Reply to Comment on “Gravitational Waves from ultra-short period exoplanets”

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ABSTRACT

Wong et al. (2018) recently performed an encouraging criticism to our paper “Gravitational waves from ultra-short period exoplanets” (Cunha, Silva & Lima 2018) exploring the potentialities of a subset of exoplanets with extremely short periods (less than 80 min) as a possible scientific target to the planned space-based LISA observatory. Here we call attention to some subtleties and limitations underlying the basic criticism which in our view were not properly stressed in their comment. Particularly, simple estimates show that a sphere encircling the Earth with a radius of 250 pc may accommodate a population $\sim 10^4$ ultra-short period exoplanets with characteristic strain of the same order or higher than the ones analyzed in our paper. This means that the question related to the gravitational wave pattern of ultra-short period exoplanets may be surpassed near future by the LISA instrument with new and more definitive data.

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

In a recent article (Cunha, Silva & Lima 2018), we have advocated that the quadrupolar emission of gravitational waves (GWs) from binary systems formed by nearby exoplanets of ultra-short period and their parent stars could be detected near future by the Laser Interferometer Space Antenna (LISA) observatory. Such a conjecture was supported by the existence of three ultra-short period exoplanets, actually, the shortest subset known to date, namely: GP Com b, V396 Hya b and J1433 b whose periods are nearly 46, 65 and 78 minutes, respectively.

Nevertheless, Wong et al. (2018) correctly pointed out that our conclusions were derived based on the original “classical” LISA sensitivity curve ignoring “galactic noise confusion” (Larson et al. 2000). Further, by adopting the latest updated curve (Cornish & Robson 2018), they concluded that our analysis suggesting the possible detectability of such objects through GWs was, at best, inconclusive. One exception was open to the exoplanet GP Com b whose detection, based on the current LISA curve, was roughly estimated to be possible only after nearly 8 years mission.

The basic reasons outlined by the authors for explaining the different conclusions of both analyses were the following:

(i) the existence of a stochastic GW background ($SGWB$) from binary systems, the so-called “galactic noise confusion” ($GNC$), potentially degrading the ability of LISA for detecting this kind of sources, and (ii) the low integration time (one year) associated to a signal-to-noise ratio ($SNR$) below the threshold which for nearly monochromatic sources like binary systems is usually taken to be $SNR \geq 5$ (see their Table I).

To begin with, let us observe that the present estimates of the $GNC$ from binary systems suffers from several drawbacks related to astrophysical uncertainties, such as the star formation rate and the form of its initial mass function and the same is valid for ultra-short period exoplanets. Actually, in the absence of a detectable sign there are also uncertainties about how the confusion limit is clearly defined from an observational viewpoint. More important perhaps, the galactic confusion is not stationary. It diminishes rapidly in the course of time, as long as the mission progresses and more foreground sources can surely be removed (Cornish 2004). Hence, any estimate of the $SGWB$ at present should at best be considered as an educated guess because the abundance of binary galactic GW emitters is indeed unknown. We are not claiming here that the $GNC$ should be disregarded in the ongoing and future analyses. However, we fully agree that the question related to the $SNR$ and the related observation time is the most serious difficulty to be overcome.

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Table 1. Gravitational wave parameters of three exoplanetary systems of extremely short periods as discussed by Cunha, Silva & Lima (2018) and Wong et al. (2018). In the last line we see the corresponding values for a hypothetical member (exoplanet X b) of the ultra-short period exoplanetary population (see text).

| Planet    | $m_1$ ($M_J$) | $m_2$ ($M_J$) | $P$ (min) | $a$ (au) | $D_L$ (pc) | $f_{GW}$ ($10^{-4} Hz$) | $h_c$ ($10^{-20}$) | SNR (2 yr) | SNR (4 yr) |
|-----------|---------------|---------------|-----------|---------|-----------|----------------------|------------------|-----------|-----------|
| GP Com b  | 0.435         | 26.2          | 46.6      | 0.0015  | 75        | 7.2                  | 3.44             | 2.12      | 3.47      |
| V396 Hya b| 0.345         | 18.3          | 65.1      | 0.0017  | 77        | 5.1                  | 1.35             | 0.60      | 0.91      |
| J1433 b   | 0.8           | 57.1          | 78.1      | 0.0027  | 226       | 4.3                  | 2.03             | 0.75      | 1.11      |
| X b       | 0.5           | 40.0          | 30.0      | 0.0012  | 50        | 11.1                 | 14.2             | 12.50     | 25.95     |

