Paper

Natural Electromagnetic Phenomena and Electromagnetic Theory: A Review

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We review the new findings on natural electromagnetic phenomena in the near-Earth environment and will show the importance of electromagnetic analyses in elucidating the essential points of these phenomena. The topics include (1) atmospheric phenomena related to lightning (e.g. mesospheric optical emissions); (2) seismo-electromagnetic phenomena (electromagnetic phenomena associated with earthquakes and/or volcano eruptions); (3) plasma and wave phenomena in the Earth's ionosphere and magnetosphere; and (4) electromagnetic or electrodynamic coupling among different regions. We pay our greatest attention to the unsolved essential problems for each subject, and suggest how electromagnetics would contribute to a solution to those problems.

Keywords: Natural electromagnetic phenomena, electromagnetic theory, atmospheric electricity, seismogenic emission, space plasma, computational electromagnetics

1. Introduction

We know that the near-Earth environment is occupied by electromagnetic noise over a wide frequency range from DC to VHF (1). Fig. 1 illustrates the frequency spectrum of the terrestrial electromagnetic noise environment (2). Noises of higher frequency include solar radiation, galactic noise and interplanetary noise, and there are terrestrial noises generated in the near-Earth at lower frequencies. The important electromagnetic phenomena very close to us are summarized as follows: (1) electromagnetic phenomena associated with lightning discharges in the atmosphere, (2) electromagnetic phenomena in the ionospheric/magnetospheric plasma, and (3) electromagnetic phenomena originating in the lithosphere (1). The first and second phenomena are not so new, but there have been many new discoveries about them. For example, we have observed a new phenomenon called mesospheric optical emissions associated with lightning discharges. This has led us to the interesting subject of atmosphere-ionosphere electrodynamic coupling. The third phenomenon, which is completely new, has led to the accumulation of convincing evidence about seismo-electromagnetic phenomena that could be very promising in the field of short-term earthquake prediction (3) (4). It is becoming clear that we can detect not only emissions in a wide range of frequencies, from DC, ULF to VHF, that originate in the lithosphere, but also convincing evidence on perturbations in the atmosphere and also in the ionosphere due to seismic effects. However, the generation mechanisms of those emissions and lithosphere-atmosphere-ionosphere coupling are very poorly understood.

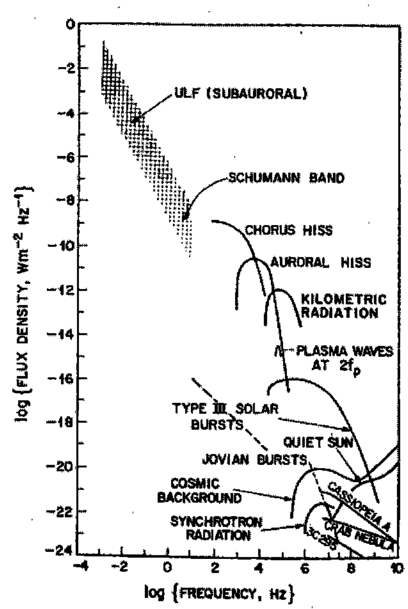

Fig. 1. Frequency spectrum of terrestrial electromagnetic noise environment (after Lanzerotti and Southwood (2))

On the other hand, we understand that a great deal of progress is being achieved in the field of computational electromagnetics because many useful methods such as the finite element method (FEM) and the finite difference time domain method (FDTD) have been developed and applied to different kinds of problems, mainly in the

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field of electrical and electronic engineering [5]. However, such computational analysis methods have not been extensively applied to geophysical or natural electromagnetic phenomena.

The Technical Committee on Electromagnetic Theory (EMT) at the Institute of Electrical Engineers of Japan (IEE) has established a new working group called the "Natural Electromagnetic Phenomena and Electromagnetic Analysis Working Group" (which the authors are affiliated with). The objective of this working group is to bring together scientists working in the fields of (1) natural electromagnetic phenomena and (2) computational electromagnetics, and to collaborate in order to elucidate the essential unsolved problems of natural phenomena by applying appropriate computational electromagnetic analytical methods.

In the following, we will describe recently discovered electromagnetic phenomena in different areas and discuss possible applications of recent computational electromagnetic methods to these natural problems.

2. Electromagnetic Phenomena Associated with Lightning

There are a few important and interesting subjects related to atmospheric lightning discharges and their coupling to transmission lines.

