Gravitational Waves From Ultra Short Period Exoplanets

J. V. Cunha,1⋆ F. E. Silva,1† J. A. S. Lima2‡

1Escola de Ciências e Tecnologia, UFRN, 59078-970, RN, Brazil
2Departamento de Astronomia, Universidade de São Paulo, 05508-900 SP, Brazil

ABSTRACT

In the last two decades, thousands of extrasolar planets were discovered based on different observational techniques, and their number must increase substantially in virtue of the ongoing and near-future approved missions and facilities. It is shown that interesting signatures of binary systems from nearby exoplanets and their parent stars can also be obtained measuring the pattern of gravitational waves that will be made available by the new generation of detectors including the space-based LISA (Laser Interferometer Space Antenna) observatory. As an example, a subset of exoplanets with extremely short periods (less than 80 min) is discussed. All of them have gravitational luminosity, \( L_{GW} \sim 10^{30} \, \text{erg/s} \), strain \( h \sim 10^{-22} \), frequencies \( f_{gw} > 10^{-4} \, \text{Hz} \), and, as such, are within the standard sensitivity curve of LISA. Our analysis suggests that the emitted gravitational wave pattern may also provide an efficient tool to discover ultra short period exoplanets.

Key words: gravitational waves - instrumentation: detectors - stars: planetary systems

1 INTRODUCTION

Recently, the LIGO and Virgo collaborations have directly detected gravitational waves (GWs) from merging pairs of black holes and neutron stars thereby opening a new observational window to astrophysics and cosmology (Abott et al. 2016a, 2016b, 2017). This successful centenary prediction of general relativity is now pressing for world-wide observational efforts involving the next generation of space-based and ground-based detectors of GWs, planned to “listen” unprobed frequency bands from a large variety of sources.

The recent detection of GWs is the result of a long process. Implicitly, it also suggests that the existence of numerous sources with different characteristic frequencies is quite probable. Currently, we are just starting the exciting work of studying and characterizing the basic properties of GWs and their potential sources regardless of its cosmic abundance or even whether they are nearby or very far from the solar system.

It is also usually believed that the main observable candidates to GW observations are ultracompact binary black hole and neutron star systems, rotating black holes and supernovas, that is, very massive and extremely compact systems because these violent systems or events can generate gravitational waves intense enough to be detected even at very great distances (Maggiore 2008). However, since these sources are rather exotic it seems interesting to investigate the potentialities of nearby and less extreme sources. In principle, the small distance from nearest sources may compensate their relatively low intensity thereby providing important targets for a continued observation.

In this concern, an increasing number of exoplanetary systems were observed in the last few years, some of them composed by super Jupiters with orbits very near to their parent stars. Such galactic system have recurrently been reported and are much closer to the solar system than known pulsars and binaries of black holes or neutron stars (the only identified sources up to now).

Beyond the expected emission from the orbital motion, usually treated in the quadrupole approximation, the gravitational wave intensity from exoplanets can also be amplified from gravitational interaction, as for instance, through the resonant excitation of oscillating modes from central stars (Kajima 1987; Berti & Ferrari 2001).

On the other hand, the already observed population of exoplanets can be extrapolated to obtain the abundance of such objects in the Galaxy and even in all the Universe. Recent estimates are claiming the existence of at least one planet per star thereby leading to nearly two hundred billions of exoplanets in the Milky Way (Cassan et al. 2012). Some authors have also predicted the collective contribution of exoplanets appearing as a stochastic GW background (SGWB) from the Milky Way and also from the whole Universe, a result relevant to space-based instruments like LISA.

© 2017 The Authors
In principle, such an approach may provide near future an interesting window to probe the cosmic abundance of such objects (Ain, Kastha & Mitra 2015). Here, instead to analyze the collective emission forming the SGWB, a different strategy it will be adopted.

Basically, we are interested on a special class of exoplanetary systems already identified in the very recent literature. This happens because these Galactic GW sources are very near to us and orbiting their parent star with ultra short periods, say, of the order of one hour or less. Further, there is also a growing interest of the community with several large international consortia pointing to an increasing rate of known systems. Thus, it is reasonable to expect that a part of them must have ultra short periods.

