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Anomalous sporadic-E layers observed before M 7.2 Hyogo-ken Nanbu earthquake; Terrestrial gas emanation model

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Abstract: Before the M 7.2 Hyogo-ken Nanbu earthquake of January 17, 1995, anomalous f_0E_s increases above 7 MHz were observed at Shigaraki about 120 km northeast of the epicenter and at Kokubunji about 500 km east of it in the daytime on January 15, 1995. Since there were very quiet geomagnetic conditions and no solar event on January 15 and the f_0E_s is normally below 5 MHz in the Japanese winter, the anomalous f_0E_s increases above 7 MHz observed on January 15 may be presumably an ionospheric seismic precursor. An upward tornado-type seismic cloud with rapid air currents occurred between altitudes of 680 m and 2000 m over the epicenter region, and anomalous radon ion density increases of about 100 times the normal radon ion density were also observed at epicentral distance of about 200 km before this earthquake. The epicentral area of the anomalous f_0E_s increase occurrence before this earthquake is about the same as that of the terrestrial gas emanation from active faults before great earthquakes (C.-Y. King; J. Geophys. Res., 91B, 12269, 1986). The radon ions carried up to cold high altitudes produce positively charged ice crystals in the topside cloud and the bottom-side cloud has negative charges. An electrostatic field is set up in the lower ionosphere by positively charged cloud-to-ground lightning discharges. A temporal electrostatic field above the air breakdown electric field causes ambient electron heating and ionization of neutrals in the lower ionosphere. Times for producing the anomalous f_0E_s increases computed by the quasi-electrostatic heating and ionization process at altitude of 100 km are comparable with seismic flash duration before great earthquakes.

key words: anomalous sporadic-E, great earthquake, upward seismic cloud, radon ion emanation from active faults

1. Introduction

The M 7.2 Hyogo-ken Nanbu earthquake occurred at 0546 JST (UT + 9 h) on January 17, 1995 at the seismic center below the sea level of Akashi Strait as shown by a star mark in Fig. 1 (Yamanaka *et al.*, 2002). A wide area around the Kobe city suffered great damage and about 6500 people were dead. The critical frequency of sporadic-E layer, f_0E_s increased above 8 MHz in the daytime on January 15, 1995 at Shigaraki about 120 km northeast of the epicenter as shown by Table 1 and Fig. 2 and at Kokubunji about 500 km east of it (Fig. 3) before the M 7.2 Hyogo-ken Nanbu earthquake onset (Ondoh and Hayakawa, 1999). Another f_0E_s increases up to 9 MHz were also observed around 1600 JST on January 12, 1995 before this earthquake at

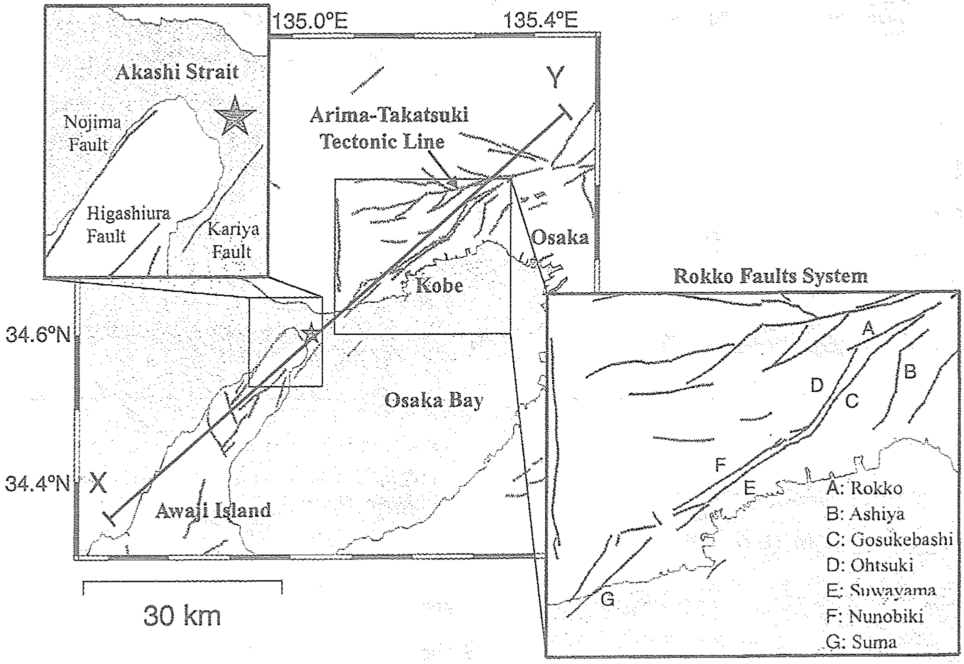


Fig. 1. Locations of active faults around the Arima-Takatsuki tectonic line. A star-mark shows the epicenter of Hyogo-ken Nanbu earthquake (after Yamanaka et al., 2002).