2.1 Coupling of Lightning Discharges to Transmission (and/or Power) Lines The problem of the coupling of external electromagnetic waves (such as lightning discharges and geomagnetic disturbances) to transmission (and/or power) lines, is of fundamental importance in the field of electromagnetic compatibility (EMC). Direct coupling of lightning to transmission/power lines has been widely and extensively studied, but little study has been done on the induction of power transmission lines when a lightning discharge strikes the ground close to a line [6].

2.2 Mesospheric Optical Phenomena Associated with Lightning Discharges and Related Electromagnetic Phenomena Summertime lightning normally is a negative cloud-ground (CG) discharge, but we know that about 10% of the lightning discharges are +CG. It has recently been found that on some occasions when we have +CG, we observe optical emissions in the mesosphere along with several other related phenomena. The most fascinating optical emission is called "Red Sprites"; blue jets and elves are among the others. The presence of this kind of possibility of cloud-to-ionospheric discharge was suggested many years ago, but Franz et al. were the first to detect sprites by means of a highly sensitive video camera [1]. A great deal of work on optical emissions has been accumulated since then. In particular, after 1994, an American group has conducted a series of special sprite campaigns. Another type of mesospheric optical emission has been found by Fukunishi et al. (1996) [7]. Several related phenomena, including ionospheric perturbations, ELF transients, γ-ray emissions etc. that are associated with these mesospheric optical emissions have been observed. Fig. 2 provides a summary of them.

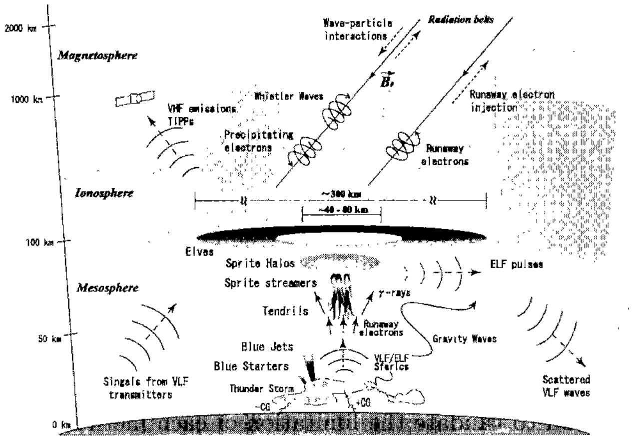

Fig. 2. Schematic illustration on the mesospheric optical emissions associated with lightning discharges and the related phenomena [8]

Modeling of sprites and elves has been extensively carried out during the past few years. It was suggested that sprites are produced by large quasi-electrostatic (QE) fields at mesospheric altitudes, resulting from the sudden removal of charge due to +CG discharges (Pasko et al., 1997) [9]. They used the electrostatic (ES) code for this study. Elves are generally believed to be due to the direct heating (and/or ionization) of the lower ionosphere by means of lightning radiation. Cho and Rycroft (1998) have developed a model including both the QE field and electromagnetic pulse processes by means of the electromagnetic (EM) code [10]. Further electromagnetic studies are required before we reach a general agreement.

Recently, Takahashi et al. [11] and Hayakawa et al. [12] have studied the sprites associated with winter lightning in the Hokuriku District. Japanese winter lightning over the coast of the Japan Sea is known to be significantly different from summer lightning on the continents. Significant differences for the Hokuriku lightning are their large charge, smaller cloud height, small-scale, and nearly equal occurrence of − and +CGs etc. The winter lightning in the Hokuriku area is found to be much smaller than the minimum size of 50∼70km for sprite generation, but we have observed sprites in Hokuriku. We show one example from our observations in Fig. 3. The most essential difference is a much simpler shape for the Hokuriku sprites as compared with the continental sprites [12]. However, we have found the conditions of (1) positive polarity and (2) charge transfer (Q ds) larger than the threshold (∼200 C·km), which are supporting the continental results [12]. Why and how is such a small-scale structure able to trigger a sprite in the Hokuriku area? We are performing fractal analysis of radar images of thunderstorms, which may indicate some effect of self-organization in the thundercloud. We think that such fine structures in the thundercloud may not be a minor effect, but play a central role in the sprite generation. This effect should be seriously taken into account in computer simulation using the ES and EM codes.

