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Incessant excitation of the Earth's free oscillations

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We, for the first time, report the evidence of incessant excitation of the Earth's free oscillations, mainly the fundamental spheroidal modes in a frequency range from 0.3 to 5 mHz, based on the three year record of a superconducting gravimeter at Syowa Station, East Antarctica. The frequency-time spectrogram of this record is striped by more than 30 lines at nGal level parallel to the time axis, mostly corresponding to the fundamental spheroidal modes. This spectrogram is characterized by relatively efficient excitation of gravest fundamental modes, enhancement of signal intensities in the austral winter and amplification of signal in the frequency band from 3 to 4 mHz. Assuming that earthquakes are only the sources for the free oscillations, we calculate the synthetic spectrograms, which have not shown such a series of parallel lines as observed. The result of this synthetic test and characteristics of the observed spectrogram suggest that the mode signals we found are not of earthquake origin. We tentatively suggest atmospheric or oceanic origin for this newly discovered phenomenon of the solid Earth.

1. Introduction

Observation of the Earth's free oscillations was first reported for the great Chilean earthquake of May 22, 1960 in a memorial paper "Excitation of the free oscillations of the earth by earthquakes" (Benioff *et al.*, 1961). Since then, as this title indicates, the excitation of free oscillations has been thought to be a transient phenomenon due to the occurrence of earthquakes. Although earthquakes large enough to excite free oscillations now include silent earthquakes which may occur several times a year (Beroza and Jordan, 1990), they altogether are still not frequent enough to maintain the solid earth in a freely vibrating state at an observable level. We, for the first time, report the evidence of incessant excitation of the Earth's free oscillations, based on the three year record of a superconducting gravimeter at Syowa Station, East Antarctica.

Detection of weak signal of continually excited free oscillations, if exists, requires an instrumental system with high resolution, low noise and long-term stability at a measuring site quiet enough in the normal mode band. The superconducting gravimeter SG016 (GWR Instruments Inc., model TT70 #16) operated at Syowa Station (69.0 S, 39.6 E) meets such requirements. Slow drift of about 10 μGal/year and low sensor noise in the cryogenic environment make it possible to search nGal level signals (1 nGal $= 1 \times 10^{-11}$ ms^{-2}) with a resolution of 10^{-14} ms^{-2}/DU (digital unit). The local seismicity is so low that the sensor mass position is unlikely to be offset by nearby seismic shocks (Sato *et al.*, 1995, 1996).

2. Observation and Data Analysis

The output signal from the SG016 is passed into two analog filters, TIDE and MODE, which are the same as those used in the IDA network (Agnew *et al.*, 1986). The amplitude response of the MODE filter is flat in a period range from about 1 hour to 1 minute. The filtered output is A/D converted to 7.5 digits at a sampling rate of 2 seconds. The system time base is always kept to UTC by a GPS clock. The amplitude scale factor of the SG016 was determined by comparing the observed M_2 tide amplitude to the one from the calibrated LaCoste-Romberg D73 gravimeter operated in parallel (Kanao and Sato, 1995). We obtained a value of 2.2915×10^{-14} ms^{-2}/DU at 3.0 mHz, which explains the amplitudes of other tidal modes as well with relative differences of less than 0.1% (Sato *et al.*, 1996).

We analyze the MODE channel record in the three year period from March 22, 1993, to December 31, 1995. The data are moving-averaged and resampled at a rate of 10 seconds. The Earth tide components are removed with a least-squares method. We edit 1015 records of a data length of 3 days with a mutual time lag of 1 day. Each record is tapered with a zero-order 4-π prolate taper (Park *et al.*, 1987) and the fast Fourier-transform is applied. We define the spectral intensity as the absolute value of complex coefficient of the Fourier series expansion. The intensity has been corrected for the effect of tapering but not for the effect of filtering. The total of the 1015 spectra are pasted up along the time axis to obtain a spectrogram, which enables us to examine the temporal variation of the spectrum.