Table 1. Anomalous f_oE_s increases observed at Shigaraki on January 15, 1995.

JST	1230	1245	1300	1315	1330	1345	1400	1415	1430	1445	1500
f_oE_s MHz	4.2	4.5	7.0	8.2	7.6	9.0	8.3	7.6	6.5	4.9	4.2

Kokubunji.

Figure 2 shows mid-latitude l-type (low) transparent E_s traces at 100 km height. The l-type E_s occurs in the daytime and its occurrence rate increases in the northern-hemisphere summer (Leighton *et al.*, 1962). The electron density of transparent E_s layer is classically defined by the lowest O-mode frequency visible through E_s layer (about 4 MHz in this case). Signals of the daytime l-type E_s echoes show interfering fading, while the nighttime f-type E_s and tropical s- and q-type E_s echoes show scattered fading and scattered flutter fading, respectively (Tao, 1966). The l-type E_s echoes seem to be reflected from E_s irregularities. The anomalous f_oE_s which is much larger than the f_oE (Fig. 2) was observed two days before the M 7.2 Hyogo-ken Nanbu earthquake, although the normal transparent f_oE_s is close to the f_oE of E-layer. So, we investigate an unusual pre-seismic process which causes the anomalous electron density increases of E_s irregularities in this paper. Recent simultaneous observations of mid-latitude E_s plasma by MU radar, FMCW radar, and ionosonde indicate that E-region field-aligned irregularities increase with increasing localized E_s density gradient given by f_oE_s-f_bE_s