As for the ionospheric perturbations associated with these optical emissions, there have been several electromagnetic papers dealing with the scattering of VLF signals. Such ionospheric perturbations are detected as anomalies in amplitude and phase of subionospheric VLF propagation, and they are called "Trimpi" phenomena. Trimpi modeling is a typical subject of electromagnetics or electromagnetic scattering. Initially, a few papers were published on Trimpi modeling by means of the Born approximations (Poulsen et al., 1993) [(13)]. Later the non-Born method was developed by Baba and Hayakawa(1996) by using the FEM, though this was two-dimensional [(14)]. Then, Nunn et al. (1998) compared the 3D Born approximation with the non-Born method to validate the limitation of each method [(15)].

The VLF scattering from the ionospheric perturbations associated with elves is found to be relatively weak. This can be well understood by any of the computational methods. However, the structure and dynamics of ionospheric perturbations in the case of a sprite occurrence are poorly understood. The VLF scattering is known to be extremely strong, but it is very difficult to account for it. Dowden et al. (1996) have postulated the presence of sprite-induced plasma columns with a diameter of a few kilometers, but the theoretical estimation for these kinds of very thin plasma columns has indicated the weak scattering observation [(16)]. Further theoretical studies on Trimpi modeling especially for the sprite occurrence are required to arrive at agreement between the observation and modeling. Recently, Nagao et al. have succeeded in performing a simulation of elves by means of the EM code [(17)].

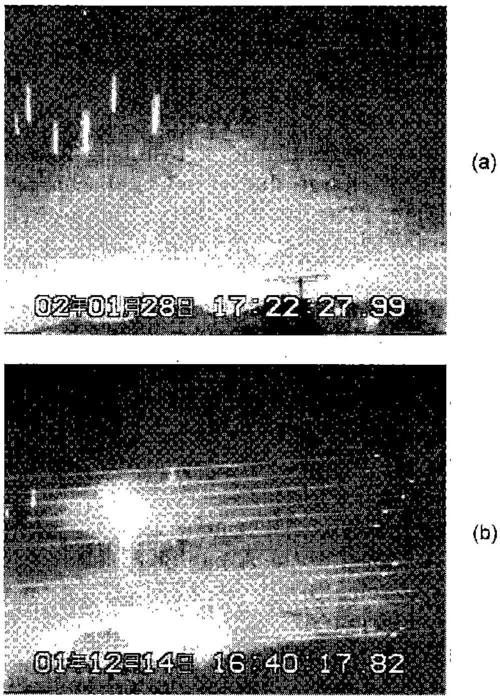

Fig. 3. An example of winter sprites in the Hokuriku area (Japan sea side)

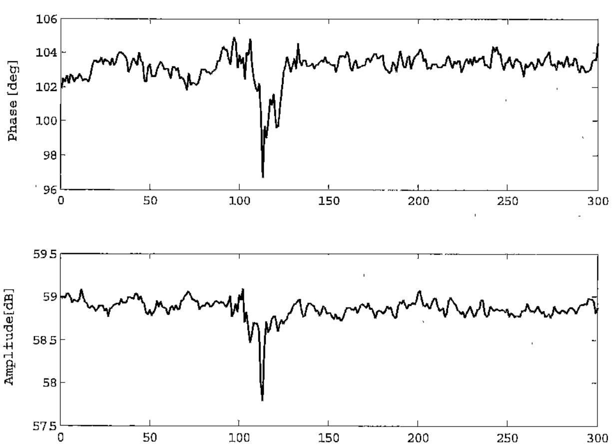

Fig. 4. An example of lightning-induced Trimpis as an anomaly in subionospheric VLF propagation (in amplitude and phase).

We finally comment on the ELF radiation associated with sprite occurrence. From simultaneous measurement of bulk-sprite brightness and ELF-radiating current-moment waveforms, it is found from the observation that sprite-producing lightning discharges exhibit a second current peak proportional to the sprite brightness, suggesting that the observed second ELF pulse is produced by intense electrical currents flowing in the sprite body (see Fig. 5) [(18)]. This subject, which is poorly understood, is closely related to the above Trimpi modeling. Here, substantial work is required by means of the electromagnetic and electrodynamic theory.

