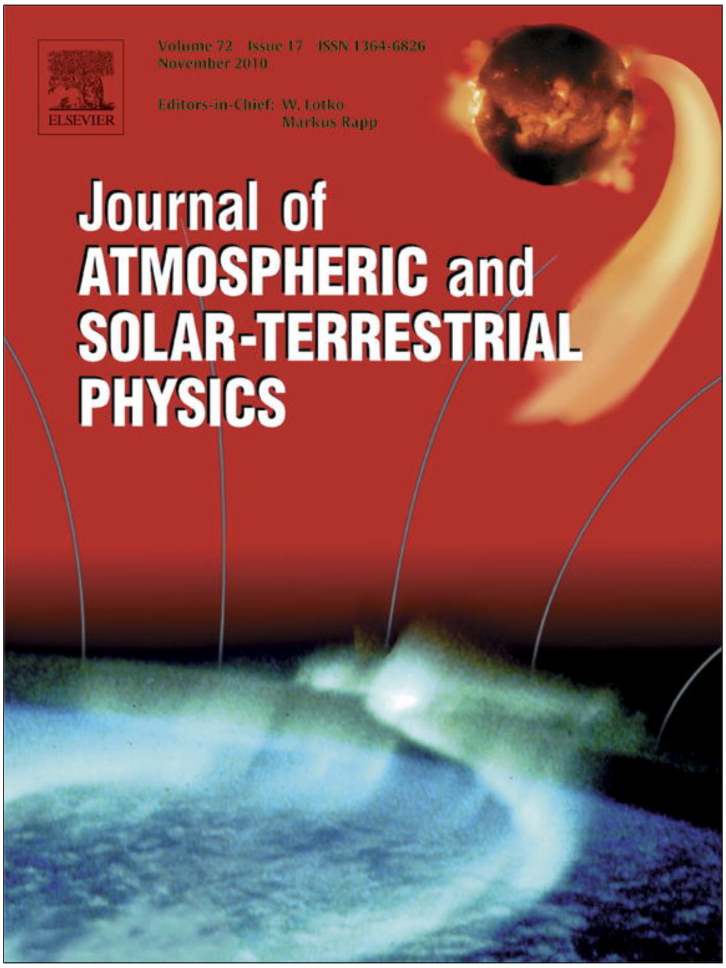
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Interpretation in terms of gyrotropic waves of Schumann-resonance-like line emissions observed at Nakatsugawa in possible association with nearby Japanese earthquakes

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ABSTRACT

The observation of ULF/ELF electromagnetic waves in the frequency range below 50 Hz has been continued at Nakatsugawa (in the Gifu prefecture), Japan since 1998. This paper summarizes anomalous Schumann resonance (SR) phenomena and SR-like line emissions observed at Nakatsugawa in possible association with recent nearby earthquakes (EQs) (the 2004 Mid-Niigata prefecture and the 2007 Noto-Hanto (peninsula) EQs), which have been already described in detail by Ohta et al. (2009). The intensity of particular modes of SR increased before these large EQs and the excitation of other anomalous SR-like line emissions also existed at the frequency shifted by about 2 Hz from the typical SR modes. Since temporal changes of the anomalous SR modes and line emissions are synchronous in time, there might be a possibility that the line emission is a consequence of the anomalous SR. In this paper we propose an interpretation of those anomalous phenomena in terms of excitation of gyrotropic waves due to input wave from below with a band from 15 to 20 Hz as an exciter. The theoretical computational results seem to be generally consistent with the observational finding.

1. Introduction

There have been recent reports on a lot of evidences on electromagnetic phenomena associated with EQs (Hayakawa, 1999, 2009; Hayakawa and Molchanov, 2002; Molchanov and Hayakawa, 2008; Hayakawa and Hobara, 2010). These seismogenic electromagnetic effects can be classified customarily into two categories; the first is direct radiation of electromagnetic emissions from the lithosphere (such as ultra-low-frequency (ULF) electromagnetic emissions; Hayakawa et al., 2007; Fraser-Smith, 2009; Kopytenko et al., 2009) and the second is seismo-atmospheric and -ionospheric perturbations due to the indirect consequence of precursory seismic effects in the lithosphere and also detected by means of pre-existing transmitter signals in different frequency ranges such as VHF, VLF/LF, etc. in the form of propagation anomalies (e.g., Hayakawa, 2007; Hayakawa, 2009a, 2009b).

The subionospheric VLF/LF signals have been found to be very effective in elucidating perturbation in the lower ionosphere (D/E region) associated with EQs (Hayakawa, 2007), and there have been publications of a lot of studies, including case studies for specific huge EQs (like the Niigata-chuetsu EQ, Niigata chuetshu-oki EQ, Sumatra EQ, etc.), and also statistical studies on the correlation between ionospheric perturbations as VLF/LF propagation anomalies and EQs (Hayakawa, 2009b; Hayakawa et al., 2010a, 2010b).

The ionospheric region that is even lower than the reflection height of VLF/LF waves can be monitored by ELF waves (Nickolaenko and Hayakawa, 2002). The only possible way is the use of natural SR phenomena in the ELF band, even though there are very few transmitters at ELF (Yano et al., 2010). Frequencies of SR modes are very stable, so that they can be treated just like VLF/LF transmitter signals. The first anomaly in SR was found in the data at Nakatsugawa in Japan in possible association with a huge EQ (so-called Chi-chi EQ) in Taiwan (Hayakawa et al., 2005), and they have interpreted the anomalous increase in SR fourth (or sometime third) mode in terms of interference between the direct signal from the lightning source and that scattered (or reflected) by the ionospheric perturbation

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over Taiwan (Hayakawa et al., 2005; Nickolaenko et al., 2006). This kind of SR anomaly has been then confirmed by a statistical study of observation in Nakatsugawa for EQs with magnitude greater than 5.0 in Taiwan over a period of six years (Ohta et al., 2006). Hayakawa et al. (2008) have further confirmed the presence of similar SR higher mode enhancement at Moshiri, Japan, in possible association with the so-called Ping-tong EQ in Taiwan.