The gravitational luminosity of such systems can be even greater than their electromagnetic counterpart, an aspect that may have a strong influence on the so-called habitable planetary zone. Thus, since they are not far away, we believe that such systems are excellent candidates for a new class of targets whose pattern of GWs are not only different from the ones presented by extreme events (like the ringdown of binary black holes) but also have the advantage that the emitted GWs can be continuously detected.

In this Letter we show that exoplanetary systems are also interesting sources of gravitational waves for the next generation of detectors. For a subset of extra solar planets orbiting their parent stars with extremely short periods, we calculate the local GW luminosity, the strain and the conditions for detecting the emitted pattern of gravitational waves. As we shall see, they are within the standard sensitivity curve of LISA and other planned instruments. Reciprocally, we also argue that the GW astronomy may provide a complementary window to identify extrasolar planets, a new procedure that may be even more efficient than the available methods (like the transit time) based on optical instruments and techniques.

2 BASIC EQUATIONS

The gravitational quadrupole emission from two orbiting celestial massive bodies like an extrasolar system formed by a star and a given planet can be precisely calculated (Peters & Mathews 1963; Maggiore 2008). If the system have masses $m_1$ and $m_2$ moving in Keplerian orbits around the center of mass with an effective semi-major axis $a$ and eccentricity $e$, the total average gravitational emission over one period of the elliptical motion reads:

$$L_{GW} = \frac{32}{5} \frac{G^2 m_1^2 m_2^2}{c^5} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4\right),$$

(1)

which is the same equation used to calculate the gravitational luminosity emitted from ultracompact binary systems (Maggiore 2008; Postnov & Yungelson 2014). For a source of absolute luminosity $L_{GW}$, the flux or apparent luminosity ($\ell$) received on Earth is $\ell = L_{GW}/4\pi a^2$.

It is also widely known that the emitted radiation in the eccentric case is no longer monochromatic. In general, the absolute GW luminosity in the $n^\text{th}$ harmonic, at a frequency $f = n\omega_a/\pi$, is given by

$$L_{GW}^{(n)} = \frac{32}{5} \frac{G^2 m_1^2 m_2^2 (m_1 + m_2)}{c^5} \frac{1}{a^5} B(n, e),$$

(2)

where,

$$B(n, e) = \frac{n^4}{32} \left( J_{n-2}(ne) - 2e J_{n-1}(ne) + \frac{2}{n} J_n(ne) + 2e J_{n+1}(ne) - J_{n+2}(ne) \right)^2 + (1 - e^2) \times [J_{n-2}(ne) - 2e J_{n-1}(ne) + J_{n+2}(ne)]^2 + \frac{4}{3n^2} [J_n(ne)]^2,$$

(3)

where $J_n$ denotes the Bessel function of first kind. The above equations imply that the average radiated power is a rapidly rising function of the eccentricity (Peters & Mathews 1963). It is also worth noticing that whether a binary system has a non-zero eccentricity and the emission of GWs is strong, its motion rapidly degenerate into a circular orbit. This happens because the average value $< de/dt >$ is negative in virtue of the radiation reaction.

In what follows, we are interested only in exoplanetary systems with very short periods which potentially may produce reasonably intense GW emission. So, let us approximate (1) by taking $e = 0$ to calculate the GW emission. In practice, this means that we have a lower bound on the absolute GW luminosity. In this case, the frequency of the emitted GW, $f_{GW} = \frac{\dot{\nu}}{2\pi} = \frac{1}{4} \sqrt{\frac{\mu m_1 m_2}{a^3}}$, is twice the orbital frequency. Another important quantity when studying gravitational waves is the strain, the perturbation in the spacetime metric. To obtain it, we let consider two point masses $m_1$ and $m_2$, but due to our approximation we consider again only circular orbits. In the quadrupole approximation (Landau & Lifshitz 1985), the GW amplitudes are fully determined by the so-called “chirp mass” of the binary system, $M_\bullet = \mu^{3/5} m_1^{2/5}$, where $\mu = m_1 m_2/(m_1 + m_2)$ is the reduced mass and $m = m_1 + m_2$ is the total mass.