2.3 ELF Propagation in the Earth-ionosphere Waveguide The ELF transients discussed in the previous section are known to propagate in the Earth-ionosphere waveguide as the TM_0 mode of propagation [(19)]. This cavity is known to exhibit resonances in the ELF range, which are triggered by lightning discharges. Known as "Schumann resonances," the resonances peak at the frequencies of 8, 14, 21Hz, etc. [(19)].

There have been a lot of investigations of this ELF propagation in the Earth-ionosphere waveguide (see recent reviews [(19)(20)]), and detailed description of the ionospheric modeling has been summarized in Nickolaenko and Hayakawa (2002) [(19)]. The factors making this ELF problem very complicated, are (1) vertical (radial) atmospheric conductivity (ionospheric density)

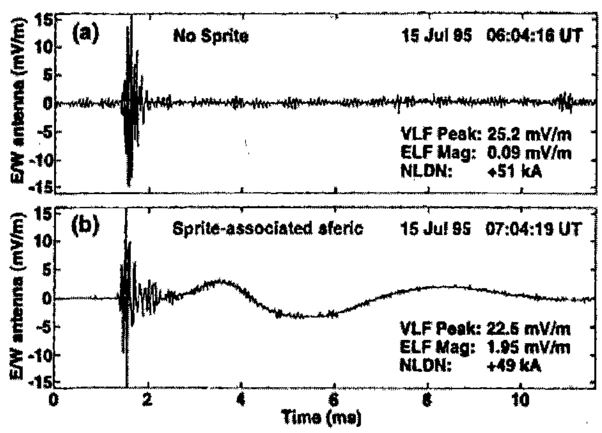

Fig. 5. An example of slow-tails observed in association with red sprites [(18)]

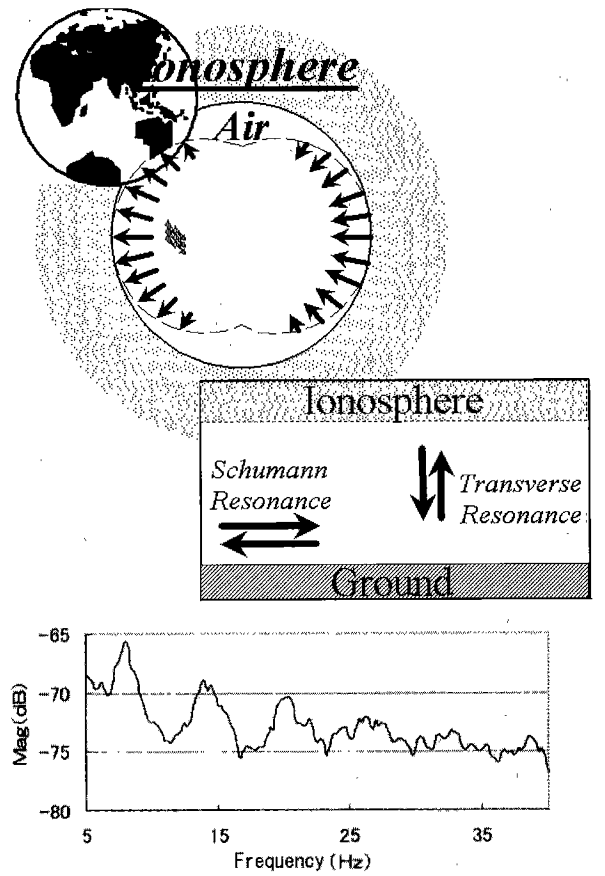

Fig. 6. Schumann resonances and their frequency spectrum

inhomogeneity; (2) the presence of day-night asymmetry in the ionosphere; and (3) local perturbations. It is very difficult to obtain analytical solutions for the complicated cavity structure. We have proposed the use and application of one of the currently popular computational methods, the FDTD method, to this ELF problem [21]. This would allow us to investigate in full detail the validity of previous approximate models and the reflection mechanism of ELF waves in the ionosphere. Extensive comparison between the observed data (i.e. resonance amplitude, resonance frequency, etc.) and theoretical modeling by any computational method would enable us to study global lightning distribution and atmospheric conductivity (or ionospheric plasma density) information.

