Geophysical Journal International

Geophys. J. Int. (2019) **216,** 515–520
Advance Access publication 2018 October 11
GJI Seismology

doi: 10.1093/gji/ggy420

EXPRESS LETTER

Unexplained spectral peaks in Earth tremor

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Accepted 2018 October 10. Received 2018 October 8; in original form 2018 July 25

SUMMARY

Independent multi-year analyses of Earth tremor have suggested a continuous excitation of Earth normal modes by ocean storms, but also a number of unexplained spectral peaks extraneous to them, mostly in the 0.2–2 mHz frequency band. We reassess the worldwide existence of such peaks by stacking the multitaper high-resolution spectra of all stations of the International Geodynamics and Earth Tide Service superconducting gravimeter network with at least 30 months of uninterrupted record, analysing a global epoch of 656 months. The analysis, beyond showing the predominance of ${}_0S_n$, $n = 0, .., 12$ Earth spheroidal modes, confirms the existence of unexplained spectral peaks which (1) cannot be ascribed to instrumental noise, (2) occur at frequencies extraneous to Earth normal modes, (3) have a statistical significance comparable to them and (4) appear incompatible with any natural or anthropic terrestrial source. While at odds with the hypothetical Earth 'tune in' on a continuum detectable gravitational wavefield, the peaks appear to be compatible in terms of amplitude, frequency and—according to cosmological constraints—expected number, with the independently calculated gravitational wave monochromatic emission of a few binary systems consisting of a star with mass ∼1/10 of the sun captured in close orbit by the supermassive black hole at the centre of our galaxy.

Key words: Tides and planetary waves; Fourier analysis; Surface waves and free oscillations; Seismic noise.

1 INTRODUCTION

Seismic *hum*, that is, the low-frequency continuous background tremor of the Earth apparent in seismic and gravimetric records, can be mostly explained by the ocean excitation of the Earth normal modes (Webb 2008). However, when analysed through multitaper high-resolution spectral methods, it also shows a number of spectral peaks in the sub-millihertz and millihertz band that cannot be ascribed to any known tremor source (Nawa *et al.* 1998; Tanimoto *et al.* 1998; Thomson & Vernon 2015). The existence and possible origin of such spectral peaks is reassessed by analysing two decades of recordings of the International Geodynamics and Earth Tide Service (IGETS) superconducting gravimeter network and focusing on frequencies below 2 mHz, where most of them occur.

2 DATA AND ANALYSIS

The IGETS, operated by GFZ-Potsdam, collects and archives gravimetric records from a worldwide network of superconducting gravimeters, making data web available at https://isdc.gfz-potsdam.de/igets-data-base/. The IGETS data were analysed here under the following constraints: (1) all stations for which Level 2 data were available, that is, corrected for gravity and pressure according to a same protocol (Voigt *et al.* 2016); (2) all stations with at least 30 months of uninterrupted data, in order to guarantee a Rayleigh resolution of at least 10^{-7} Hz, and (3) no further restriction aimed at selecting 'quiet' periods, in order to preserve data integrity.

The spectra of the records of Apache Point, Boulder, Lhasa and Lijiang stations appeared faulty—possibly due to instrument malfunction—and were not considered. Under the above rules it was possible to analyse the data sets reported in Table 1 and Fig. 1, for a total of 13 stations and 656 months.

Establishing the statistical significance of an *a priori* unknown number of spectral peaks is a difficult problem. Spectral analysis was performed here by multitaper techniques, the only ones capable of adequate resolution and stability (Thomson & Haley 2014). In fact, the Slepian representation of tapers in a series of orthonormal functions is the only one to solve objectively the problems of inconsistency, bias and resolution that affect periodograms. Under adequate prewhitening and standardization, the distribution of multitaper spectral peaks is χ^2 with 2α degrees of freedom, where $\alpha \lesssim K \lesssim 2NW = 2C_R$, with K the number of tapers, N the number of data and W the bandwidth. However, several practical difficulties arise in establishing the significance of spectral peaks under general conditions. In order to identify spectral peaks and evaluate their significance, we proceeded as follows: for each data set we calculated the multitaper power spectrum in the 0.2–2 mHz band with $C_R = 4$,

Table 1. The gravimetric stations, the periods and their duration (in decreasing order) that could be analysed under the above rules.