After averaging over the orbital characteristic periods, the standard expression for the GW amplitude is readily obtained (Roelofs et al. 2006; Postnov & Yungelson 2014):

$$h = \left(\frac{32}{5}\right)^{1/2} \frac{G^{5/3} M_\bullet^{5/3}}{c^4} \frac{\pi m}{d} \left(\frac{\pi f_{GW}}{\nu}\right)^{3/2} \sqrt{\cos^2 i + 6\cos^2 i + 1},$$

(4)

where $i$ is the inclination of the binary system, the angle between the line of sight to the binary orbit. Usually, the inclination effect is small but always increases the strain.

Other key quantity when studying GW from binary systems is the period deviation or, more specifically, the cumulative period variation. By considering $e = 0$, such an expression is easily obtained:

$$\dot{\nu} = -\frac{96}{5} \frac{G^{5/3} \mu m^{2/3}}{c^3} \left(\frac{\mu}{\nu}\right)^{8/3},$$

(5)

where the cumulative shift of periastron time expression is

$$\Delta \text{Periastron} = \frac{\dot{\nu}}{\nu} (\Delta t)^2,$$

(6)

where $\Delta t$ is the time of periastron passage (Maggiore 2008).

Given these well known results, let us now consider a specific sample of short period exoplanetary systems which can be seen as promising targets for a direct GW detection.

3 EXOPLANETARY (SHORT PERIOD) DATA

Surely, in comparison with black holes and neutron star binaries, one may expect that exoplanetary systems are rel-
Gravitational Waves From Ultra Short Period Exoplanets

4 DISCUSSION

It is widely known that Hulse and Taylor indirectly measured GWs from the binary radio pulsar PSR 1913+16 and tested the predictions of general relativity based on its cumulative deviation of the periastron. We argue here that the same can also be done for a subset of exoplanets, starting by the three short period systems listed in Table 2.

In Figure 1a we display the calculated GW luminosity as a function of the frequency for the 14 binary systems (redpoints) appearing in Table 1. For comparison we have also shown (see black dot) the Hulse-Taylor pulsar.

To see how the distance is crucial, we recall that the binary Hulse-Taylor (H-T) pulsar emits $\sim 7.5 \times 10^{31} \text{ergs}^{-1}$ it is at 8.4 kpc and has cumulative period shift of the periastron of 45 seconds in 33 years (Weisberg, Nice & Taylor 2010). The three proposed targets have emission $\sim 10^{30} \text{ergs}^{-1}$ and distances of the order 75–226 pc while their cumulative period deviation fall between 5–20 seconds (see Table 2 and Figure 1b). In general, the ratio between the apparent GW luminosities of exoplanet systems (Es) and other binary systems [e.g., pulsar systems (Ps)] arriving at the Earth surface reads:

$$\frac{\ell_{Es}}{\ell_{Ps}} = \frac{\ell_{Es}}{\ell_{Ps}} \left( \frac{d_{Ps}}{d_{Es}} \right)^2.$$  \hspace{1cm} (7)

| Table 1. | Orbital quantities of 14 confirmed short period exoplanetary systems. The data were taken from http://exoplanet.eu/catalog. Due to their short period, the emitted gravitational power can be measured by the next generation of detectors (see next section). |
|----------|-------------------------------------------------|
| Planet   | $M_p/M_J$ | $a/10^5 \text{km}$ | $P(\text{days})$ | $i/rad$ |
| GP Com b | 0.26      | 0.35            | 0.032             | 0.028     | 75       |
| V396 Hya b | 0.18      | 0.345           | 0.045             | 0.264     | 77       |
| J1433 b | 0.57      | 0.18            | 0.054             | 3.97      | 226      |
| PSR J1807-2459b | 0.94    | 0.18            | 0.070             | 5.58      | 2790     |
| PSR 1719-14b | 1       | 0.900           | 0.090             | 6.58      | 1200     |
| PSR J2051-0527b | 28.3    | 1.4             | 0.099             | 7.05      | 1280     |
| PSR J2241-3236b | 12      | 1.35            | 0.145             | 8.96      | 500      |
| Kepler-70 b | 0.014    | 0.496           | 0.240             | 8.95      | 1180     |
| Kepler-70 c | 0.002    | 0.496           | 0.342             | 11.3      | 1180     |
| Kepler-78 b | 0.005    | 0.81            | 0.355             | 13.7      | 1264     |
| PSR B1957+20b | 22      | 1.4             | 0.380             | 17.3      | 1530     |
| EPIC 20163715b | 1.4     | 0.6             | 0.381             | 13.0      | 225      |
| CVS0 30 b | 6.2       | 0.39            | 0.448             | 12.6      | 330      |
| Kepler-42 c | 0.006    | 0.13            | 0.453             | 8.75      | 38.7     |