3. Electromagnetic Phenomena Associated with Earthquakes (and/or Volcano Eruptions)

To arrive at a practical earthquake prediction, we need basic scientific research on seismo-electromagnetics. Fortunately, much convincing evidence has recently been gathered on the precursor signature of earthquakes, especially on the many electromagnetic phenomena found to be associated with earthquakes. Seismo-electromagnetic phenomena are found to occur in a wide frequency range from DC to VHF, but we pay great attention to some specific frequency ranges that are promising from the standpoint of short-term earthquake prediction.

3.1 DC Electric Field Variation (SES) The Varotsos' group has been working on seismic electric signals (SES) since the beginning of the 1980's. They have been using SES for earthquake predictions in Greece [22]. They have suggested the use of short and long dipoles oriented in both directions (NS and EW), which enables them to distinguish SES from other noise sources. The RIKEN group has established SES stations all over Japan to find the seismic signature in Japan.

A few mechanisms have been suggested as the mechanism generating SES, including the electro-kinetic effect [1][3][4]. Based on the detailed observational facts, further studies on the generation mechanism will be required. The propagation mechanism is not well understood. In particular, the Greek group has found the presence of "selectivity" (or sensitive site), which indicates that SES cannot always be detected at the observation site nearest the epicenter [22]. This observational fact may be indicative of the inhomogeneity (or heterogeneity) of the lithosphere. Varostos et al. (1998) have studied the propagation of DC signals in an inhomogeneous media including the presence of active faults [23]. This kind of realistic structure in the lithosphere should be studied by means of the electromagnetic (or to be exact, electrostatic) method (preferably be means of computational electromagnetics). Recently a Japanese electric company group has found an earthquake signature in the zeroth phase current of the power transmission line, and they have tried to interpret it by means of the boundary element analysis method [24].

3.2 ULF Seismogenic Emissions Though the history of this observation of ULF seismogenic emissions is not long, we believe that further study would be very promising for short-term earthquake prediction. A few very convincing evidences of seismogenic ULF emissions have already been obtained for a few large earthquakes. The first example is the Spitak earthquake with a magnitude of ~7. The Russian team had obtained precursory ULF emissions [25]. The Stanford group has reported on the generation of ULF emissions before the large Loma Prieta earthquake with a magnitude of 6.9 [26]. The temporal evolution of ULF emissions has indicated that there is one broad peak one-to-two weeks before the quake (see Fig. 7), followed by a quiet period, and that we have a sharp increase a few days before the quake. The most important frequency is found to be 0.01Hz (100s period).

After these quakes, Hayakawa et al. (1996) analyzed ULF data for another earthquake in Guam (with a magnitude of ~8.0) by means of a new method of analysis, the so-called polarization method, which uses the ratio of vertical to horizontal magnetic field components [27]. They succeeded in detecting very convincing precursory ULF emissions before the quake. Their polarization method has been extensively used to discover any significant ULF signature of earthquakes.

Further detailed analyses have been developed and applied to the ULF data for some earthquake events.

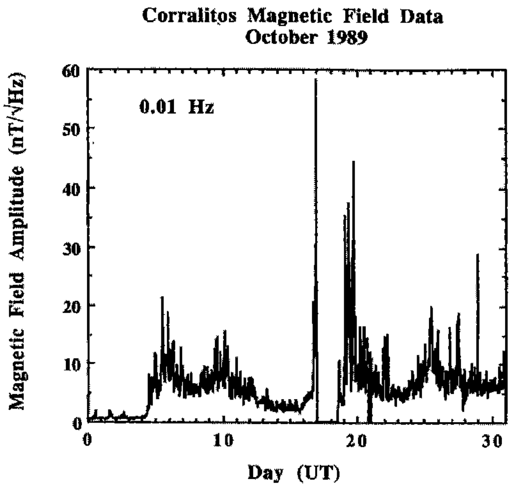

Fig. 7. Temporal evolution of ULF emission for the Loma Prieta earthquake (frequency = 0.01Hz).

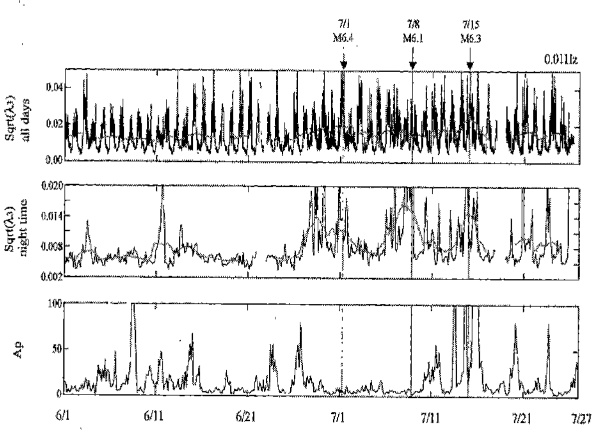

Fig. 8. Temporal variation of 3rd principal component (seismogenic emission) for the Izu island earthquakes in July 2000.