Station	Period	Months
Wuhan	2000 Jan 1–2006 Dec 31	84
Medicina	1998 Jan 1–2003 Dec 31	72
Sutherland	2001 Jan 1–2006 Dec 31	72
Membach	2000 Jan 1–2004 Dec 31	60
Pecny	2007 May 1–2011 Oct 31	54
Wien	1998 Jan 1–2001 Dec 31	48
Cantley	2000 Jan 1–2003 Dec 31	48
Syowa	1997 Jul 1–2000 Dec 31	42
Matsushiro	2000 Jul 1–2003 Aug 31	38
Metsahovi	2008 Jan 1–2010 Dec 31	36
Strasbourg	2000 Jan 1–2002 Dec 31	36
Wettzell	2008 Jan 1–2010 Sep 30	33
Bad Homburgh	2004 Jan 1–2006 Sep 30	33

$K = 7$ and a 10^{-7} Hz step, that is, for 18 000 spectral ordinates. We then standardized the spectrum in Thomson sense (ibid.) through: (1) pre-whitening by normalization to an AR Yule–Walker spectrum (Y–W of order 4 was found adequate); (2) segmenting the multi-tapered spectrum into frequency segments of equal length (lengths from 100 to 240 μHz were explored, finding marginal differences) centred at frequency f_j ; (3) standardizing each segment to unit mean and variance; (4) shifting the central frequency f_j of each segment by one frequency unit to the right, and repeating the previous step to cover the whole 0.2–2 mHz interval with segments totally overlapping except for the first and last points in order to guarantee a smooth standardized spectrum; (5) stacking over all stations to enhance sensitivity on common signals (Ding & Chao 2015); (6) estimating significance with Thomson jackknife approach (Thomson 2007); that is, with variance approximated by $(K-1)^3(K-3)/[(K-1/2)K(K-2)^3]$; (7) considering only stacked spectral peaks with significance comparable to that of peaks unquestionably related to Earth normal modes.

3 SPECTRAL PEAKS

The stacked spectrum (Fig. 2) shows several peaks statistically significant above the 0.99999 confidence level. Some of these are immediately identified as related to Earth normal modes since they occur precisely at their independently measured frequencies. Starting with the most significant peaks, these appear at:

(1) 0.8417 mHz, in correspondence of the Earth ‘breathing’ mode ${}_0S_0$.

(2) 1.724 mHz, in correspondence of mode ${}_0S_{10}$.

