Electromagnetic Phenomena Associated with Earthquakes

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Electromagnetic phenomena are recently found to take place prior to an earthquake, and they are regarded as the most promising candidate for short-term earthquake prediction. This report reviews the recent findings on seismo electromagnetic phenomena, including ULF emissions, seismo-atmospheric and -ionospheric perturbations, Earth’s surface temperature anomaly, in-situ observational results etc.

Keywords: Electromagnetic phenomena, earthquake, ULF emissions, subionospheric VLF/LF propagation anomaly, lithosphere-atmosphere-ionosphere coupling

1. Present Situation of Short-term Earthquake Prediction

In recent years the wind prevailing in the scientific community does not appear to be favorable for the earthquake prediction research, in particular for the research on short-term prediction. Considering the difficulties associated with such factors as the highly complex nature, rarity of large earthquakes and subtleties of possible presiseismic signatures, the present negative view is not groundless.

However, the earthquakes are nothing but physical phenomena and science should have some predictive power on the future behavior of any physical system. Actually, some significant new waves have been rising in earthquake prediction science with the introduction of new ideas and technologies. Seismo-electromagnetics is a new and promising approach. The International Workshop on Seismo Electromagnetics (IWSE) organized by M. Hayakawa (the 4th IWSE was held in March, 2005) has been extremely active in promoting this discipline during the last decade.

2. Observation Methods of Seismogenic Phenomena

Recently there have been accumulated a lot of convincing evidence on the presence of precursory electromagnetic signature of earthquakes1-5. Based on the recent results on those seismogenic effects, we can summarize and classify the principal observational methods as follows:

(1) Passive observation: We observe the electromagnetic emissions from the lithosphere, and try to correlate these emissions with an earthquake.

(2) Active measurement (or radio probing) of the environment: With the use of pre-existing radio transmitters in different frequency ranges (from VLF to VHF), we try to observe the seismo-atmospheric and -ionospheric perturbations. GPS is a new direction in this category, to study the TEC (total electron contents).

(3) In-situ (satellite) observation: Radio emissions, ionospheric plasma perturbations etc. are detected on board a satellite, to be correlated with the ground-data on seismo-electromagnetics and with earthquakes.

(4) Earth’s surface measurement: Remote sensing from a satellite enables us to monitor the situation of Earth’s surface temperature and any associated phenomena.

As will be found in the following sections, the atmosphere and ionosphere are found to be strongly perturbed due to the seismic activity. So that, our new science is sometimes called, “Seismo Electromagnetics”, but we prefer the terminology, “Lithosphere-Atmosphere-Ionosphere (LAI) Coupling” or “Electromagnetic Phenomena in the Coupled Lithosphere-Atmosphere-Ionosphere System” from the standpoint of science. This means that the lithospheric changes due to pre-seismic activity can be regarded as the initial condition (in the time sequence) of the LAI coupling and also as the lower-bottom boundary condition of this coupled and complex system.

3. ULF Emissions and Recent Findings

There have been reported convincing results on ULF (frequency less than 1Hz) emissions for the three big earthquakes in the world; Spitak, Loma Prieta and Guam earthquakes4-6. The observation for the Loma Prieta earthquake indicates that there is the first enhancement from two weeks to one week before the earthquake, followed by a quiet period about one week before and a sharp increase a few days before the earthquake. It is confirmed by the subsequent studies that this temporal evolution is universal for any earthquake.

We will show the recent works on seismogenic ULF emissions. First is related to the observational system development, the second, sophisticated signal processing to indentify weak seismogenic emissions and the third, the generation mechanism of ULF emissions.

Firstly, we have established a network of ULF measurement in the Kanto (Tokyo) area in order to prepare for any large earthquakes in Tokyo6-7. It is important to predict any large earthquakes with M≧6 in a highly populated region to mitigate the disasters. The network is composed of several stations: (1) Izu peninsula, (2) Boso (Chiba) peninsula, (3) Kakioka, (4) Chichibu and (5) Matsushiro. The interstation distance is about 80-100km, which is based on the full-wave estimation by Molchanov et al. (1995), who have shown that we could detect ULF emissions within a radius of ~100km for an earthquake with magnitude=7 and within ~80-70km for a M=6 earthquake. Furthermore, there are three or four closely-spaced stations both in the Izu and Boso peninsulas. The observations by this Kanto network have been going good for the last few years. Similar ULF networks are known to be installed in Kamchatka (Uyeda et al., 2001), Taiwan,
Greece, etc. The ULF observation is being continued with great efforts in these countries.

The second point is the signal processing. In addition to the conventional intensity measurement, there have been proposed several methods for polarization analysis, fractal analysis (mono and multi), wavelet analysis, direction finding measurement etc. The polarization analysis is based on the measurement of the ratio of vertical magnetic field component to the horizontal one, and it is found that this method is of potential use in distinguishing seismogenic effect from other noises. The wavelet analysis is also used in identifying the seismogenic ULF emissions. The fractal analysis is based on the concept of self-organized criticality (SOC), which tries to study the nonlinear dynamics taking place in the lithosphere. Direction finding is a promising technique to locate the source region of a future earthquake; gradient of the wave magnetic field, goniometer etc. Development of further sophisticated signal processing is highly required.