3. Frequency-Time Spectrogram

Figure 1 shows the frequency-time spectrogram in the normal mode band, where the eigenfrequencies of the fundamen-

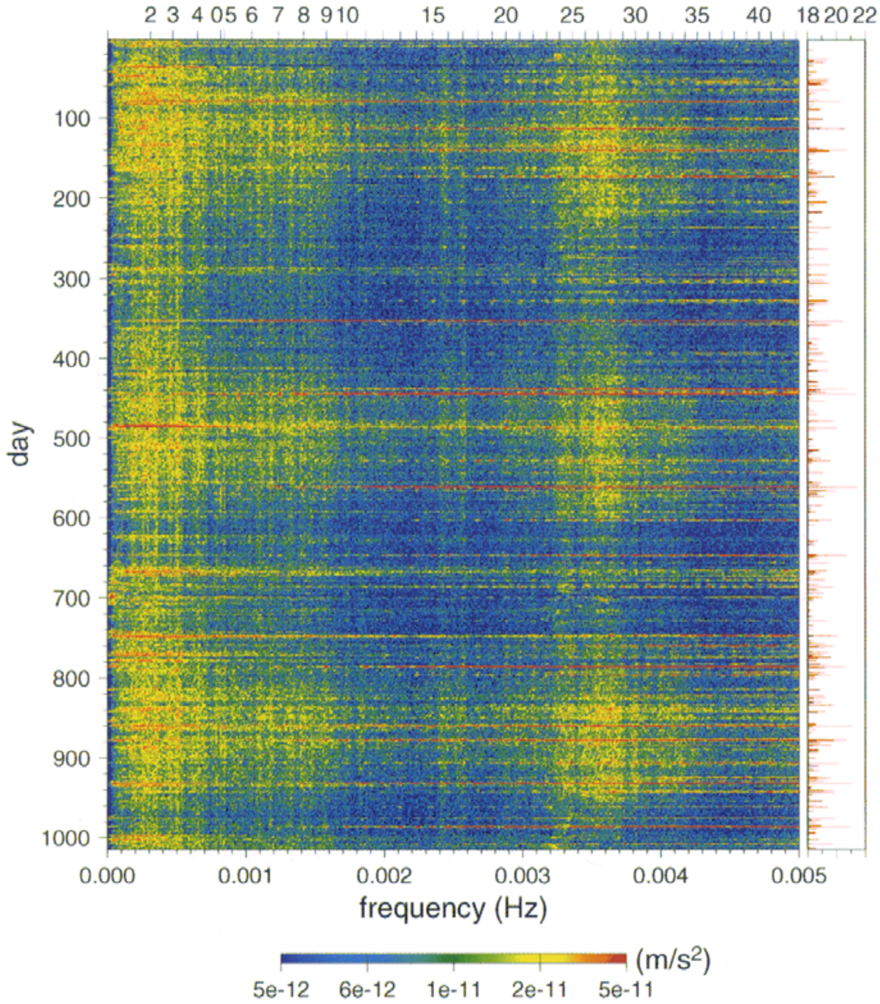


Fig. 1. Frequency-time spectrogram of the SG016/MODE from 1993/3/22 to 1995/12/31. Time is measured by elapsed day from 1993/3/22. Numbers at the top frame are angular orders of the fundamental spheroidal modes. The detected modes are summarized in Table 1. Bars at the right frame indicate logarithm of seismic moment (Nm) of the Harvard CMT solutions. The Kuril islands earthquake of October 4, 1994, is on the 562 day.

tal spheroidal modes calculated for the Earth model PREM (Dziewonski and Anderson, 1981) are indicated at the top. The occurrence of earthquakes with seismic moments (*Mo*) larger than 10^{18} Nm, corresponding to moment magnitudes (*Mw*) greater than 5.9, are indicated by horizontal bars at the right. Larger events excite more normal modes of the free oscillations so that they can easily be identified as red horizontal lines on the spectrogram. In general, rapid decay of these modes makes it difficult to identify them as vertically straight lines. A remarkable exception is the fundamental radial mode ${}_0S_0$ at a frequency of 0.815 mHz excited by the Kuril islands earthquake of October 4, 1994 (562 day), which lasted at a visible level for about 45 days after the event.