The purpose of this paper is to summarize the first new observational facts as regards the anomalous SR higher modes and new resonance-like emissions at a Japanese station of Nakatsugawa in possible association with two huge Japanese EQs (Ohta et al., 2009), and we try to interpret those experimental characteristics in terms of gyrotropic waves as studied by Sorokin and Hayakawa (2008).

2. Observation and analysis of ELF waves at Nakatsugawa and EQs treated

Three magnetic field components (B_x, B_y and B_z) were measured at Nakatsugawa (geographic coordinates: 35°25′N, 137°32′E) by means of orthogonal induction coil magnetometers. B_x is defined by the magnetic field in the N–S direction, while B_y that in the E–W direction. B_z is its vertical component. The sampling frequency is 100 Hz, and the digitized data are stored on a hard disc. Details of this ELF observation system at Nakatsugawa are described in Ohta et al. (2001, 2006) and Hayakawa et al. (2005).

The signal analysis is performed by the FFT algorithm with a data length of 1024. Then the temporal resolution is 10.25 s and the frequency resolution is 0.097 Hz ($\sim$0.1 Hz). We can estimate the ratio of amplitude and phase difference of the two components among the 3 magnetic fields.

Two huge EQs are treated. One is Chuetsu-EQ in the Niigata prefecture (formal name is 2004 Mid-Niigata EQ) whose epicenter is located at the geographic coordinates, 37.23°N, 138.78°E, and it happened at 17:56 JST on October 23, 2004. Its magnitude is $M=6.8$ and its depth 20 km. Another EQ is called the Noto-peninsula EQ (37.22°N, 136.69°E), which happened at 09:41 JST on March 25, 2007. Its magnitude was $M=6.9$ and its depth 11 km.

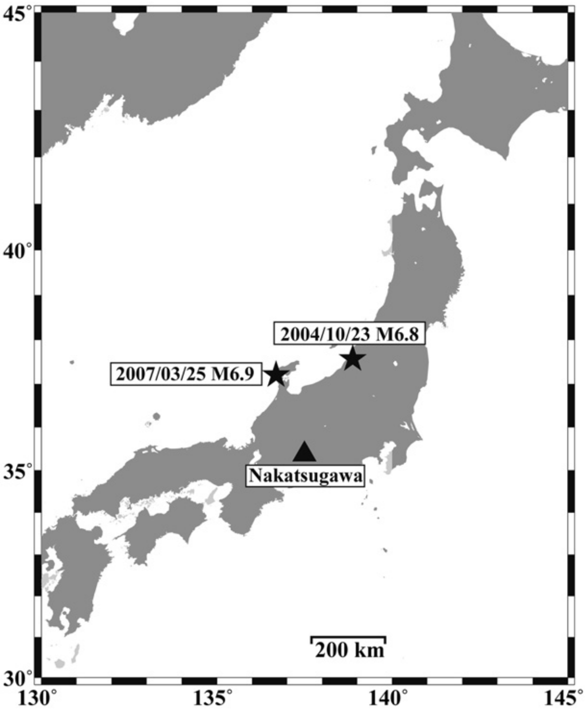

Fig. 1. Location of the Nakatsugawa observation station (indicated by a black triangle) and epicenters of the 2004 Mid-Niigata Prefecture and the 2007 Noto-Hantou EQs (indicated by stars). The epicentral distances for these two EQs are 250 and 200 km, respectively.

Fig. 1 illustrates the relative location of our ELF observation station at Nakatsugawa (a black triangle) and two EQs whose epicenters are indicated (two stars). The distance between our ELF station and the 2004 Niigata-chuetsu EQ is 250 km, and the distance between Nakatsugawa and the 2007 Noto-peninsula EQ is 200 km.

3. Anomalous ELF phenomena observed

SR is a global electromagnetic resonance phenomenon excited by lightning discharges in the cavity formed by the Earth's surface and the ionosphere (Nickolaenko and Hayakawa, 2002). The frequency of the SR fundamental mode is approximately 8 Hz (fundamental mode: $n=1$) and the frequencies of higher modes are approximately 14 Hz (second mode: $n=2$), 20 Hz (third mode: $n=3$), 26 Hz (fourth mode: $n=4$), and so on. The frequencies of these modes are known to be so stable that the fluctuation is only about 0.2 Hz (Nickolaenko and Hayakawa, 2002). But the intensity of each resonance mode depends on the intensity of lightning activities and the distance between the lightning source and the observatory (Hayakawa et al., 2005). Already Ohta et al. (2009) have described the anomalous phenomena in detail, so that we will repeat only the essential points as follows.

3.1. Anomalous phenomena before the 2004 Niigata-chuetsu EQ

The 2004 Niigata-chuetsu EQ (M6.8, depth 20 km) as indicated by a right star in Fig. 1 occurred at 17:56 L.T. on October 23, 2004. The anomalous resonance was observed during the period from the afternoon on October 20th to the morning on October 22nd.