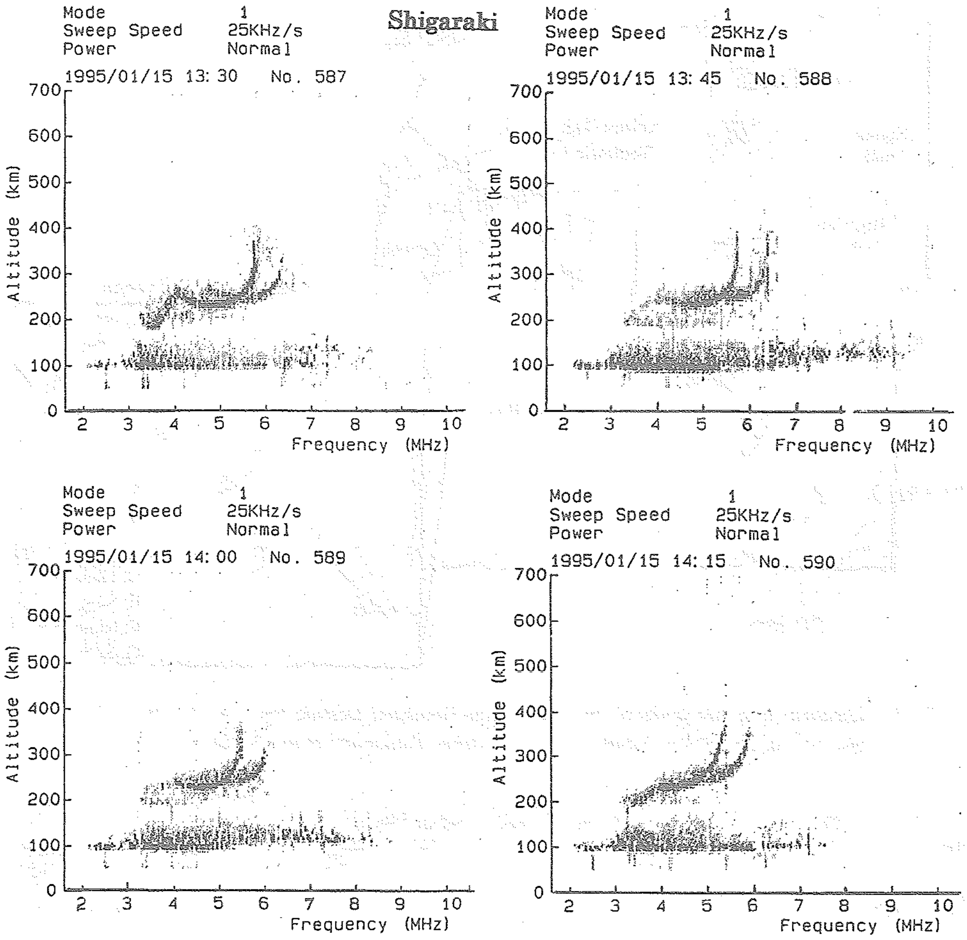


Fig. 2. *Ionograms of anomalous f_oE_s increases above 7 MHz observed at 1330, 1345, 1400, and 1415 JST on January 15, 1995 at Shigaraki. The f_oE_s is the right-end value (in MHz) of the sporadic-E trace at apparent height of 100 km.*

(Ogawa *et al.*, 2002). SEEK-2 rocket observations of mid-latitude E_s show an E_s electron density of $2\times10^5/\mathrm{cm}^3$ at 103 km height (Wakabayashi and Ono, 2002), intense electric fields above 10 mV/m within E_s plasma irregularities associated with quasi-periodic FAI radar echoes, and E_s irregularities associated with a plasma accumulation (Yokoyama *et al.*, 2002). These results demonstrate that E_s plasma irregularities have really high electron densities above $10^5/\mathrm{cm}^3$ as shown by the f_oE_s in Fig. 2 ionograms. Geomagnetic conditions on January 15, 1995 at Kakioka were very quiet as shown by Fig. 4, and there was no solar event and no unusual increase in the F10.7 (solar radio flux at 2800 MHz received at Ottawa) on January 15, 1995. In Japan, the f_oE_s is normally below 6 MHz in the winter and it increases above 6 MHz between May and August. Therefore, the anomalous f_oE_s increases observed at Shigaraki and Kokubunji

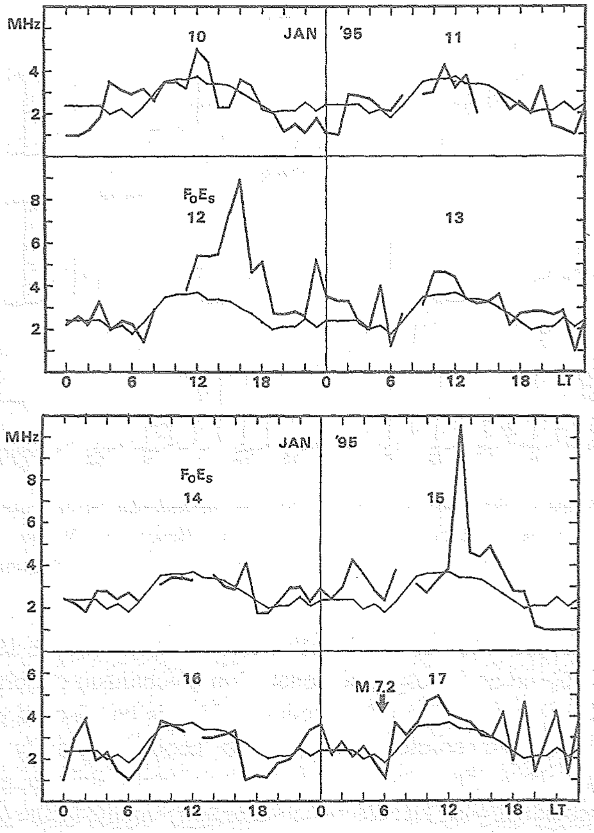


Fig. 3. *Time variation of the f_oE_s hourly values (thick line) observed at Kokubunji for January 10–17, 1995. A downward arrow indicates the onset time of the Hyogo-ken Nanbu earthquake. Anomalous f_oE_s increases occurred for 12–18 h JST, January 12 and for 12–14 h JST, January 15, 1995. Thin line shows hourly values of the monthly f_oE_s median.*