Figure 1 is the global summary on the pre-seismic ULF magnetic field changes. An open circle indicates the presence of seismogenic emissions, while a black circle, the absence of seismogenic ULF emissions. All of the events published are summarized in this figure. This figure is given in the form of magnitude (M) versus epicentral distance R. The broken line is the threshold for possible appearance or detection of seismogenic ULF emissions, which can be expressed by 0.025R=M−4. This empirical threshold seems to be consistent with the theoretical estimation by Mochanov et al. (1995)4). A few mechanisms of generation of seismogenic ULF emissions have been proposed. The first one is electro-kinetic effect, and another is based on microfracturing. Several authors have extended this microfracturing mechanism (see Ref.(4)).

Theoretical calculations are made on electromagnetic field in the ULF range on the ground surface and above the ionosphere included by any stochastic microcurrent activity inside the future seismogenic sources on the assumption of cylindrical symmetry of the effective current and three types of polarization (Molchanov et al., 1995). The intensity of ULF magnetic and electric precursors observed on the ground, and their spatial distribution can be explained by using their computational results.

Being closely associated with the generation mechanism, the most important quantity for the ULF source is the estimation of current source intensity, although there are some uncertainties in the source structure. By using both the full-wave method by Molchanov et al. (1998) and the Biot-Savart’s law, Kawate et al. (1998) tried to estimate the current source for the Guam earthquake and estimate the frequency spectrum and intensity, which is in good agreement with the observation.

4. Other Phenomena in the Lithosphere and Anomaly of Earth’s Surface

ULF emission is one aspect of the boundary and initial condition of the LAI coupling system. Another physical quantity is the acoustic emissions (AE), reflecting information on the microfracturing in the lithosphere. We have found that the AE intensity increases about 12 hours before an earthquake and decays over half a day5).

Another measurement is monitoring of Earth’s surface temperature. Tronin et al. (2002) have indicated the presence of positive thermal anomalies associated with large linear structures and fault systems in the Earth’s crust5). Recently, some other groups (Italian, Indian/American and NASA groups) have started this satellite image studies. This would be an important input to the seismic effect taking place in the atmosphere.

5. Seismo-atmospheric Perturbations

The seismo-atmospheric perturbations have been studied by means of over-horizon VHF signal reception (Fukumoto et al., 2001). Initially it was a report that we could observe the over-horizon VHF signals in possible association with an earthquake, and they assumed that this is due to the ionospheric scattering. Fukumoto et al. (2001) have employed a direction finding system composed of Yagi-antennas directed in different directions in azimuth and in elevation. When they have observed anomalous reception at Chofu of over-horizon FM signals from Sendai, they have found that the elevation is extremely small, leading them to consider that such over-horizon reception of VHF signals is attributed to the perturbation in the atmosphere (not ionospheric effect). The correlation between such reception and earthquakes has indicated that the anomalous reception takes place about one week before an earthquake6). Further studies on the characteristics of such over-horizon VHF signals are highly required; such as the development of interferometric direction finding and also the mechanism of generating such seismo-atmospheric perturbations.

6. Seismo-ionospheric Perturbations as Detected by Subionospheric VLF/LF Propagation

We were the first to present convincing results on ionospheric perturbations associated with the Kobe earthquake (on January 17, 1995) by means of subionospheric VLF propagation (Hayakawa et al., 1996a; Molchanov et al., 1998)5). We proposed a new method of analysis based on terminator time. We discovered a significant shift in terminator times as shown in Fig. 2, illustrating the day-to-day sequence of diurnal variations of the phase (10.2kHz) as measured at Inubo (geographic coordinates; 35°42’ N, 140°52’ E) using a VLF Omega signal transmitted from Tsushima (34°37’ N, 129°27’ E). The terminator time is defined as the time when the diurnal phase (or amplitude) variation exhibits a minimum around sunrise and sunset (which we call morning (tm) and evening (te) terminator times). Figure 2 shows a significant change in terminator times before the quake, because the hatched area means the deviation in the terminator time from the
and (e) NLK (24.8kHz, USA). We have already accumulated
(c) NPM (21.4kHz, Hawaii), (d) JJI (22.2kHz, Ebino, Kyushu)
(a) JJY (40kHz, Fukushima), (b) NWC (19.8kHz, West Australia).

Each station, we have been receiving several VLF/LF transmitters;
Shimizu, Kasugai (Nagoya), Maizuru (Kyoto) and Kochi. Then, at
stations; Moshiri (Hokkaido), Chofu (UEC), Chiba (Tateyama),
established a VLF network in Japan, consisting of seven observing
earthquakes, and the second is concerned with event studies for
the study on the correlation between ionospheric perturbations and
the associated statistical
simultaneously. The first is the accumulation of convincing results
above network. We are now going in two directions
several years of data on the basis of observations by means of the
Japanese VLF network, the papers by Shvets et al. (2002, 2004),
Kamchatka station is being operated simultaneously with our
Kamchatka, where we receive a few VLF/LF transmitters. This
mention here is that we also installed our VLF receiver in
Hokkaido, and has the magnitude of 8.3. An important point to
note is the fact that the earthquake was named "Tokachi-oki earthquake" (5).
It occurred on September 23, 2003 in the area of the Oki Islands, and has the magnitude of 8.3.