Now, let us discuss the SNR for ultra-short period exoplanets and its possible detection by LISA. In our viewpoint the challenging question is to justify (beyond reasonable doubt) whether ultra-short period exoplanets are interesting scientific targets for LISA.

In Table 1 we present a short list of systems containing ultra-short period exoplanets including their masses and orbital parameters, planet period (P), major semi axis (a) distance to the Earth ($D_L$), GW frequency ($f_{GW}$), the calculated characteristic strain $h_c$ and the associated SNR for 2 and 4 years of observation time.

The first three lines in Table I stand for the super Jupiters already observed and discussed in the paper and comment. Apart the SNR of J1433 b for 2 years in the comment, our results in the last two columns agree with the ones presented by Wong et al. (2018). Note also the presence of a hypothetical exoplanet X b (fourth line), assumed to be a regular super Jupiter because its orbital parameters suggest that it is not a special or extreme object. It is easy to show that such a possible candidate of the class has SNR = 12.50 and SNR = 25.95 for observation times of 2 and 4 years, respectively. All the SNR results were averaged over sky/polarization and inclination. Naturally, less massive planets than X b with shorter periods and distances are not forbidden, and different SNR would be obtained for reasonable choices of the basic parameters. In particular, like verification and other galactic binaries (Cornish & Robinson 2018), such possibilities reinforce the idea that a cloud of ultra-short period exoplanets may occupy the left upper corner of the current sensitivity LISA curve around a frequency of $10^{-3} Hz$ (see Figure 1 and discussion next).

In principle, objects with similar parameters would play a special role as a scientific target for LISA. Therefore, at this point it is natural to ask about their abundance. In other words: Is there a class of such objects at the Earth neighborhood? In our view this is very probable and the basic reasons are justified below.

The average density of stars in the solar neighborhood is about 0.14 stars pc$^{-3}$. Hence, within a spherical shell encircling the Earth with a radius of 250 pc (nearly 25 pc higher than the distance to the farthest ultra-short period exoplanet known, J1433 b in Table 1), one may expect at least the existence of 10$^7$ stars. Note that the distance also need to be small in order to present a reasonable characteristic strain. On the other hand, at present, nearly 3000 stars with exoplanets from which only three of them own ultra-short period exoplanets already identified. Such a result can be translated to a naive but conservative estimate of nearly 10$^4$ objects of this class up to 250 pc (we are neglecting the remaining 11 candidates from Table I in Cunha, Lima & Silva 2018).

In Figure 1, we display the classical (red line) and current (black line) LISA sensitivity curves where the latter already includes the GCN. Basically, they are the same curves presented by Wong et al. (2018) but now including the hypothetical X b exoplanet with SNR = 12.50 for two years observation time (see also Table I).

In light of the above considerations, it is very tempting to conjecture the existence of a class of super Jupiters filling the left upper corner of the space parameter as indicated by the grey ellipsoidal region in Figure 1. The possible existence of this class was explicitly suggested in our work. As it appears, this class is only partially contaminated by the GCN, and, as such, a large portion of it is potentially detectable by LISA. This central point underlying our work in our view was not properly stressed in previous papers.

Summarizing, after nearly 5,000 thousand planets already identified, someone may consider that the golden age of hunting planets through optical methods (transiting time, radial velocity, etc.) is coming to an end. However, the above numbers suggest that such a frontier may be replaced by an equally challenging hunting process now based on grav-
itational waves searching for nearby ultra-short period exoplanets. Finally, we also stress that the present discussion involving galactic noise and the possible detection of ultra-short period exoplanets through LISA observatory may be surpassed by new and definitive data in the near future.

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