on January 15 are regarded as an ionospheric seismic precursor. Figures 5a–5c show time variations of f_oE_s observed at Yamagawa, Okinawa, and Wakkanai from January 14 to 17, 1995 as well as Fig. 3, where thick lines denote observed f_oE_s values, a thin line the monthly f_oE_s median at each station, and a downward arrow the onset time of M 7.2 Hyogo-ken Nanbu earthquake. All f_oE_s values in Figs. 3 and 5 are referred from Ionospheric Data in Japan for January 1995, Vol. 47, No. 1 issued from the Communications Research Laboratory, MPT, Tokyo, Japan. The epicentral distance of Yamagawa, Okinawa, and Wakkanai are 620 km SW, 820 km SW, and 1400 km NW, respectively. The anomalous f_oE_s increases on January 15, 1995 observed at Shigaraki and Kokubunji of epicentral distance within 500 km were not observed at Yamagawa, Okinawa, and Wakkanai of epicentral distance beyond 500 km. This is an important evidence for interpreting the anomalous f_oE_s increases since anomalous increases of terrestrial gas, such as the radon, helium, hydrogen, mercury, and carbon dioxide with duration of a few hours to a few days were often reported along active faults before

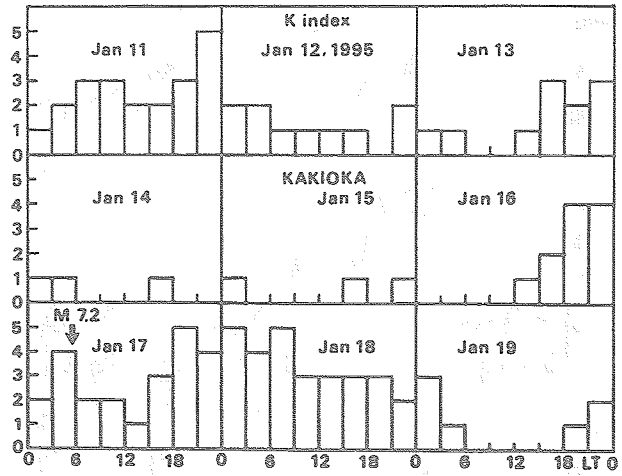
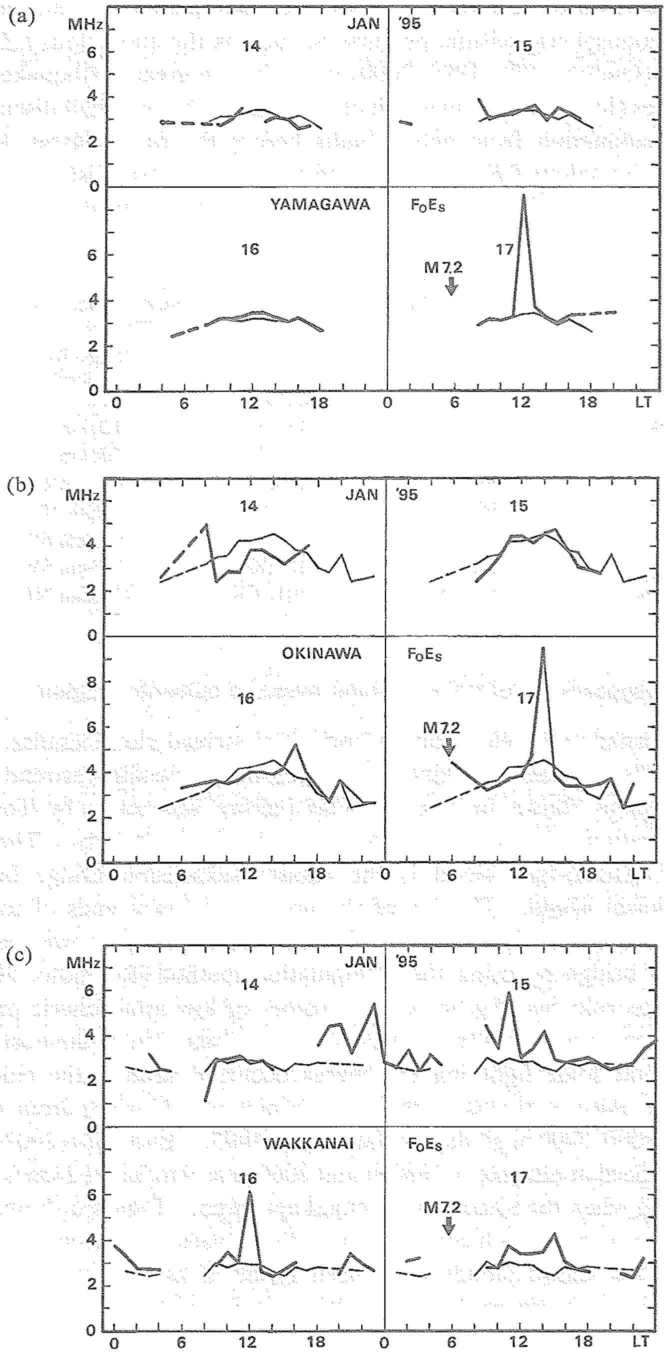