Figs. 2 and 3 illustrate the very intense anomalous resonance of the B_y and B_x components, respectively, observed at 18:00–23:55 L.T. on October 20, 2004, 3 days before the EQ. There are two strong resonances on both B_y component ("$n=3$" and "A" in Fig. 2) and B_x component ("$n=3$" and "B" in Fig. 3.). We have first analyzed the strong resonance "A" in Fig. 2. The maximum intensity of the strong resonance "A" in Fig. 2 is located in frequency from 16.11 to 16.30 Hz, which is definitely about 2 Hz higher than the typical frequency of $n=2$ (14 Hz). Phase differences between B_y and B_x for this line emission exhibit a nearly flat distribution over the phase difference from 0 to 2π, and which is completely different from the approximate linear polarization of strong SR ($n=3$) in Fig. 2, so that it seems that this resonance might be due to a generation mechanism different from that of conventional SR.

How about the frequency of strong line emission ("B" in Fig. 3)? Its median frequency is found to be around 18.35 Hz, being about 2 Hz lower than the typical frequency of $n=3$ (20 Hz). Again, the information on phase difference between B_x and B_y for this emission ("B") suggests that this line emission has a very different characteristic of polarization from that of the SR $n=3$ mode.

The anomalous line emission was observed from 3 days before the 2004 Niigata-chuetsu EQ until 1 day before the EQ at Nakatsugawa station. Anomaly in intensity of particular modes of SR and other anomalous resonances different from the usual SR were observed. The frequency of the anomalous line emission on the B_y component was 16 Hz, 2 Hz higher than the typical frequency of $n=2$, and the frequency of the anomalous line emission on the B_x component was 18 Hz, 2 Hz lower than the typical frequency of $n=3$. These anomalous resonances have no

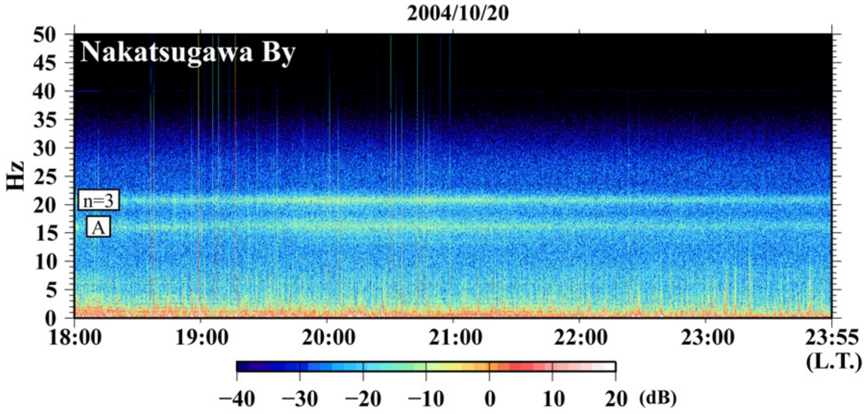

Fig. 2. Excitation of anomalous resonances at 18:00–23:55 L.T. on October 20, 2004 (Nakatsugawa, B_y component). SR $n=3$ mode and line emission labeled A. Intensity is indicated by color.

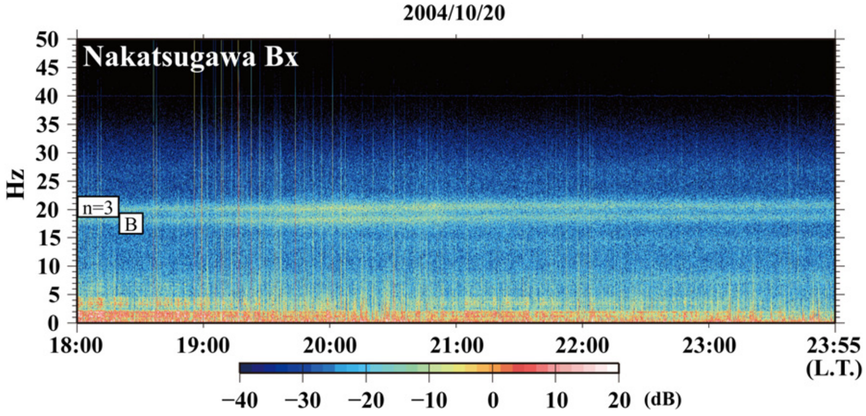

Fig. 3. Excitation of anomalous resonances at 18:00–23:55 L.T. on October 20, 2004 (Nakatsugawa, B_x component). SR $n=3$ mode and line emission B. Intensity is given in color.

peak in the histogram of phase differences between B_y and B_x, so that they are different from SR. Therefore it is considered that they are likely to be generated locally or relatively close to the observation station and might be due to a different generation mechanism from that of SR. However, it is very interesting to notice that temporal changes of intensity of line emissions are almost synchronous with those of the anomalous SR ($n=3$).

3.2. *Anomalous phenomena before the 2007 Noto-Hantou EQ*

The 2007 Noto-Hantou (peninsula) EQ (M6.9, depth 11 km) occurred at 09:41 L.T. on March 25, 2007. The anomalous resonance was observed during the period from the afternoon on March 24th to the morning on March 31st (i.e. prior to and after the EQ).

Figs. 4 and 5 depict the anomalous resonance of the B_y and B_x components, respectively, observed at 06:00–11:55 L.T. on March 25, 2007, just before and after the EQ. Since we have changed (or increased) the gain of the main amplifier of the observation system in 2006, the intensity color bar in Figs. 4 and 5 is shifted by 10 dB as compared to Figs. 2 and 3. There is a strong anomalous line emission on the B_x component but there is no obvious anomaly on the B_y component, this situation being different from the case of the 2004 Niigata-chuetsu EQ. The maximum intensity for the SR "$n=3$" mode is found to be peaked at 20.70 Hz, and polarization analysis indicates that this resonance is linearly polarized. So we can conclude that this resonance is likely to be SR ($n=3$).

Then we studied frequency of line emission of the B_x component shown as "C" in Fig. 4. The median frequency of these line emissions is found to be ~18.16 Hz, which is about 2 Hz lower than that of the typical SR $n=3$ mode, being the same as the case of the 2004 Mid-Niigata prefecture EQ. Polarization analysis suggests that the waves might be rather local.