First of all, the concept of self-organized criticality (SOC) taking place in the hypocenter might be reflected also in the ULF data, because ULF waves are coming directly from the hypocenter. Hayakawa et al. (2001) have attempted the first fractal analysis of the ULF data for the Guam earthquake [28] and have found that the ULF noise became very similar to the flicker noise before the quake. This fractal analysis is becoming popular in this field. Also, Gotoh et al. (2000) have carried out a principal component analysis (PCA) of the Izu islands earthquake swarm and have found a significant seismogenic effect in the third principal component as seen in Fig. 8 [29]. Also further study using more sophisticated signal processing, including blind separation etc., would be highly required in order to accumulate a number of convincing ULF events.

Along with attempts to increase the number of convincing events, the mechanisms of ULF emissions are being studied. As for the generation mechanism for seismogenic ULF emissions, Molchanov and Hayakawa (1995) have postulated the ULF generation based on microfracturing charge separation [30], and later theories have extended their model. Further study is required. The propagation of ULF emissions from the lithospheric source to the ionosphere has been studied by means of the analytic electromagnetic method [31], but there have been no detailed reports on electromagnetic computational studies of ULF propagation that take into account the realistic lithospheric structure as studied in the DC case. Electromagnetic computational analysis would be of essential importance in this study.

3.3 Seismo-atmospheric and -Ionospheric Effects It has been a big surprise that, in addition to the lithospheric phenomena, the atmosphere and ionosphere are also perturbed due to seismic effects. The seismo-atmospheric effect is clearly demonstrated by the use of an over-horizon VHF signal from any FM broadcasting transmitter. The FM transmitter has a covering range of the order of 50-100km, but it has been found that, as an over-horizon signal, such a signal can be received at a distance much larger than this service area. Fukumoto et al. (2001) have studied this effect extensively by means of direction-finding antenna systems (both in azimuth and in elevation), and have concluded that the reception of such an over-horizon VHF signal is due to reflection by some irregularity in the atmosphere [32]. That is, they have suggested the presence of tropospheric perturbation associated with the seismic effect, and we have to consider how the pre-seismic effect would lead to the modulation of the VHF refractive index.

The first convincing evidence of the seismo-ionospheric perturbation was obtained by Hayakawa et al. (1996) for the Kobe earthquake [33]. Fig. 9 illustrates the result of the subionospheric VLF propagation between the Omega Tsushima transmitter and the Inubo receiving station for the Kobe earthquake. Fig. 9 (a) shows the great circle path between Tsushima and Inubo; the epicenter is indicated by a cross. The propagation distance is only 1,000km, a short propagation path at VLF, which means that a lot of modes are propagated.

Fig. 9 (b) illustrates the sequential plot of the diurnal variation of phase at 10.2kHz just around the earthquake date. Just around sunrise and sunset we notice the presence of minima in the observed phase. We call these evening and morning times "terminator times." Fig. 9b suggests a very significant shift in the terminator times before the quake. Such a change in terminator times is interpreted as the possible lowering of the lower ionospheric boundary by a few kilometers [33]. Based on further analysis for the same path for a longer 13-year period, Molchanov and Hayakawa came to an important conclusion [34]. The ionospheric perturbation is expected on the probability of ~80% for earthquakes with a magnitude greater than 6.0 that take place near the great circle path and with a shallow focal distance. Being encouraged with these results, we have established a VLF/LF network consisting of seven stations in Japan within the framework of the NASDA's Earthquake Remote Sensing Frontier Project (Hayakawa was the principal scientist for this). We have already accumulated