Fig. 4. Time variation of three hourly K indices observed at Kakioka for January 11–19, 1995. A downward arrow indicates the onset time of Hyogo-ken Nanbu earthquake. The geomagnetic activity on January 14 and 15 were very quiet and that on January 12 was quiet.

great earthquakes at epicentral distances within about 500 km (King, 1986). Sorokin *et al.* (2002) have proposed an ionospheric generation mechanism of seismic geomagnetic pulsations (0.1–10 Hz) observed on the ground. This is based on a periodic structure formation of ionospheric conductivity due to acoustic gravity wave instability stimulated by ionospheric DC electric field enhancement, since a growth of seismic activity is often associated with DC electric field enhancements in the ionosphere and on the ground. However, the anomalous f_oE_s increases before the M 7.2 Hyogo-ken Nanbu earthquake do not show any periodic variation. Surkov *et al.* (2000) have investigated a generation mechanism of seismic geomagnetic ULF perturbations which result from a sum of electromagnetic fields in the conductive medium ahead of acoustic waves emitted by opening cracks. Tanaka *et al.* (1984) observed ionospheric disturbances caused by acoustic waves propagating from the ground during the M 7.1 Urakawa-Oki earthquake of March 21, 1982 by HF-Doppler sounders, but not any ionospheric disturbance before this earthquake onset. Surkov *et al.* (2002) have discussed kinetically an outward migration of fluid-filled cracks from the earth's deep interior to the ground surface, assuming crack sources located around the crust-mantle boundary (400 km depth below the ground) of which temperature and pressure are 1400°C, and about a hundred thousand ground atmospheric pressure, respectively. In the earth's interior, the temperature increases with increasing depth up to 6000°C, near the iron melting point at 4 million atmospheric pressure in the inner core, and the temperature increase rate with depth in the crust (0–400 km depth) is higher than that in the mantle (400–2900 km depth). In other words, since the thermal conductivity in the crust is lower than that in the mantle where the thermal energy results from the radioactive decay of radioisotopes, the thermal energy transmitted outward from the mantle could be accumulated in the lower crust to raise thermal instabilities. Basalt cracks in the lower crust would be produced by the thermal instabilities and also by a



Figs. 5a–5c. *Time variations of the f_oE_s hourly values observed at Yamagawa (a), Okinawa (b), and Wakkanai (c) for January 14–17, 1995. Downward arrows indicate the onset time of the M7.2 Hyogo-ken Nanbu earthquake. The anomalous f_oE_s increases were not observed in the daytime on January 15 at these stations.*

stress due to the downward creeping motion of a tectonic plate below another tectonic plate. However, ionospheric seismic precursors, such as the anomalous f_oE_s increases and f_oF_2 decreases (Ondoh, 1998, 1999, 2000) occur before great earthquakes ($M>7.0$) with shallow sources (hypocenters) in depth of 10–35 km. So, we shall discuss an effect of terrestrial gas emanation from active faults before the M 7.2 Hyogo-ken Nanbu earthquake on the anomalous f_oE_s increases observed at epicentral distances within 500 km. Table 2 indicates locations of observatories used and the epicenter.

Table 2 Locations of ionospheric and geomagnetic observatories used and the epicenter.