To our surprise, the spectrogram is striped by vertical lines persistent through the three year period of observations. We identify at least 40 lines in total (Table 1). Relatively intense are several lines at frequencies less than 2 mHz, those between 3 and 4 mHz and two lines near 2.5 mHz. Other lines are weak but still recognizable. None of these lines are distinguishable as spectral peaks on a single spectrum profile in seismically quiet periods. We enlarge the spectrogram along the frequency axis to measure the central frequency and broadness of a target line. The results of such measurements are summarized in Table 1. Figure 2 shows a part of the enlarged spectrogram in a frequency range 1–3 mHz. Large arrows indicate the lines listed in the table. Small arrows represent weaker lines that are still recognizable but difficult to identify as continuous lines and for this reason not listed in Table 1. As indicated in Table 1, among the total of the 41 observed lines, 30 measured frequencies agree with the theoretical eigenfrequencies of the fundamental spheroidal modes of PREM with differences of less than 0.02 mHz. The agreement is perfect within the accuracy of measurement ($\sim$0.01 mHz) for 25 modes. Such agreement strongly indicates that most of the observed vertical lines represent the normal modes of the Earth's free oscillations.

The ten vertical lines are left to be unidentified. The first unidentified line is separated by only 0.03–0.04 mHz from the one identified as ${}_0S_2$, but this separation is still too wide to explain in terms of the spectral splitting of ${}_0S_2$ due to the Earth's rotation and asphericity (Buland *et al.*, 1979). Two lines are located at the frequency positions corresponding to

Table 1. Observed frequencies and their identification.

Observed	Identified		Observed	Identified	
mHz	PREM	mode	mHz	PREM	mode
0.25–0.26			2.88	2.8785	$_0S_{20}$
0.29	0.3093	$_0S_2$	3.08	3.0754	$_0S_{22}$
0.35			3.18	3.1714	$_0S_{23}$
0.45	0.4686	$_0S_3$	3.22–	3.2660	$_0S_{24}{}^{**}$
0.50			–3.38	3.3595	$_0S_{25}{}^{**}$
0.65	0.6471	$_0S_4$	3.45	3.4520	$_0S_{26}$
0.78			3.53∼3.54	3.5438	$_0S_{27}$
0.84–0.85	0.8405	$_0S_5$	3.64∼3.65	3.6349	$_0S_{28}$
1.02∼1.03	1.0383	$_0S_6$	3.82	3.8157	$_0S_{30}$
1.09∼1.10	1.1063	$_3S_2{}^*$	3.90∼3.91	3.9056	$_0S_{31}$
1.17∼1.18	1.1729	$_1S_4{}^*$	4.00	3.9952	$_0S_{32}$
1.32			4.09	4.0847	$_0S_{33}$
1.40∼1.41	1.4136	$_0S_8$	4.18	4.1741	$_0S_{34}$
1.46∼1.47			4.26	4.2635	$_0S_{35}$
1.57∼1.58	1.5783	$_0S_9$	4.35	4.3528	$_0S_{36}$
1.72∼1.73	1.7266	$_0S_{10}$	4.44∼4.45	4.4421	$_0S_{37}$
1.82∼1.83			4.53	4.5315	$_0S_{38}$
2.23	2.2315	$_0S_{14}$	4.62	4.6209	$_0S_{39}$
2.29			4.72	4.7104	$_0S_{40}$
2.43	2.4583	$_0S_{16}$	4.80	4.8000	$_0S_{41}$
2.57	2.5672	$_0S_{17}$	4.89	4.8897	$_0S_{42}$

Bar (–) and tilde (∼) indicate a sharp band and a smeared band, respectively. $*$ suspected identification. $**$ identification within the mutually unseparable band.

overtones $_3S_2$ and $_1S_4$, yet it would be difficult to invoke a mechanism to excite only these two modes better than other numerous overtones.

The intensity of the mode signal is on the order of nGal. Intensities in the lowest frequency range (<2 mHz) are comparable to those at higher frequencies, suggesting that the mode signals are not of earthquake origin. If the fundamental spheroidal modes were excited by earthquakes, their amplitudes should decrease, in general, with decreasing frequency (see Fig. 3(b)). The spectrogram shows a seasonal variation. The intensity level is relatively high in the austral winter from June to October corresponding to the days 70–225 ('93), 435–590 ('94), 800–955 ('95). In these periods not only the background noise but the mode signals seem to be enhanced so that the mode signals are not masked by the increased noise. The spectrogram shows high amplitudes not only at frequencies less than 2 mHz but in a range from 3 to 4 mHz, where we can expect efficient coupling between the solid Earth and atmosphere (Watada, 1995). In fact, such coupling has been observed as long-period harmonic Rayleigh waves after the eruption of Mt. Pinatubo in 1991 (Kanamori and Mori, 1992; Widmer and Zürn, 1992).

