existing IPTA will make the first direct detections of GWs and also the first characterizations of the GW sources. With the upgraded version of the SKA1 (the SKA2) detailed properties of the GWs and their sources will be able to be studied opening the door for revolutionary discoveries in astrophysics, cosmology and fundamental physics. The most expected discoveries/scientific outcomes include: *Study of galaxy evolution.* The characterization of the properties of a GW background from coalescing supermassive black holes will provide constraints on models for galaxy evolution and black hole formation and growth. *Study of GWs from cosmological origin.* As we have already mentioned, cosmic strings could generate a GW background with different properties as compared to a GW generated by supermassive black hole binaries, in particular it will have a different spectral index. By identifying the GW background of cosmic strings we can have access to the physics at the energies of Grand Unification Theories or even beyond in the case such GW background would have been produced by cosmic superstrings. *Testing the theory of gravity.* The detection of GWs by PTA projects can provide information about the polarization states of GWs (two in GR but up to 6 in alternative theories of gravity) as well as constraints on the Compton wavelength of the GWs (or to the mass of the graviton) which affects the propagation of the different components of the GWs. Information of these two aspects of GWs will allow the study of the radiative sector of gravitation and/or help constraining alternative theories of gravity.

From the point of view of the Spanish scientific community, the GW science that the SKA has the potential to produce is of interest for existing groups working not only in GW astronomy but also in the astrophysics of supermassive black holes, cosmology, and fundamental physics of the Early Universe. The involvement of Spanish GW groups in the analysis of the data of the SKA is also possible and will benefit those groups by enlarging their expertise in GW data analysis.

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