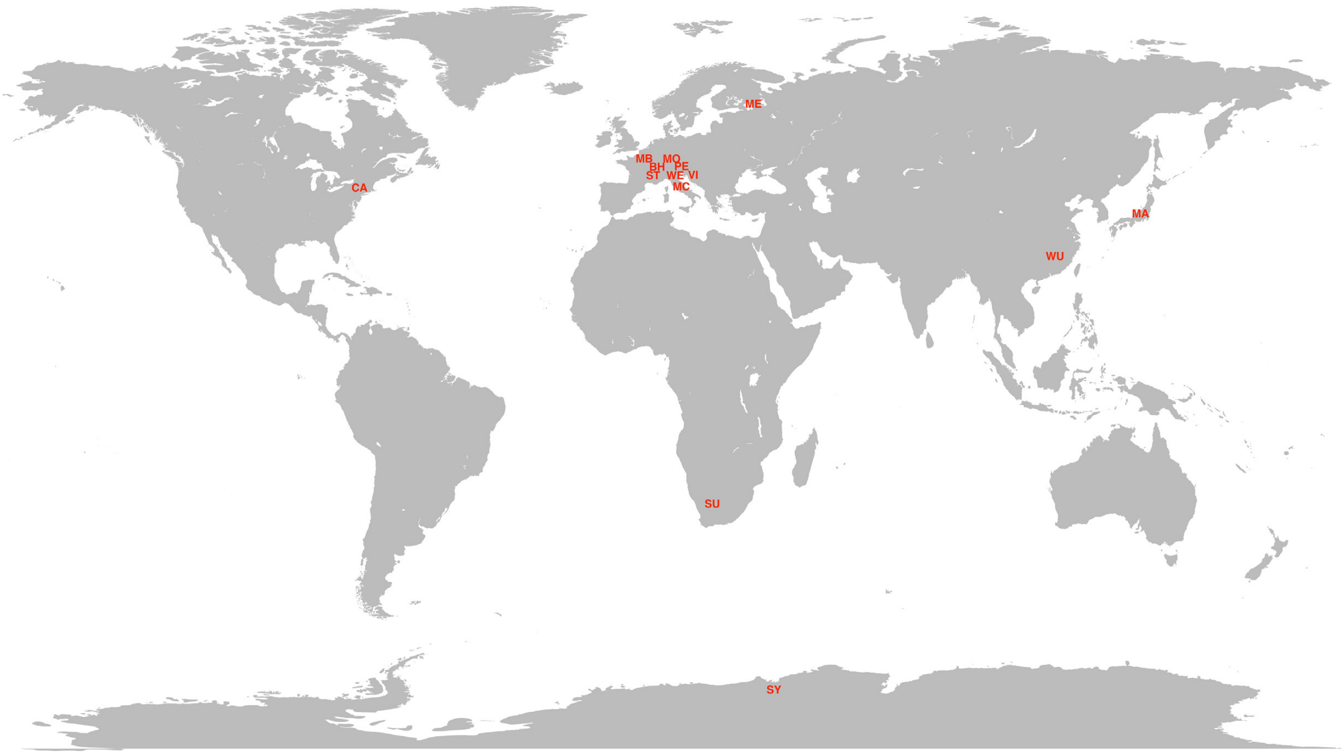


Figure 1. The geographic location of the gravimetric stations analysed: BH, Bad Homburgh; CA, Cantley; MA, Matsushiro; MB, Membach; MC, Medicina; ME, Metsahovi; PE, Pecny; ST, Strasbourg; SU, Sutherland; SY, Syowa; VI, Wien; WE, Wettzell; WU, Wuhan.