4. Synthetic Test

The SG spectrogram is thus characterized by relatively efficient excitation of gravest fundamental modes, enhancement of signal intensities in the austral winter and amplification of signal in the frequency band from 3 to 4 mHz. These characteristics suggest that the mode signals of our interest are not of earthquake origin but of atmospheric origin. To augment this suggestion, we synthesize spectrograms for the 1994 period at Syowa Station, assuming that earthquakes are only the sources for the free oscillations.

We take PREM as the Earth model and calculate synthetic seismograms by summing all the normal modes at frequencies lower than 10 mHz (Gilbert and Dziewonski, 1975). We use earthquake parameters given by the 1994 catalogue of the Harvard Centroid Moment Tensor (CMT) solutions (Dziewonski *et al.*, 1995). We vary the data length of synthetic seismograms according to earthquake size: the min-

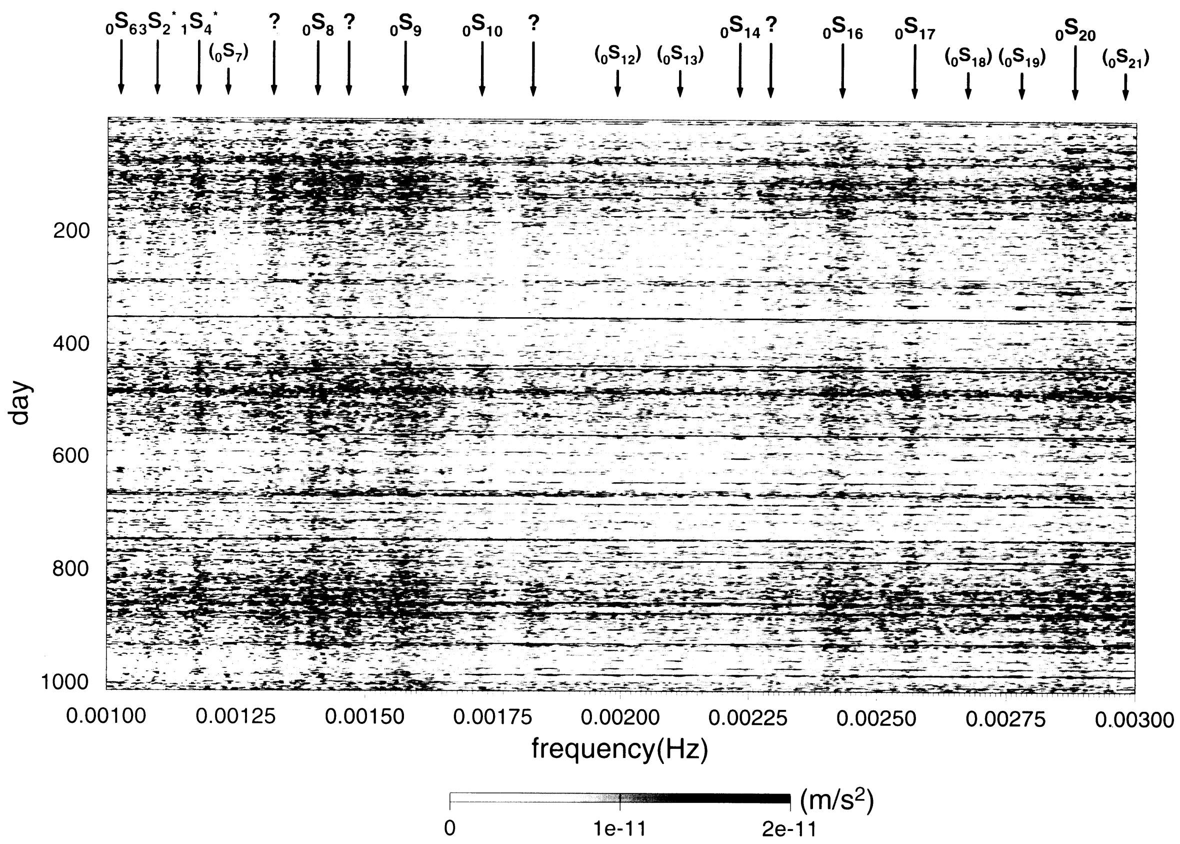


Fig. 2. A part of the frequency-time spectrogram enlarged along the frequency axis between 1 and 3 mHz. Large arrows indicate the lines listed in Table 1. The identified modes are shown by their nomenclatures. For the suspected identification asterisk (*) is attached. The unidentified lines are marked by a symbol '?'. Small arrows indicate the positions of some of the fundamental spheroidal modes in PREM, in the vicinity of which very weak lines are visible. These lines are not listed in Table 1.

imum is taken to be 10 days and the maximum is about 100 days for the Kuril Islands earthquake of October 4, 1994. We merge and connect them to create a one-year synthetic seismogram.