| Table 2. | Calculated gravitational wave parameters of 3 exoplanetary systems of extremely short periods which are within the standard LISA sensitivity curve (see next section). The luminosity, $L_{GW}$, is given in erg s$^{-1}$ and $P/P$ in s$^{-1}$. In the last column we see the value of the inclination needed to obtain the strain $h$ according to equation (4). |
|----------|-------------------------------------------------|
| Planet   | $L_{GW}(10^{30})$ | $h(10^{-22})$ | $\ell_{GW}(10^{17})$ | $i/rad$ |
| GP Com b | 1.45      | 0.98            | $-3.44$             | 0.97      |
| V396 Hya b | 0.17      | 0.98            | $-0.83$             | 0.91      |
| J1433 b | 2.69      | 0.89            | $-2.78$             | 1.47      |
Table 1. The LISA sensitivity curve was obtained using the predicted curves for the exoplanets with the binary radio H-T pulsar. By comparing with the three predicted curves for the exoplanets listed in Table 2. For comparison we show the standard result for the H-T pulsar (solid black curve).

Now, let us finish this section drawing attention to some interesting physical effects of gravitational waves from exoplanetary systems of ultra short period to different areas:

- The planetary habitable zone is, primarily, the distance to the parent star where liquid water may exist. Thus, exoplanetary systems whose GW luminosity is of the same order or greater than the electromagnetic luminosity from the central star (see the specific example in Section 3) may change significantly the planetary habitable zones as long as there is a mechanism converting gravitational radiation into heat. Corrections of the order of \( \left( \frac{L_{GW}}{L_{EM}} \right)^{1/2} \) where \( L_{EM} \) is the electromagnetic luminosity, are expected. This could be the first direct connection involving general relativistic effects, habitable zone and the possibility of formation and maintenance of life. The physical consequences of GW for circumstellar habitable zones deserves a closer scrutiny and will be detailed investigated in a forthcoming communication.

- To date many multiple exoplanetary systems were already discovered (see, for instance, Luger et al. 2017). The presence of any inner short period planet will change not only the local habitable zone but also creates new interesting possibilities. The remaining planets behave like gravitational antennas by absorbing and transforming in heat part of the incident GWs energy. This is interesting because the energy changes in planets are well modeled, especially Earth-like planets whose electromagnetic environmental interaction has been discussed for decades (Coughlin & Harms 2014; Lopes & Silk 2015; Mulargia 2017). Any observed anomalous thermal behavior may impose constraints on the cross section and also in the interaction between matter and the incident gravitational waves. In principle, this kind of observation could be used to test new aspects of general relativity and other gravity theories.

- Detection of exoplanets by optical techniques is a time-consuming task. For transiting time, for instance, this happens because not all planet’s orbit as seen from the Earth have the precise geometry to eclipse, and, as such, the prob-
ability to obtain the right narrow range of inclinations is very low (the transit probability to the Earth viewed outside from Solar System is less than 1%). Actually, precise transit time measurements require nearly edge-on planetary orbits observable only by a special class of observers. Apart measurements with enough precision, time sampling and spectroscopic follow-up observations, the low probability also explains why a great number of stars must be searched before expecting to find a transiting planet. However, this is not the case for a direct detection through gravitational waves. For ultra short period systems like the ones appearing in Table 2, the detection of gravitational waves may provide an interesting tool for discovering new exoplanets, in principle, even more efficient than the available optical methods.