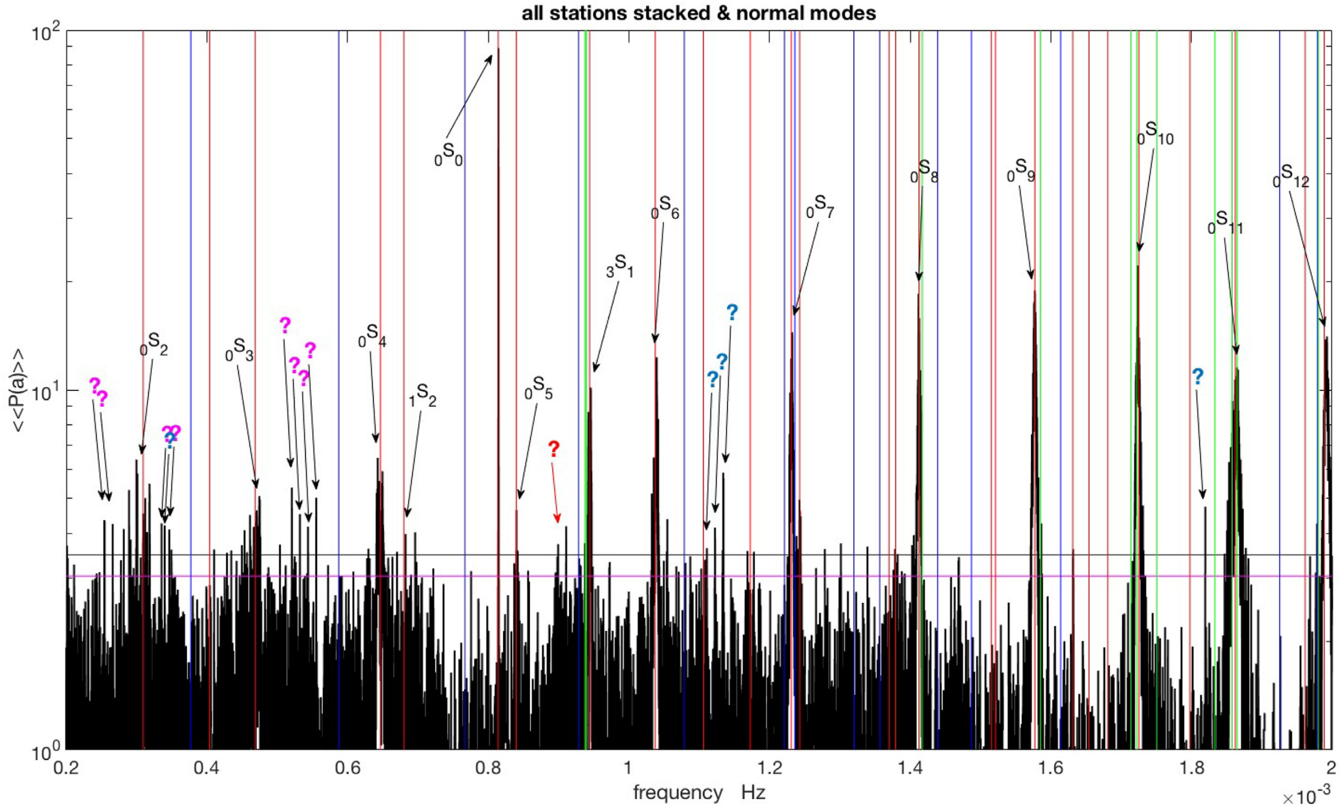


Figure 2. The normalized stacked power spectrum of the all the stations analysed with a 0.180 mHz standardizing window (see text). The magenta and black horizontal lines indicate, respectively, the 0.9999 and 0.99999 confidence levels. The red vertical lines mark the spheroidal modes $_nS_m$, the blue lines the toroidal modes $_nT_m$ and the green lines the modes of either type which so far has never been measured experimentally and is calculated according to Earth models (mostly the PREM model). The modes identified are labeled while the unexplained peaks are marked by a magenta '?', the ones most likely due to instrumental error by red '?', and the ones for which an interpretation in terms of normal modes is questionable are marked by blue '?'. The complete list of the normal modes up to 2 mHz is reported in Table 2.

(3) 1.577 mHz, in correspondence of mode $_0S_9$.
(4) 1.413 mHz, in correspondence of mode $_0S_8$.
(5) 1.990 mHz, in correspondence of mode $_0S_{12}$.
(6) 1.232 mHz, in correspondence of mode $_0S_7$.
(7) 1.039 mHz, in correspondence of mode $_0S_6$.
(8) 1.866 mHz in correspondence of mode $_0S_{11.}$
(9) 0.9457 in correspondence of mode $_3S_1$.
(10) 0.643, 0.474 and 0.309 mHz, respectively, in correspondence of modes $_0S_4$, $_0S_3$, $_0S_2$.
(11) 0.840 mHz, in correspondence of mode $_0S_5$.
(12) 0.6827 mHz, in correspondence of mode $_1S_2$.

Some other peaks are at the border of this level and in similar apparent correspondence of Earth modes, like the peak at 1.1727 mHz, in correspondence of $_1S_4$ mode, the peak at 1.631 mHz, in correspondence of $_1S_0$, etc.

In addition to these, and comparably significant, several other spectral peaks are apparent extraneous to Earth normal modes and to their related Coriolis spectral splitting. The latter, originated by Earth daily rotation at $F = 0.01157$ mHz, is the Zeeman-like splitting of any exciting frequency f into the five singlets f, $f \pm F$, $f \pm 2F$, as routinely observed after large earthquakes (Dahlen & Tromp 1998). Excluding the peaks tied to normal modes by Coriolis splitting, unexplained significant spectral peaks are apparent at (see Fig. 3):

(1) 0.2546 and 0.266 mHz, at mutual Coriolis splitting distance.
(2) 0.3335 and 0.3466 mHz, at mutual Coriolis splitting distance, and 0.3401 mHz.
(3) 0.5208, 0.5324, 0.5440 and 0.5555 mHz, all four at mutual Coriolis splitting distance.
(4) 0.899, 0.910 mHz.
(5) 1.111, 1.123 and 1.134 mHz, at mutual Coriolis splitting distance, but their frequency proximity and the relatively 'fat' peak shape—standing for lower Q-values—suggest that they may rather be linked to the $_3S_2$ mode, with a little frequency shift imposed by Earth asphericity (Masters & Widmer 1995).
(6) 1.820 mHz close to Coriolis splitting of the spheroidal mode $_3S_4$ at 1.833 mHz; however, the latter peak has so far never been measured experimentally (thus marked in green in Fig. 3), and also in the present case the spectrum shows no power at its centre frequency.