Anomalous resonance for the 2007 Noto-Hantou EQ is more obvious than the anomaly for the 2004 Niigata-chuetsu EQ, and the anomalous resonance began about 20 h before the EQ. In Figs. 4 and 5, near the origin time (09:41 L.T.) there is a pulse noise generated by the oscillation of magnetic coils because of the main shock of the EQ. Intensity of the anomalous resonance "C" was maximum at 07:40 L.T., about 2 h before the EQ, and decreased after the EQ. This anomalous resonance has no peak in the histogram of phase difference between B_y and B_x exactly like the case of the 2004 Niigata-chuetsu EQ.

3.3. *Summary of observational facts*

The characteristics of anomalous resonances are summarized as follows as already mentioned in Ohta et al. (2009).

1. Intensity of a particular mode of SR increased before the large EQ near the observation station and decreased after the occurrence of the EQ.

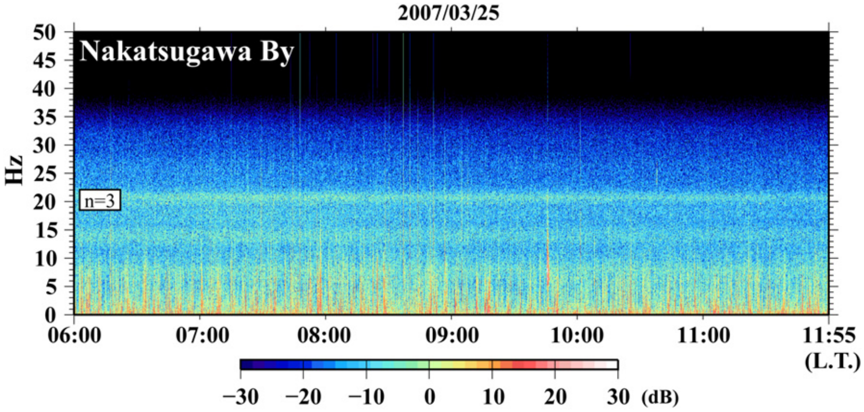

Fig. 4. Excitation of anomalous resonances at 06:00–11:55 L.T. on March 25, 2007 (Nakatsugawa, B_y component). SR $n=3$ mode. Intensity is given in color.

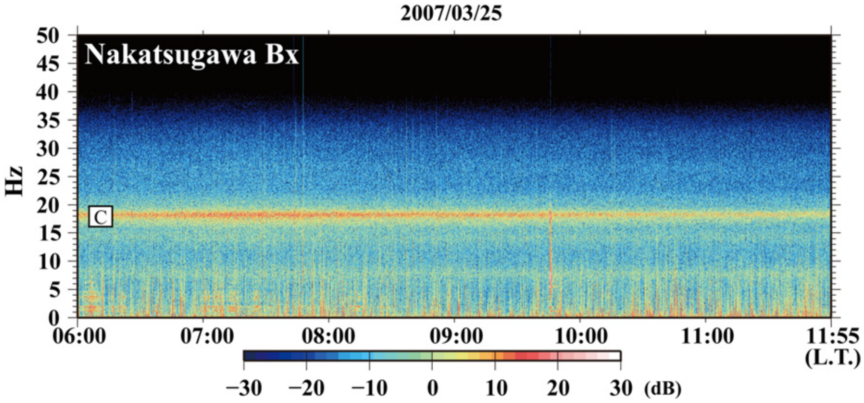

Fig. 5. Excitation of anomalous resonances (line emission C) at 18:00–23:55 L.T. on March 25, 2007 (Nakatsugawa, B_x component). Intensity is given in color.

2. Excitation of another anomalous resonance (line emission) was also observed at the frequency shifted by about 2 Hz from the typical frequency of the SR: ~16 Hz on B_y and ~18 Hz on B_x for the 2004 Niigata-chuetsu EQ, while ~18 Hz only on B_x for the 2007 Noto-Hanto EQ. This anomalous resonance had a higher Q factor (more than 5 times the conventional Q value of SR) and stronger intensity.
3. Since temporal changes of intensity of the anomalous SR and another excited anomalous line emission were almost the same, there is a possibility that the anomalous resonance line emission was closely related with SR.
4. These line emissions are not simultaneous to both B_x and B_y components, but they are observed either on the B_x or B_y component.

4. A possible generation mechanism of SR-like missions

As summarized in the previous section, the new line emissions observed seem to be a local phenomenon. Also the generation of these line emissions tends to be synchronous with those of anomalous intensity of some SR modes. It is difficult to say which is the cause and which is the result, but it seems much more reasonable for us to attribute the well-known SR effect to the cause and to consider that line emissions are its result. As already shown by Ohta et al. (2001) and Schekotov et al. (2007), it is shown that radio emissions in the ELF band are observed prior to an EQ. So the first point in the summary is indicative of suggesting the presence of some seismogenic emissions in a relatively narrow band, including the SR 2nd to 3rd modes as an enhancement of background intensity.

Based on the assumption of incidence of narrow-band ELF seismogenic emissions from below near the observing station, we tried to interpret new line emissions in terms of gyrotropic waves. These gyrotropic waves are excited by coherent polarization electric currents located in the irregularities of ionospheric conductivity, and these currents are assumed to be generated by the narrow-banded ELF seismogenic emissions from below (Sorokin and Fedorovich, 1982; Sorokin and Pokhotelov, 2005). The oscillating noise electric field forms polarization currents on the irregularities of ionospheric conductivity. Gyrotropic waves are propagated within a thin layer of lower ionosphere along the Earth's surface with small attenuation and with phase velocities of the order of tens to hundreds of km/s. Details on these waves have been mentioned in Sorokin and Hayakawa (2008), but we will repeat the parts necessary for further discussion.