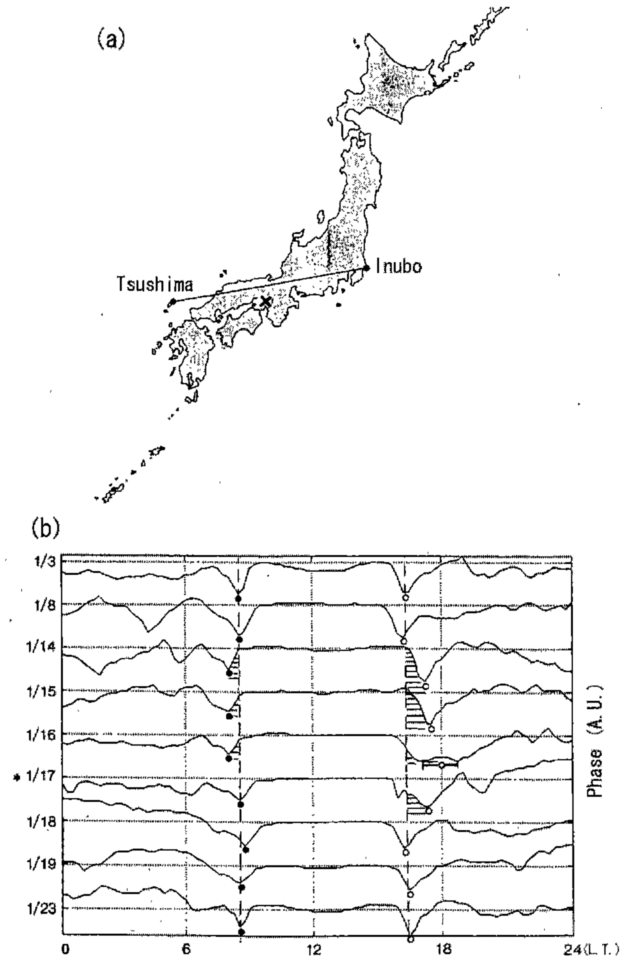

Fig. 9. Propagation anomaly on the Tsushima-Inubo VLF propagation path for the Kobe earthquake in terms of the change in terminator times

convincing data ready for statistical analysis [35].

Some electromagnetic modelings have been attempted in order to interpret such changes in VLF/LF terminator times. Soloviev et al. (2003) have tried to account for the observed changes at the terminator times on the basis of their 3D scattering model [36]. Further detailed modeling is required, because it will allow us to infer the ionospheric perturbation structure and dynamics by comparing the computation with the observational data.

We have proposed the terminology "lithosphere-atmosphere-ionosphere coupling" or "electromagnetic phenomena in the coupled lithosphere-atmosphere-ionosphere system" which has caught on in the society of seismo-electromagnetics. Fig. 10 shows our summary of the possible channels of such lithosphere-atmosphere-ionosphere coupling [35]: (1) a chemical channel (geochemical effects such as radon, ions etc. emanating from the ground would modify the atmospheric conductivity profile, leading to the change in the atmospheric electric field and then to the redistribution of the ionospheric plasma); (2) an acoustic channel (a pre-seismic effect will induce the atmospheric oscillation in the form of acoustic gravity waves that propagate upward) resulting in the modification of ionospheric plasma); and (3) an electromagnetic channel (ULF seismogenic emissions

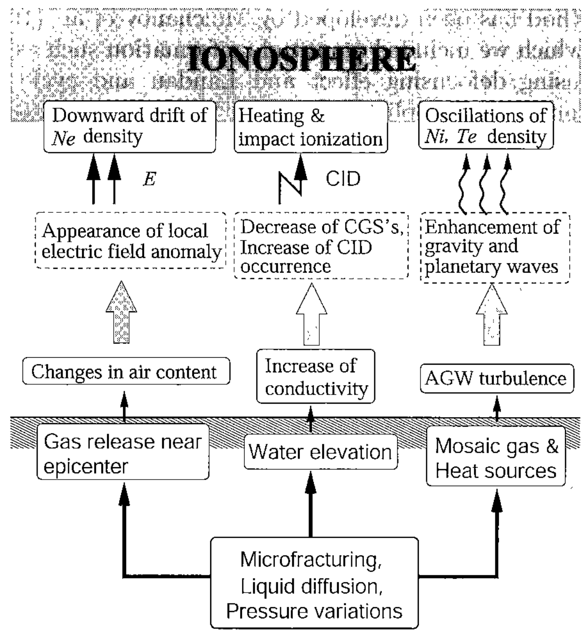

Fig. 10. Schematic illustration on the lithosphere-atmosphere-ionosphere coupling.

that propagate into the inner magnetosphere and interact with high energy protons, leading to the precipitation of those protons into the lower ionosphere). Several theoretical works, including electromagnetic and plasma analyses, have been conducted [3][4], but further extensive studies are very highly required.