Just as for normal modes, other peaks are at the border of the 0.99999 confidence level, for example, the peak at 0.9703 mHz, which was independently identified as significant on seismic records (fig. 1 in Thomson & Vernon 2015).

4 THE ORIGIN OF THE UNEXPLAINED SPECTRAL PEAKS

The stacked spectrum shows primarily the signature of the Earth spheroidal normal modes $_0S_n$, with $n = 0, 1, .., 12$, but also at least three groups (the first three above) of significant spectral peaks with frequencies extraneous to Earth normal modes. These peaks, which approximately coincide with those previously identified (Nawa *et al.* 1998; Thomson & Vernon 2015), consist of multiple peaks separated by Coriolis frequency, $F = 0.01157$ mHz. If these were part of genuine Coriolis quintets, their central frequency would not be uniquely defined, with a constrained guess possible only for the quadruplet and setting its central frequency at either 0.5324 or 0.5440 mHz. Taking the first option and considering the 0.266 mHz peak of the first doublet as central, one could hypothesize the third group to be an overtone of the first one.

What is the origin of such unexplained peaks, clearly incompatible with a tidal or meteoric origin for their $Q \gg 10$ (Webb 2008; Thomson & Vernon 2015)? It could be an instrumental problem: the superconducting gravimeters of the IGETS network are all of the same type, manufactured by GWR Instruments Inc. They are equipped with an active tilt compensation system designed to keep the instrument aligned to the vertical to better than a few microradians through a thermal expansion suspension system that has a proper time of 1100–1300 s (fig. 3 of Riccardi *et al.* 2009). This might be responsible for the unexplained peaks around 0.9 mHz, which are therefore prudentially excluded. Another instrumental problem could be a sensitivity to magnetic disturbances, supported by the coincidence of unexplained peaks with some peaks of the magnetic spectrum (Thomson *et al.* 2007; Thomson & Vernon 2015). However, a spurious sensitivity of the GWR gravimeters has been experimentally ruled out (Goodkind 1999), and it would in any case be difficult to explain why only few of the many peaks of the magnetic spectrum are apparent in tremor and show Coriolis splitting. Another possibility is a strong local artefact, like an electrical machinery, which could in principle have a precise frequency, but would hardly affect stations in different parts of the world.