We consider the generation of gyrotropic waves due to the occurrence of irregularities in conductivity in the presence of a background electromagnetic field due to the seismogenic effect from below. The magnetic meridian plane is the (x, z)-plane and the magnetic field B is directed in the x direction. The z-axis of our Cartesian coordinate system is locally vertical. This coordinate configuration corresponds to the equator but is considered to be a simplification to the low latitude case as in Japan. The lower ionosphere is assumed to be plane and horizontally stratified with Hall conductivity σ_H and Pedersen conductivity σ_P. Each conductivity is given in the form of $\sigma_{P,H}=\sigma_{P_0,H_0}+\sigma_{P_1,H_1}$, where the subscripts 0 and 1 correspond to the unperturbed and perturbed values, respectively. Typical height profiles of the unperturbed σ_{P_0} and σ_{H_0} conductivities can be found in Sorokin and Hayakawa (2008).

We decompose the electric field and the perturbation of magnetic field as $E = E_0 + E_1$ and $b = b_0 + b_1$, where E_0 and b_0 stand for the electromagnetic field of background noise when $\sigma_{P_1,H_1} = 0$, and E_1 and b_1 are their perturbations caused by the presence of ionospheric inhomogeneities. Ionospheric irregularities are assumed to be stretched along the y-axis, and the spatial scale of conductivity variations in these irregularities is much larger than the temporal scale of electromagnetic oscillations. Let E_{0y} be the horizontal component of electromagnetic background noise (in the present case, this is seismogenic ELF noise from below). The wave is assumed to propagate in the x direction, and the electromagnetic field of this wave has the transverse components, E_{1y} and E_{1z}, which depend on x and z. Then the field component of the wave along the x-axis is equal to zero, $E_{1x} = 0$. Assuming the perturbations to be small, ($|\sigma_{P_1}| \ll |\sigma_{P_0}|$, $|\sigma_{H_1}| \ll |\sigma_{H_0}|$), and neglecting small terms of second order in the ULF/ELF frequency region $\omega \ll 4\pi\sigma_{P,H}/\varepsilon_0$ (ε_0,free space dielectric constant) $\approx 10^7\, s^{-1}$, one finds the equations for the electric field perturbations as follows (Sorokin and Hayakawa, 2008):

$$\begin{aligned}
&k^2 E_{1z} + i\frac{4\pi\omega}{c^2}(\sigma_{H_0}E_{1y} - \sigma_{P_0}E_{1z}) = -i\frac{4\pi\omega}{c^2}\sigma_{H_0} f_H \\
&\left(\frac{d^2}{dz^2} - k^2\right)E_{1y} + i\frac{4\pi\omega}{c^2}(\sigma_{P_0}E_{1y} + \sigma_{H_0}E_{1z}) = -i\frac{4\pi\omega}{c^2}\sigma_{P_0} f_P \\
&E_{1x} = 0
\end{aligned} \tag{1}$$

In Eq. (1) the following designations are introduced:

$$\begin{aligned}
&E_{1,x,y,z}(k,z,\omega) = \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dt\, E_{1,x,y,z}(x,z,t)\exp(-ikx + i\omega t) \\
&f_P(k,\omega) = \int_{-\infty}^{\infty} P(x)E_{0y}(x,\omega)\exp(ikx)dx \\
&f_H(k,\omega) = \int_{-\infty}^{\infty} H(x)E_{0y}(x,\omega)\exp(ikx)dx \\
&P(x) = \sigma_{P_1}(x,z)/\sigma_{P_0}(z),\ H(x) = \sigma_{H_1}(x,z)/\sigma_{H_0}(z)
\end{aligned} \tag{2}$$

The propagation speed of horizontal irregularities in ionosphere conductivity above a seismic region is of the order of acoustic wave velocity u, which is much smaller than that of gyrotropic waves. We choose the dependence of ionosphere conductivity irregularities on the coordinate x in the following form:

$$H(x) = P(x) = A_0 \exp(-x^2/4x_0^2)\cos(k_0 x) \tag{3}$$

where $k_0 = 2\pi/\lambda_0$, $\lambda_0 = uT$, the horizontal spatial scale of conductivity irregularities, T is the temporal scale of conductivity irregularities, $ux_0 \gg \lambda_0$ the horizontal spatial scale of the seismic region, and A_0 the maximal value of relative conductivity disturbances.

The horizontal spatial scale of the background electric field exceeds considerably the spatial scale of conductivity irregularities in the ULF/ELF frequency range. This means that the field varies slowly over the horizontal scale of the irregularities $E_{0y}(x,\omega) \approx E_{0y}(\omega)$. For the solution of Eq. (1) we use the boundary conditions connecting the tangential components of the electrical field and its vertical derivative above and below the ionospheric conducting layer. According to Sorokin and Hayakawa (2008), one finds the horizontal component of magnetic field disturbances on the Earth's surface ($z = -z_1$):

$$\begin{aligned}
&b_{1x}(x, z = -z_1, \omega) = b_{0x}(\omega)\Phi(x,\omega) \\
&\Phi(x,\omega) = \frac{A_0}{2}\exp\left(-\frac{x^2}{4x_0^2}\right)\left[F\left(k_0 + i\frac{x}{2x_0^2},\omega\right)\exp(ik_0x)\right. \\
&\qquad\left. + F\left(k_0 - i\frac{x}{2x_0^2},\omega\right)\exp(-ik_0x)\right]
\end{aligned} \tag{4}$$