All these connections reinforce the idea that nearby short period exoplanetary systems provide a key class of GW emitters which may be relevant both from a methodological and a physical viewpoint. Potentially, as argued here, such systems are capable to open new avenues of investigation.

5 CONCLUSIONS

Based on some already observed sources we have shown that a subset of ultra short period exoplanetary systems are suitable targets to direct detection of gravitational waves for the next generation (space-based) instruments (see Table 2 and Figure 2). In principle, as shown in (Figure 1b), even indirect observations of gravitational waves through the cumulative time variation of the periastron for this sort of extrasolar planets should be considered an interesting possibility.

The examples discussed here suggest the existence of a subset of nearby exoplanetary systems composed by relatively massive bodies endowed with small orbital period thereby making the GW emission (and the associated strain) strong enough to be detected from Earth. Although less intensive than extreme binary systems, the gravitational wave emission of ultra short period exoplanets are interesting targets for the next generation of planned instruments.

Some interesting observational consequences are: (i) the gravitational wave emission must change the electromagnetic habitable zone around multi-exoplanetary systems; (ii) limits on the absorption cross section of the gravitational wave interacting with matter can be constrained by the outer planets working like gravitational antennas absorbing and decreasing the original signal, and (iii) the emitted gravitational wave pattern may provide an efficient tool to discover new ultra short period exoplanets. Hopefully, studies in this field may bring valuable results to different areas including astrobiology, physics and astrophysics.

ACKNOWLEDGEMENTS

The authors thank L. A. Almeida, J. D. Nascimento and C. E. Pellicer, for helpful discussions. JASL is grateful to CAPES (PROCAD project, 2013), FAPESP (LLAMA Project) and fellowship from CNPq. The basic ideas of this paper were discussed during the 3rd Workshop on Cosmology and Gravitation: Celebrating the 100 years of Cosmology (1917–2017) in Natal-RN, Brazil.

REFERENCES

Abbott B. P. et al. (LIGO Scientific Collaboration and Virgo Collaboration), 2016a, Phys. Rev. Lett., 116, 061102
Abbott B. P. et al. (LIGO Scientific Collaboration and Virgo Collaboration), 2016b, Phys. Rev. Lett., 116, 241103
Abbott B. P. et al. (LIGO Scientific Collaboration and Virgo Collaboration), 2017, Phys. Rev. Lett., 118, 221101
Ain A., Kastha S., Mitra S., 2015, Phys. Rev. D, 91, 124023
Antoniadis J. et al., 2013, Science, 340, 448
Berti E., Ferrari V., 2001, Phys. Rev. D, 63, 064031
Cassan A. et al., 2012, Nature, 481, 167
Coughlin M., Harms J., 2014, Phys. Rev. Lett., 112, 101102
Gair J. R. et al., 2013, Living Rev. Relativ., 16, 109
Kajima Y. 1987, Prog. Theor. Phys., 77, 297
Hernández Santisteban J. V. et al., 2016, Nature, 533, 366
Landau L. D., Lifshitz E. M., 1985, The Classical Theory of Fields, Elsevier, Oxford
Larson S. L. et al., 2000, Phys. Rev. D, 62, 062001
Lopes L., Silk J., 2015, ApJ, 807, 135
Luger R. et al., 2017, Nature Astron., 1, 0129
Maggiore M., 2008, Gravitational Waves Vol. 1: Theory and Experiments, Oxford, New York
Mullargia F., 2017, MNRAS Lett., 464, L11
Petitjean A. et al., 2008, Phys. Rev. D, 77, 023002; see also http://www.srl.caltech.edu/~shane/sensitivity/
Postnov K. A., Yungelson L. R., 2014, Living Rev. Relativ., 17, 166
Prince T. A. et al., 2002, Phys. Rev. D, 66, 122002
Roelofs G. H. A. et al., 2006, MNRAS, 371, 1231
Showman A. P., 2016, Nature, 533, 330
Taylor J. H., Weisberg J. M., 1989, ApJ, 345, 434
Weisberg J. M., Nice D. J., Taylor J. H., 2010, ApJ, 722, 1030

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.