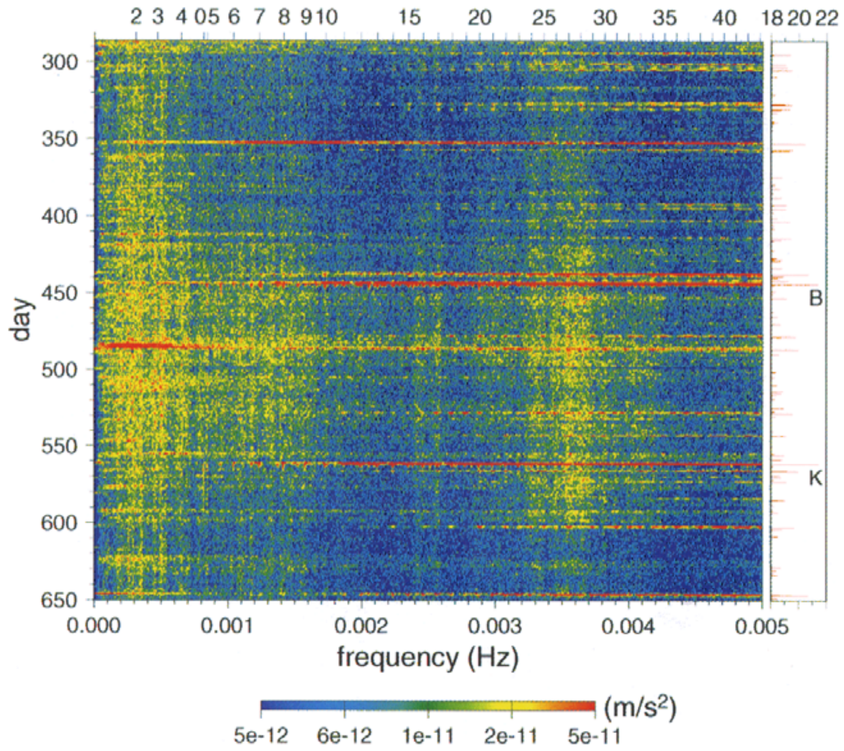
One may argue that a larger number of smaller earthquakes not included in the catalogue may be responsible for the weak but incessant excitation of the free oscillations. We examine this possibility by incorporating synthetic seismograms of smaller earthquakes into the one-year synthetic seismogram. We note that in the CMT catalogue earthquakes with Mo larger than $10^{17.2}$ Nm ($Mw = 5.4$) follow approximately the Gutenberg-Richter (G-R) magnitude-frequency relation with a b-value of 1. Assuming that the G-R relation can be extended to smaller earthquakes, and assuming that their random occurrence is described by Poisson's distribution, we generate a total of about 2000 earthquakes with Mo down to 10^{16} Nm ($Mw = 4.6$), for which the waveform is assumed to be the same and only the amplitudes are varied according to their magnitudes.

The one-year synthetic seismogram so obtained is superposed by synthetic tides calculated by the method of Tamura (Tamura, 1987) with the tidal factors obtained by analyzing the TIDE channel record (Tamura *et al.*, 1997). We further add synthetic random noise, the power spectrum of which is shaped as for the observed SG records in the quietest periods of observation (e.g. 605–615 days in Fig. 3(a)). More specifically, the power spectrum of the synthetic noise is flat (white noise) at frequencies higher than 2 mHz, while it increases with decreasing frequency as f^{-1} (f^{-1} noise) if $f < 2$ mHz. The resultant acceleration record is filtered with the MODE response and digitized with the same resolution unit as for the real data-logger, and then processed to obtain the frequency-time spectrogram.