Some functions in Eq. (4) are given below:

$$\begin{aligned}
&F(k,\omega) = \frac{g_1 q\sinh(ql) - g_2[1 - \cosh(ql)] + g_3 q^2}{G_1 q\sinh(ql) + G_2 q^2\cosh(ql)} \\
&g_1 = \kappa_H^2; g_2 = \kappa_H^2(|k| - i\kappa_P); g_3 = i\kappa_P; G_1 = \kappa_H^2 - 2k^2 + i\kappa_P|k| \\
&q^2 = k^2 - \kappa_H^2; \kappa_H = 4\pi\omega\sigma_{H_0}/c^2 k; \\
&k_P = 4\pi\omega{\textstyle\sum_{P_0}}/c^2(\textstyle\sum_{P_0},\text{height integrated Peterson conductivity}(\sigma_{P_0}))
\end{aligned} \tag{5}$$

Below we consider the relative spectrum of magnetic pulsations at the epicenter of a seismic region $x = 0$ on the Earth's surface. The magnetic field of background noise $b_{0x}(\omega)$ impacting from below to the ionosphere when $\sigma_{P_1} = \sigma_{H_1} = 0$ has a Gaussian spectrum as follows:

$$b_{0x}(\omega) = b_m \exp\left[-\frac{(\omega - \omega_m)^2}{\Delta\omega^2}\right] \tag{6}$$

where b_m is the maximum amplitude, ω_m the frequency of maximum intensity, and $\Delta\omega$ the width. Substituting Eq. (6) in Eq. (4) one finds

$$b_{1x}(\omega) = b_m A_0 F(k_0,\omega)\exp\left[-\frac{(\omega - \omega_m)^2}{\Delta\omega^2}\right] \tag{7}$$

In the following computations with Eq. (7), we first adopt the following reasonable ionospheric parameters: $A_0 = 0.2$, $\sigma_{H_0} = 2 \times 10^6\,\mathrm{s}^{-1}$, $l = 3 \times 10^6$ cm, $\sum_{P_0} = 5 \times 10^{11}$ cm/s, and $k_0 = 4.5 \times 10^{-7}$ cm^{-1}. The most important point to be consistent with the measurement is that we have to adopt a reasonable spectrum for the input signals from below (in our case, ELF noise in the SR band), i.e. ω_m and $\Delta\omega$ in Eq. (6). The upper panels in (a)–(d) of Fig. 6 indicate the input signals from below, so you can find possible changes in the background ELF spectra. By assuming those input ELF spectra in Fig. 6(a)–(d), the lower panels illustrate the frequency spectra of gyrotropic waves excited in the ionosphere and are expected to be observed on the ground surface, computed for each input ELF signal. The first glance on these figures in Fig. 6 indicates the presence of a few narrow-banded (or line) emissions at ~16 and ~20 Hz. The appearance of these line emissions seems to be rather consistent with the observation in the sense of generating line emissions. However, detailed frequency characteristics are not exactly coincident with the observation, which needs further study. Also, the polarization property (that is, signal A (~16 Hz) on B_y and signal B (~18 Hz) on B_x for the 2004 Niigata-chuetsu EQ, while signal C (~18 Hz) only on B$_x$) should be extensively considered in future by making the modeling more realistic.

As mentioned above we used a simple model of the generation of gyrotropic waves. This model allows us to find the physical mechanism of unusual signal properties. However, calculations based on such a model do not give explanation for all features of the experimental data. We have suggested that horizontal irregularities of ionosphere conductivity are stretched transverse to the geomagnetic field. In this case the wave is propagated along the magnetic meridian in the NS direction and the magnetic field perturbation of gyrotropic waves has only the NS component. Therefore such a simple model does not allow us to calculate the spectral line of the EW magnetic field component. If the horizontal irregularities are stretched under any angle to the plane of magnetic meridian the gyrotropic waves are propagated at an angle to the geomagnetic field. In this case longitudinal perturbation of the magnetic field of gyrotropic waves has two components—NS and EW. Based on the results by Sorokin et al. (2009) it can be shown that the frequency dependences of NS and EW magnetic field components are variable.