In-situ satellite observations would be of extreme importance in
the study of LAI coupling. Previous in-situ observations on
ionosphere's sudden change during daytime 1 days before the
earthquake. Subsequent statistical studies on F2 and some
parameters (geomagnetic activity etc.) and seismic activity
perturbations with special reference to their relation to geophysical
processes becomes apparent mainly for M>5.5. The most probable
times of phase amplitude anomalies are 7 and 2-3 days before
the earthquake.

7. Seismic Effects in the Upper Ionosphere

It is already evident that the lower ionosphere is strongly
perturbed during and after a large earthquake. If we are to
understand the mechanism of the perturbations, it is necessary to
study the ionospheric changes associated with seismic activity
and the magnetic field. The lower ionosphere is strongly
perturbed due to the seismic effect. Lower ionosphere is extremely
disturbed, with a few kilometers of plasma density perturbation in possible association with
different propagation paths from the Japanese LF transmitter (JJY,
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Further studies are being continued on the theoretical estimation
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8. LAI Coupling Mechanism

The most important contribution of our NASDA’S Frontier Project is the accumulated evidence of ionospheric perturbations associated with earthquakes and some findings on seismo-atmospheric effects, in addition to the already-existing many results on lithospheric phenomena as revealed by subsurface measurements. This leads to a new science field such as “LAI coupling”, or “Electromagnetic phenomena in the coupled LAI system” and large amount of effort is now being devoted to understanding more fully the mechanisms of this coupling. Figure 3 illustrates the possible channels we suggest for the LAI coupling. The first one is the chemical channel, the 2nd one, the acoustic channel and the 3rd one, the electromagnetic channel. As for the chemical channel, the change in geochemical parameters (gas or radon emanation, water elevation etc.) leads to changes in the conductivity of the air and results in modification of the atmospheric electric field. This field will then influence the plasma density in the ionosphere. As for the acoustic channel, we may except excitation of atmospheric oscillations, which propagate upward into the ionosphere, modifying the ionospheric plasma density. As for the electromagnetic channel, we know that ULF emissions are generated before an earthquake and those emissions propagate into the inner magnetosphere and they interact with energetic particles there. Then we expect the precipitation of those particles into the lower ionosphere. Or, we may expect the direct heating (and/or ionization) of the ionosphere by means of seismo-ELF/VLF waves.

What we have to do in near future, is to understand which channel is major in the LAI, and there have been recently done a lot of works in this direction. Molchanov and Hayakawa (1998a) have found the significant enhancement of the fluctuation with periods of ~5 days and/or 10~11 days in the frequency range of planetary waves before the large earthquakes, which may indicate the important role of atmospheric oscillation in the LAI. Then, Molchanov et al. (2001) have experimentally examined the fluctuation in the gravity wave range in the VLF/LF signals, and have found significant enhancement of the fluctuation in this frequency range just around the earthquakes. The existence of modulation due to gravity waves in LF signal amplitude is presented to support the above hypothesis. Some further supports to the acoustic channel have been provided, for example, as presented in Section 2.3 in this paper for a specific large earthquake of Tokachi-oki earthquake. However, Russians and Taiwanese are in favor of the chemical channel.

Finally, we have to comment on the French DEMETER satellite (Parrot, 2002). It was launched in the end of June, 2004, which is strongly expected to have intensive coordination with the ground-based observations as mentioned in this paper. This satellite-ground coordination would surely contribute a lot to the better understanding of the LAI coupling.

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References


Masashi Hayakawa (Member) was born in Nagoya, Japan on February 26, 1944. He received the B.E., M.E., and Doctor of Engineering degrees, all from Nagoya University in 1966, 1968 and 1974, respectively. In 1970, he joined the Research Institute of Atmospherics, Nagoya University, as a Research Associate. He became an Assistant Professor in 1978 and an Associate Professor in 1979, at the same Institute. Since 1991, he has been a Professor with the University of Electro-Communications, Tokyo, Japan. He has been engaged in space physics, atmospheric electricity, seismo- electromagnetics, signal processing, EMC, radio communication, and inversion problems. Dr. Hayakawa is the former (1996-1999) URSI Commission E Chair, and the former President of the Society of Atmospheric Electricity of Japan. He is now Associate Editor of Radio Science, Editor of J. Atmos. Electr., and on the editorial board of Indian J. Radio and Space Physics. He is on the Technical Committee of Zurich EMC Symposium, on the Scientific Program Committee of Wroclaw EMC Conference etc., He is a member of the American Geophysical Union, URSI, Institute of Electronic Information Communications Engineers Japan, the Society of Atmospheric Electricity of Japan, and the Society of Geomagnetism and Earth, Planetary and Space Science.