4. Wave and Plasma Phenomena in the Ionosphere and Magnetosphere

As shown in Fig. 1, there are many interesting wave phenomena in the ionospheric/magnetospheric plasma. Quasi-free space waves exist when the frequency is higher than the electron plasma (or gyro) frequency. In this frequency range, we observe AKR (auroral kilometric radiation). When the frequency becomes lower than the electron gyro-frequency but higher than the lower hybrid resonance frequency, there is only the whistler mode of propagation, and there are a lot of natural waves (whistlers and VLF/ELF emissions). When the frequency is below the lower hybrid resonance frequency, we have magnetohydrodynamic waves (Alfvén wave and modified Alfvén wave). The generation mechanisms of these emissions should be examined by means of plasma instability studies, but we can propose a few subjects in which the electromagnetic theory or analysis would play an essential role.

4.1 Propagation in Inhomogeneous and Anisotropic Plasmas Wave propagation in inhomogeneous and anisotropic plasmas is a general subject for electromagnetics. The ionosphere and magnetosphere are such media. The propagation of whistler-mode waves in the magnetosphere has been studied by means of ray-tracing methods because the ray theory is valid for the inhomogeneity of the magnetosphere at VLF/ELF. In ray tracing, the propagation path is of central importance, but a more developed ray-tracing method has been developed by Molchanov et al. (1995) in which we included amplitude information such as the focusing/defocusing effect and Landau and cyclotron damping (or amplification etc.) [37]. This ray-tracing method, including the amplitude information, should be applied for other wave phenomena at different frequency ranges (Pc1 in ULF and AKR at higher frequencies), and for other planets [38].

ULF emissions are important geophysical phenomena that bring us a lot of information on the global magnetosphere structure and dynamics. However, their propagation characteristics are poorly understood, and we believe that the recent progress in computational electromagnetics should be of essential importance in further studies on these ULF waves (i.e. global propagation in the magnetosphere, ULF transmission through the ionosphere, etc.).

5. Electrodynamic Coupling among Different Regions

As for the sprite problems in the atmosphere, we have suggested the importance of electrodynamic coupling between the atmosphere and ionosphere. Then, the subject of seismo-electromagnetics is found to be closely related to the lithosphere-atmosphere-ionosphere coupling. In this sense, the coupling between different regions of interest would be an interesting and challenging field of science. In addition, electromagnetic studies would be of potential importance in these couplings.

Another type of coupling is that between human activity and the natural environment. As a typical example of this, we can suggest the radiation of power-line harmonics and their contamination of the earth's magnetosphere. This is coupling between the atmosphere and ionosphere/magnetosphere coupling from the standpoint of regional coupling. With an increase in human activity, we would expect an increase in power consumption. Satellite observations have found the presence of radiation of power line harmonics in the ionosphere and magnetosphere [39]. Further studies have indicated that such power line harmonic radiations propagated in the whistler mode interact with high energy electrons in the radiation belt, leading to the precipitation of those electrons into the lower ionosphere. This means that this human activity would very much influence the Earth's natural environment.

Furthermore, increased energy electron precipitation would modify atmospheric conductivity, which would then modify the occurrence of lightning. Ando et al. (2002) have conducted electromagnetic analysis of the penetration of power line harmonic radiation into the ionosphere [40]. Together with satellite observation, this kind of theoretical study, would allow us to quantitatively estimate the amplification of these radiations in the magnetosphere-to be compared with plasma instability estimates. Further detailed studies on the penetration of power line harmonics radiation for more realistic power transmission systems would be highly required.

6. Summary

We have introduced several recent topics on the natural electromagnetic (and plasma) phenomena taking place in the near-Earth environment, and we can conclude that electromagnetic theory (especially computational electromagnetics) would contribute a great deal to the elucidation of unsolved essential points in regard to these recent topics. Collaboration of scientists working in the fields of natural phenomena and of computational electromagnetics will be essential for our working group.

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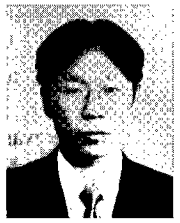

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