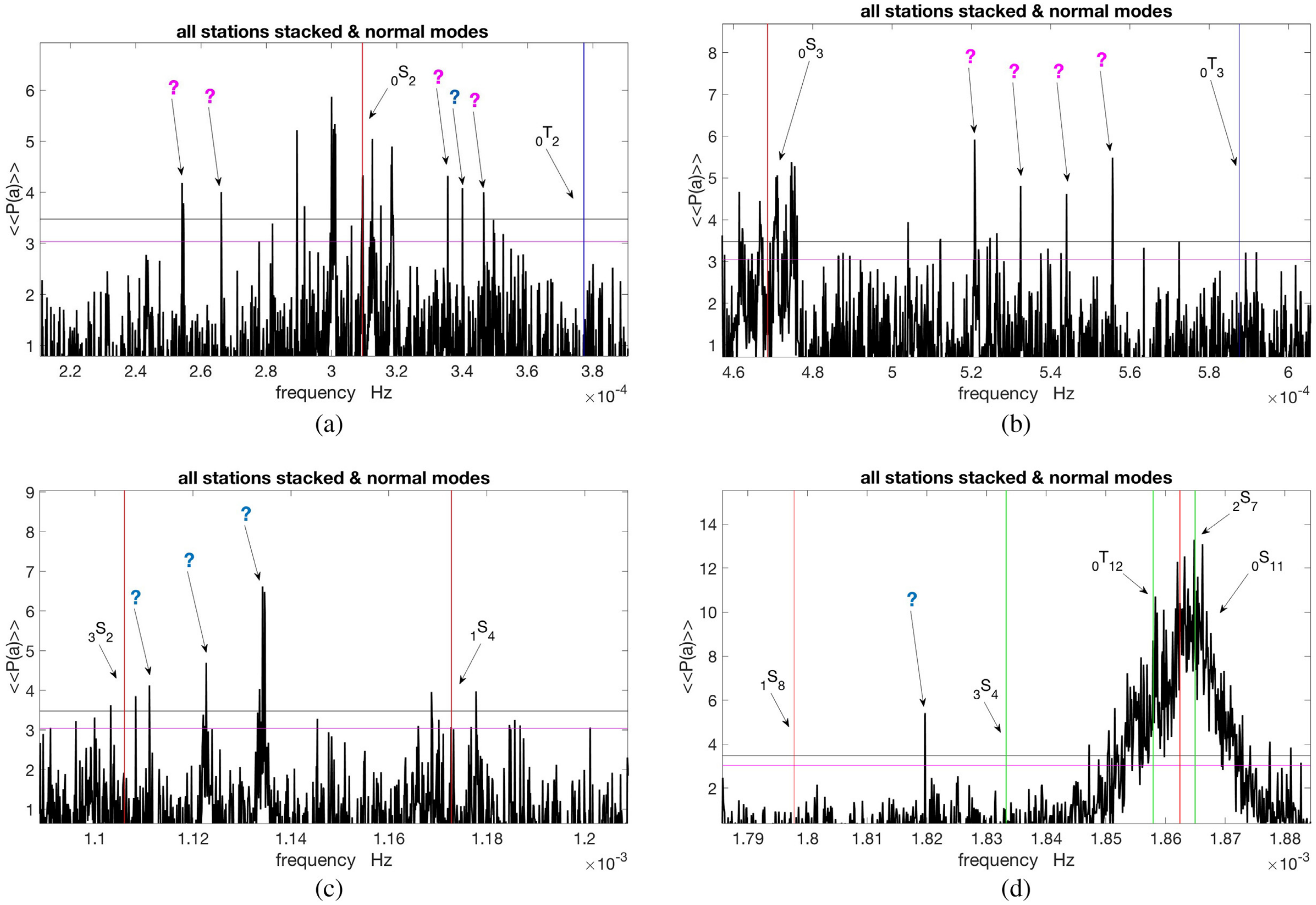
Summing up, experimental evidence seems to point to an origin external to the Earth. The high Q values, the apparent coincidence with some solar acoustic normal modes and the correlation with the magnetic field measured both on the Earth and in space satellites suggested an unknown acoustic–magnetic–elastic excitation of the Earth by the sun (Thomson & Vernon 2015). However, (1) the mechanism producing this is unknown, (2) the number of solar acoustic modes is very much larger than that of the unexplained peaks, so that (3) an equally unknown selection mechanism should be advocated. An alternative extraterrestrial mechanism proposed for the origin of the unexplained peaks was the Earth mechanical response to gravitational wave (from now on GW) monochromatic illumination (Mulargia 2017), a hypothesis which is further explored here.

Assuming the Earth potentially illuminated by GW at all frequencies, it could 'tune in' to the most favourable ones, which would therefore represent the upper limit of GW excitation thanks to selective viscoelastic amplification. A detailed calculation of the quadrupole viscoelastic coupling coefficients for a spherical, stratified, self-gravitating non-rotating Earth model by a most eminent seismologist (Ben-Menahem 1983) suggested a leading-order excitation of the ${}_nS_2$, $n = 0, 1, ..$ spheroidal modes and ${}_nT_1$ toroidal modes, with detectable GW induced strains $h \sim 10^{-20}$ at millihertz frequencies. This same approach has been recently adopted in combination with model calculated Earth response (Coughlin & Harms 2014) to study pair cross-correlation among the superconducting gravimeters of the same IGETS network we analyse here, finding no evidence of detection at normal mode frequencies and setting upper limits for GW induced h strains detectable in tremor a few orders of magnitude above Ben-Menahem's estimate.

Table 2. The experimental spectral frequencies of the Earth normal modes (Masters & Widmer 1995). The PREM label stands for the modes theoretically predicted by PREM model (Dziewonski & Anderson 1981) which have so far never been measured.