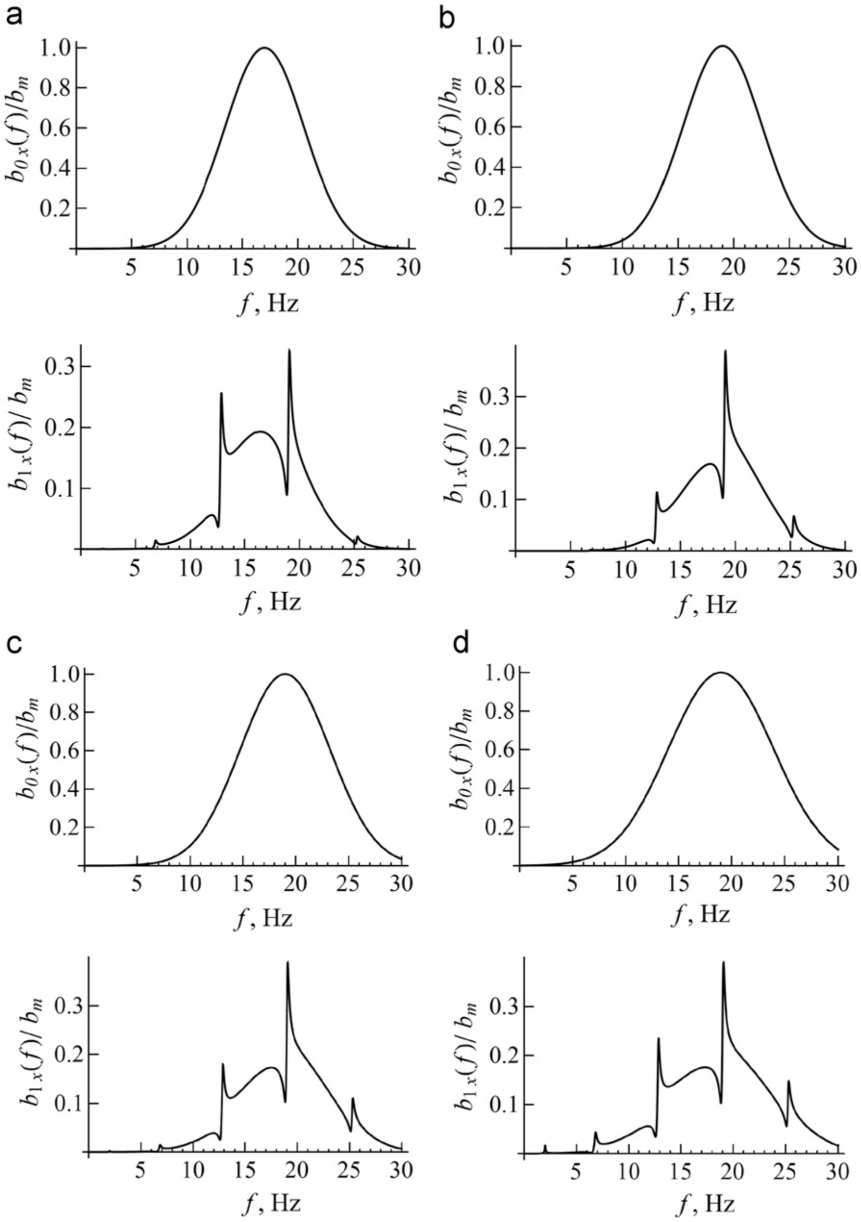

Fig. 6. Calculation results of the frequency spectrum of gyrotropic waves (b_{1x} (f)/b_m, upper panel) on the following different conditions of background noise from below (b_{0x} (f)/b_m, lower panel): (a) f_m=17 Hz, Δf=5 Hz; (b) f_m=19 Hz, Δf=5 Hz; (c) f_m=19 Hz, Δf=6 Hz; and (d) f_m=19 Hz, Δf=7 Hz.

Moreover the difference in spectrum of NS and EW components can be related to the more composite horizontal spatial distribution of ionosphere irregularities, which are the source of gyrotropic waves. Such a source generates waves with various wave vectors with amplitude and direction, which leads to a difference in the spectrum. All these problems require further theoretical work.

As shown above, the characteristics of spectral lines (frequency of maximum, width) depend on conductivity of the ionosphere. No day/night asymmetry observed in spectral line characteristics denotes a small variation of conductivity from day to night. Such a situation can be realized when the electric current flows from the atmosphere into the ionosphere over a region of EQ preparation. Based on the electrodynamic model of atmosphere–ionosphere coupling (Sorokin, 2007; Sorokin and Chmyrev, 2009) it can be shown that the atmosphere current in this region leads to an increase in conductivity of the night time ionosphere by 15 times while the change of conductivity of the ionosphere is negligible at day. Consequently, the effect of atmosphere current results in an insignificant variation of ionosphere conductivity over the seismic region. Therefore, all parameters of spectral lines have a small variation in this region. Of course we can say that no day/night asymmetry as observed in this paper warrants further investigation.

5. Conclusion

Anomalous SR phenomena and associated line emissions have been detected in possible relation to two EQs (the 2004 Niigata-chuetsu EQ and the 2007 Noto-Hantou EQ) close to the observatory of Nakatsugawa. The epicentral distance is a few hundred kilometers. In the case of the former EQ, the SR third (n=3) mode is enhanced, together with the generation of line emission signal A (~16 Hz) on the B_y component and another line signal B (~18 Hz) on the B_x component. On the other hand, for the latter EQ the SR third mode is enhanced and the line signal

C ($\sim$18 Hz) appeared only on the B_x component. These anomalous effects are observed a few days or a few hours prior to the EQ (as an EQ precursor). These general characteristics of line emissions have been tried to be interpreted in terms of generation of gyrotropic waves as a consequence of the background noise from below. In conclusion, the agreement at the moment is not satisfactory, but not so bad, which might indicate that the abnormal line emissions are an experimental evidence of gyrotropic waves as suggested by Sorokin and Hayakawa (2008). However, there are still a few points to be clarified, including a small difference between the theoretical expectation and observation, how to explain the polarization of anomalous line emissions, etc., so we need more refinement of the model.

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References

Fraser-Smith, A.C., 2009. The ultralow-frequency magnetic fields associated with and preceding earthquakes. In: Hayakawa, M. (Ed.), Electromagnetic Phenomena Associated with Earthquakes. Transworld Research Network, Trivandrum, India, pp. 1–20.

Kopytenko, Yu.A., Ismagilov, V.S., Nikitina, L.V., 2009. Study of local anomalies of ULF magnetic disturbances before strong earthquakes and magnetic fields induced by tsunami. In: Hayakawa, M. (Ed.), Electromagnetic Phenomena Associated with Earthquakes. Transworld Research Network, Trivandrum, India, pp. 21–40.

Hayakawa, M. (Ed.), 1999. Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. TERRAPUB, Tokyo, 996pp.

Hayakawa, M., 2007. VLF/LF radio sounding of ionospheric perturbations associated with earthquakes. Sensors 7, 1141–1158.

Hayakawa, M. (Ed.), 2009. Electromagnetic Phenomena Associated with Earthquakes. Transworld Research Network, Trivandrum, India, 279pp.

Hayakawa, M., 2009a. Seismogenic perturbation in the atmosphere. In: Hayakawa, M. (Ed.), Electromagnetic Phenomena Associated with Earthquakes. Transworld Research Network, Trivandrum, India, pp. 119–136.