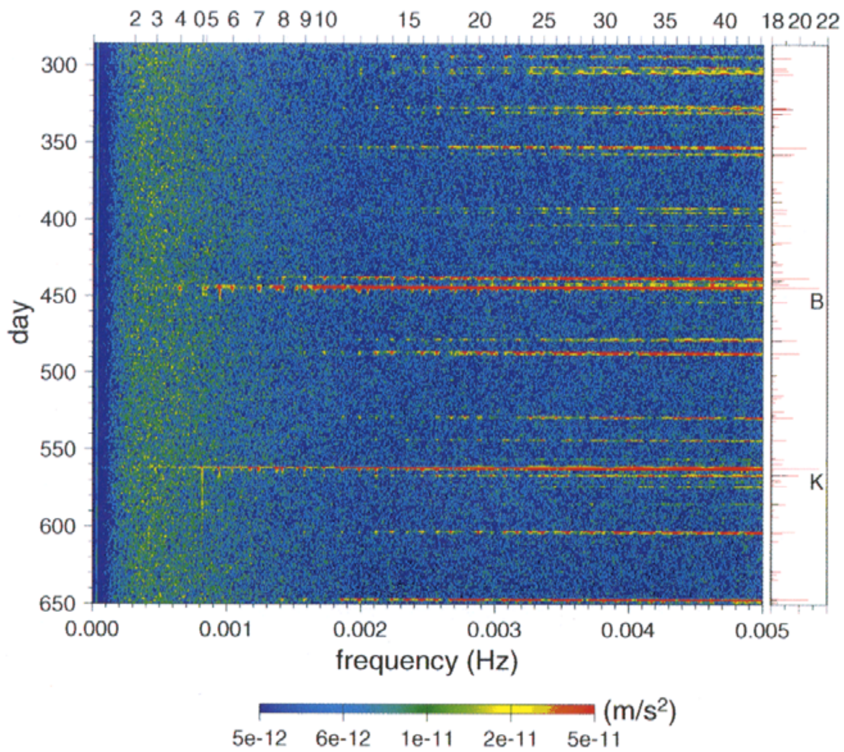
Figure 3(b) shows the synthetic spectrogram of 1994 compared to the observed spectrogram (Fig. 3(a) taken from Fig. 1). The well excited modes are largely confined in the higher frequency range and only a few largest earthquakes excite significantly modes at lower frequencies. In general, the modes excited by earthquakes decay so rapidly that they are hardly visible as a series of vertically straight lines. It is difficult to explain the observed stripe as a consequence of earthquake activity.

5. Discussion

Silent earthquakes large enough to excite free oscillations may occur several times a year (Beroza and Jordan, 1990). Even if these are included, however, seismicity would not be powerful enough to shake the whole Earth incessantly at an observable level. We have tentatively suggested barometric variation as an alternative excitation mechanism. A rough estimate has shown that random atmospheric loading on the globe can excite fundamental spheroidal modes, from the



(a)



(b)

Fig. 3. Frequency-time spectrograms of (a) the observation as adopted from Fig. 1 and (b) the synthetic seismogram in 1994. The time axis is taken to be consistent with the one in Fig. 1. The synthetic seismogram is calculated for all the earthquakes listed in the Harvard CMT catalogue and for the smaller earthquakes randomly generated according to the Gutenberg-Richter law with a b-value of 1. The synthetic random noise is added. Symbols, B and K, indicate the Bolivian deep earthquake, June 9 (445), and the Kuril islands earthquake, October 4 (562), respectively.

lowest to higher frequencies, at the nGal level (Kobayashi, 1996). Another possible source is the oceanic effects, such as tidal loading, breaking waves on the coast and ocean bottom friction. In any case the source is likely to be on the surface of the Earth, as originally hypothesized by Benioff *et al.* (1959).

Our observation indicates clearly that low-frequency ground noise at a quiet site consists mainly of fundamental spheroidal modes of the Earth's free oscillations. If these free oscillation modes are regarded as signal, then the "real" ground noise must be at a much lower level than one so far considered to be the ground noise. In the observed spectrogram, there are several vertical lines unidentified and a few of the fundamental spheroidal modes are missing. These unidentified and missing lines remain to be explained. We are currently searching for another evidence of incessant excitation of the free oscillations. We have found a stripe of vertical lines corresponding to the fundamental spheroidal modes in a frequency range from 2 to 7 mHz on the spectrograms of the IDA network data, a subject to be reported in a separate paper.

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