Frequency (mHz)	Earth mode
0.30945	${}_0S_2$
0.3773	${}_0T_2$
0.40396	${}_2S_1$
0.46855	${}_0S_3$
0.5876	${}_0T_3$
0.6468	${}_0S_4$
0.680	${}_1S_2$
0.76690	${}_0T_4$
0.81439	${}_0S_0$
0.84008	${}_0S_5$
0.92855	${}_0T_5$
0.93785 (PREM)	${}_2S_2$
0.93960	${}_1S_3$
0.94420	${}_3S_1$
1.03755	${}_0S_6$
1.07890	${}_0T_6$
1.106	${}_3S_2$
1.17277	${}_1S_4$
1.2215	${}_0T_7$
1.23096	${}_0S_7$
1.2361	${}_1T_1$
1.24296	${}_2S_3$
1.320	${}_1T_2$
1.3567	${}_0T_8$
1.37001	${}_1S_5$
1.37960	${}_2S_4$
1.41264 (PREM)	${}_4S_1$
1.41274	${}_0S_8$
1.41719 (PREM)	${}_3S_3$
1.43913	${}_1T_3$
1.4873	${}_0T_9$
1.51527	${}_2S_5$
1.52136	${}_1S_6$
1.577374	${}_0S_9$
1.5855 (PREM)	${}_1T_4$
1.6141	${}_0T_{10}$
1.63136	${}_1S_0$
1.65448	${}_1S_7$
1.68117	${}_2S_6$
1.71379 (PREM)	${}_5S_1$
1.7223 (PREM)	${}_4S_2$
1.72525	${}_0S_{10}$
1.75049 (PREM)	${}_1T_5$
1.79776	${}_1S_8$
1.8333 (PREM)	${}_3S_4$
1.85794 (PREM)	${}_0T_{12}$
1.86242	${}_0S_{11}$
1.86496 (PREM)	${}_2S_7$
1.92551	${}_1T_6$
1.96172	${}_1S_9$
1.97915	${}_0T_{13}$
1.98038 (PREM)	${}_6S_1$
1.98870	${}_0S_{12}$

Note that following the normal mode 'tune in' assumption, the Earth would only be excited by GW at the frequencies of the Earth normal modes, making it impossible to support a GW origin for the unexplained spectral peaks, since they do *not* occur at normal mode frequencies. However, the normal mode 'tune in' approach relies on the cosmologically unlikely assumption (see later) that the number of Earth detectable GW source is so large to form



(a) (b) (c) (d)

Figure 3. Spectral bands of the normalized stacked power spectrum presented in Fig. 1 for (a) the first two groups, (b) the fourth group and (c) the fifth group of unexplained peaks and (d) the last unexplained peak.

a continuum of frequencies, that viscoelastic resonance is the only possible amplification mechanism and that it is purely elastic, acting only in exact correspondence of normal mode frequencies.

5 GW ORIGIN COMPATIBILITY

Let us simply assume a GW unpolarized source and disregard the detail of the interaction, which depends on the instantaneous geometry of the unknown source–station system (Ben-Menahem 1983). The *viscoelastic amplification* of an exciting monochromatic signal of angular frequency ω will approximately follow that of a 1-D damped-driven oscillator. Therefore, its spectral amplitude will depend on its proximity to the closest Earth eigenmodes with frequency ω_0 and quality factor Q, as $q \simeq 1/\sqrt{[1-\omega^2/\omega_0^2]^2+[\omega/(\omega_0 Q)]^2}$. In addition, another amplification mechanism is likely to operate since the main source of terrestrial tremor is constituted by ocean wave–wave and wave–bottom interactions, which are (1) highly nonlinear, (2) acting upon an excitable system dominated by noise and (3) ruled by thresholds, conditions known to generally produce *stochastic amplification* (Gammaitoni *et al.* 1998). Stochastic Amplification (from now on SA) is the statistical facilitation of the transition to a higher energy state by the addition of random noise, which can be traced back to Fokker–Planck equation. It affects a wide variety of phenomena, from neuron firing to climate cycles, digital image dithering, bistable lasers, superconducting quantum interference, etc. Absent by definition in classical seismology, which is based on linear elasticity, SA is essential to modern passive acoustics and seismology, where the ‘signal’ is ruled by noise interferometry (Weaver & Lobkis 2001; Snieder 2004; Mulargia & Castellaro 2008).