Hayakawa, M., 2009b. Lower ionospheric perturbations associated with earthquakes, as detected by subionospheric VLF/LF radio waves. In: Hayakawa, M. (Ed.), Electromagnetic Phenomena Associated with Earthquakes. Transworld Research Network, Trivandrum, India, pp. 137–185.

Hayakawa, M., Molchanov, O.A. (Eds.) 2002. Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. TERRAPUB, Tokyo, 477pp.

Hayakawa, M., Hobara, Y., 2010. Current status of seismo-electromagnetics for short-term earthquake prediction. Geom. Nat. Hazards Risk 1 (2), 115–155.

Hayakawa, M., Hattori, K., Ohta, K., 2007. Monotoring of ULF (ultra-low-frequency) geomagnetic variations associated with earthquakes. Sensors 7, 1108–1122.

Hayakawa, M., Ohta, K., Nickolaenko, A.P., Ando, Y., 2005. Anomalous effect in Schumann resonance phenomena observed in Japan, possibly associated with the Chi-chi earthquake in Taiwan. Ann. Geophys. 23, 1335–1446.

Hayakawa, M., Nickolaenko, A.P., Sekiguchi, M., Yamashita, K., Ida, Y., Yano, M., 2008. Anomalous ELF phenomena in the Schumann resonance band as observed at Moshiri (Japan) in possible association with an earthquake in Taiwan. Nat. Hazards Earth Syst. Sci. 8, 1309–1316.

Hayakawa, M., Kasahara, Y., Nakamura, T., Hobara, Y., Rozhnoi, A., Solovieva, M., Molchanov, O.A., 2010a. On the correlation between ionospheric perturbations as detected by subionospheric VLF/LF signals and earthquakes as characterized by seismic intensity. J. Atmos. Solar–Terr. Phys 72, 982–987.

Hayakawa, M., Kasahara, Y., Nakamura, T., Muto, F., Horie, T., Maekawa, S., Hobara, Y., Rozhnoi, A.A., Solovieva, M., Molchanov, O.A., 2010b. A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes. J. Geophys. Res. 115 (A09305. doi:10.1029/2009JA015143.

Molchanov, O.A., Hayakawa, M., 2008. Seismo Electromagnetics and Related Phenomena: History and Latest Results. TERRAPUB, Tokyo 189pp.

Nickolaenko, A.P., Hayakawa, M., 2002. Resonances in the Earth–Ionosphere Cavity. Kluwer Acad. Press, Dordrecht p. 380.

Nickolaenko, A.P., Hayakawa, M., Sekiguchi, M., Ando, Y., Ohta, K., 2006. Model modifications in Schumann resonance intensity caused by a localized ionosphere disturbance over the earthquake epicenter. Ann. Geophys. 24, 567–575.

Ohta, K., Umeda, K., Watanabe, N., Hayakawa, M., 2001. ULF/ELF emissions observed in Japan, possibly associated with the Chi-Chi earthquake in Taiwan. Nat. Hazards Earth Syst. Sci. 1, 37–42.

Ohta, K., Watanabe, N., Hayakawa, M., 2006. Survey of anomalous Schumann resonance phenomena observed in Japan, in possible association with earthquakes in Taiwan. Phys. Chem. Earth 31, 397–402.

Ohta, K., Izutsu, J., Hayakawa, M., 2009. Anomalous excitation of Schumann resonances and additional anomalous resonances before the 2004 Mid-Niigata prefecture earthquake and the 2007 Noto Hantou Earthquake. Phys. Chem. Earth 34 (6–7), 441–448 (Special issue, Electromagnetic Phenomena Associated with Earthquakes and Volcanoes, Edited by M. Hayakawa, J. Y. Liu, K. Hattori, and L. Telesca).

Schekotov, A.Y., Molchanov, O.A., Hayakawa, M., Fedorov, E.N., Chebrov, V.N., Sinitsin, V.I., Gordeev, E.E., Belyaev, G.G., Yagova, N.V., 2007. ULF/ELF magnetic field variations from atmosphere induced by seismicity. Radio Sci. 42 (RS6S90. doi:10.1029/2005RS003441.

Sorokin, V.M., 2007. Plasma and electromagnetic effects in the ionosphere related to the dynamic of charged aerosols in the lower atmosphere. Russ. J. Phys. Chem. No. 1, 138–170.

Sorokin, V.M., Fedorovich, G.V., 1982. Propagation of short-period waves in ionosphere. Radiophysics 25, 495–501.

Sorokin, V.M., Chmyrev, V.M., 2009. Atmosphere–ionosphere electrodynamic coupling. In: Dychkov, V.L., Golubkov, G.V., Nikitin, A.I. (Eds.), The Atmosphere and Ionosphere: Dynamics, Processes and Monitoring. Springer.

Sorokin, V.M., Pokhotelov, O.A., 2005. Gyrotropic waves in the mid-latitude ionosphere. J. Atmos. Solar–Terr. Phys. 67, 921–930.

Sorokin, V.M., Sergeev, I.Yu., Pokhotelov, O.A., 2009. Low latitude gyrotropic waves in a finite thickness ionospheric conducting layer. J. Atmos. Solar–Terr. Phys. 71, 175–179.

Sorokin, V.M., Hayakawa, M., 2008. On the generation of narrow-banded ULF/ELF pulsations in the lower ionospheric conducting layer. J. Geophys. Res. 113 (A06306. doi:10.1029/2008JA013094.

Yano, M., Ida, Y., Hobara, Y., Hayakawa, M., Nickolaenko, A.P., 2010. Reception of ELF transmitter signals at Moshiri, Japan, and their propagation characteristics. Radio Sci. 45 (RS1009. doi:10.1029/2009RS004224.