The relevance of SA to the unexplained tremor spectral peaks stems directly from their observed seasonal modulation by the background noise of meteoric origin (Nawa *et al.* 1998). Hence, we take the measured tremor displacement x equal to the excitation displacement u amplified by a visco-elastic response factor q and by a stochastic factor s (tied to the background noise level and dynamics at millihertz frequencies), that is, $x = qsu$ (Mulargia 2017).

6 UNEXPLAINED SPECTRAL PEAKS VERSUS EXPECTED GW EMISSION

Considering cosmological constraints, the strongest candidate sources for monochromatic gravitational wave illumination in our spatial neighbourhood are the binary systems consisting of a compact object captured in close orbit by the supermassive black hole (from now on SMBH) Sgr A* at our galaxy centre (Sigurdsson & Rees 1997; Freitag 2003; Barack & Cutler 2004). Extensive numerical simulations of the capture and orbital evolution of such systems (ibid.) yield that each compact body—be it a neutron star, a white dwarf or a small main sequence star (from now on SMSS)—flying by the SMBH at a distance $5 \doteq 20$ times the Schwarzschild radius is captured in highly elliptical orbits, with the system evolving towards merging by emitting gravitational waves. Emission occurs in progressively more circular orbits, and mostly consists of monochromatic GW in the $10^{-5}-10^{-2}$ Hz frequency band, with a longer life for the light compact body binaries. In particular, a SMSS–SMBH binary would emit most GW energy in the sub-millihertz and millihertz band by orbiting with eccentricities around 0.5 for $\gtrsim 10^4$ yr (Freitag 2003). Such inspiral orbits terminate by a slow tidal disruption of the SMSS lasting several decades (Lin *et al.* 2017) without any high-frequency chirp (Abbott *et al.* 2016), that would only occur for the $10^2 \doteq 10^3$ times more rare binaries in which the compact body is either a neutron star or a black hole (Freitag 2003).

To estimate the GW strain compatible with the unexplained spectral peaks, we consider the best constrained unexplained group, which is the quadruplet centred at 0.5324 or 0.5440 mHz. From its non-normalized median spectral amplitude, $P(a) \sim 6 \times 10^{-23}$ $(\mathrm{m^2 s^{-4}})\mathrm{Hz}^{-1}$, that is, $P(x) \sim 3 \times 10^{-13}$ m Hz^{-1} and using a bandwidth of 10^{-7} Hz, an apparent displacement amplitude $x \simeq \sqrt{2P(x)RBW} \sim 10^{-10}$ m is obtained (Mulargia & Kamentschick 2016). This, assuming a total amplification $qs \sim 10 \doteq 10^2$, yields a GW strain $h = 10^{-18} \doteq 10^{-19}$, which appears compatible with theoretical calculations of the gravitational emission of SMSS–Sgr A* binary systems (e.g. fig. 2 in Freitag 2003 and fig. 11 in Barack & Cutler 2004). Such strains in the millihertz band are well below the sensitivity of LIGO and VIRGO Earth-based gravitational interferometers, but within the resolving power of future space based gravitational interferometer eLISA, which will be able to confirm or disprove the present interpretation.

In conclusion, since the two groups of spectral peaks at 0.2546–0.266 mHz and at 0.5208–0.5324 and 0.5440–0.5555 mHz could possibly be combined as the first two modes (with theoretically comparable amplitude; Freitag 2003) of a single emitter with the fundamental tone centred at 0.266 mHz, and since no other such regularity is apparent for the other peak groups, the unexplained spectral peaks might be interpreted as originated by separate small star–SgrA* close orbit binaries, for a total of two to four systems. Cosmological constraints (Ade *et al.* 2014) suggest that the number of such simultaneously active binaries (possibly within the gravitational lensing optical resolution of future MICADO/EELT telescopes) should be ∼10 (Freitag 2003), a number compatible with the present interpretation.

ACKNOWLEDGEMENTS

This work was performed with a UniBO–RFO 2015-2016 contribution. The author is indebted to the Astrophysics group of the DIFA Department, to the Bologna INAF section, and in particular to Andrea Comastri, Bruno Marano, Luca Ciotti and Giancarlo Setti for their stimulating suggestions and to John Woodhouse for enlightening discussions on Earth normal modes.

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