Place	Geographic latitude	Geographic longitude	Distance from the epicenter
Shigaraki	34.9°N	136.1°E	120 km NE
Kokubunji	35.7°N	139.5°E	500 km E
Kakioka	36.2°N	140.2°E	600 km E
Epicenter	34.6°N	135.0°E	Depth 10 km
Yamagawa	31.2°N	130.6°E	620 km SW
Okinawa	26.3°N	127.8°E	820 km SW
Wakkanai	45.4°N	141.7°E	1400 km NE

2. Appearance of seismic cloud over the epicenter region

An upward tornado-type cloud and a horizontal striped cloud similar to airplane vapor trails were observed over the epicenter region in the evening (around 1700 JST) on January 9, 1995 as shown by Fig. 6. This picture was taken by Terumi Sugie (private communications, 2002) from Tarumi port in the Kobe city. The bridge on this side of the tornado-type cloud is the Akashi suspension bridge between the main-land and Akashi island. Heights of the upper and lower ends of tornado-type cloud have been estimated as 2000 m and 680 m, respectively, from tower height of the Akashi suspension bridge by using the triangulation method (Enomoto, 2002). According to the Meteorological Agency data, a center of low atmospheric pressure was passing over the Japan sea, a cold front extended from Hokkaido of the northern island to Awaji island, and some lightning discharges occurred around the cold front on January 15, 1995. Also, a strong wind of 10–20 m/s was blowing from the west at altitudes of about 1000–3000 m all day on January 9, 1995. Enomoto (2002) estimated the westerly wind speed at altitudes of 680 m and 2000 m as 9 m/s and 23 m/s respectively from related data when the tornado-type cloud appeared. Figure 6 shows a rotating upward tornado-type cloud which consists of rapidly upward air current. The upward tornado-type and horizontal clouds have been reported as the precursors of great earthquakes in Japanese historical literature (Wadazumi, 1996).

3. Seismic earth current and equivalent seismic dynamo model

Seismic strain changes in a porous crust produce pore pressure changes which affect fluid-rock interaction and cause the fluids to migrate in the crust. This process changes

Fig. 6. The picture shows a rotating upward tornado-type cloud and a bright horizontal striped cloud similar to the airplane vapor trail beyond the Akashi suspension bridge over the Akashi strait. The both clouds are seismic clouds which appear before great earthquakes. This picture was taken by Mrs. Terumi Sugie around 1700 JST on January 9, 1995 before the Hyogo-ken Nanbu earthquake from Tarumi Harbor in the Kobe city.

the electric resistance in the crust to generate a seismic earth current. The occurrence frequency of medium and small earthquakes has gradually increased in the Tanba mountainous region north of the epicenter region since about one year before the Hyogo-ken Nanbu earthquake. This earthquake was caused by crustal movements of the active Nojima fault around the northern part of the Awaji island. A terrestrial electric potential difference and large-scale earth current are produced by crustal electrokinetic effects and conductivity changes due to fluid diffusion and migration in the crust associated with tectonic strain changes around active faults in the earthquake preparation stage. Geomagnetic field changes associated with the seismic earth current have been often observed within a few weeks before great earthquakes. Yoshimatsu (1938) estimated a total seismic earth current of 5.4×10^5 A before the Shioya-oki earthquake of May 3, 1938 from earth current changes observed at Kakioka. We discuss an upward electric field due to the seismic earth current, which supports the formation of upward tornado-type cloud, by using the equivalent seismic dynamo model. The dynamo model has an inflow current source, $\mathbf{J}_+ (\mathbf{r}_+)$ and outflow current source, $\mathbf{J}_- (\mathbf{r}_-)$ which are located at both ends of horizontal distance, L at depth, h below the ground origin ($x=y=z=0$) in the xyz right hand coordinate system where the

z axis is upward,

$$r_+ = [(x+L)^2+y^2+(z-h)^2]^{1/2}, \text{ and } r_- = [x^2+y^2+(z-h)^2)]^{1/2}. \qquad (1)$$

An upward electric field,

$$E_Z = -\partial\phi/\partial z = J[h/(L^2+h^2)^{3/2} - 1/h^2]/(4\pi\sigma), \qquad (2)$$

at the ground origin ($x=y=z=0$) in the case of $L=30$ km and $h=10$ km is computed as 7.7 mV/m for the total seismic earth current, $J=10^5$ A and the crustal electric conductivity, $\sigma=0.01$ S/m, and as 77 mV/m for $J=10^5$ A and $\sigma=0.001$ S/m from the seismic electric potential (Ondoh, 2000),

$$\phi = J(1/r_- - 1/r_+)/4\pi\sigma. \qquad (3)$$

When the upward seismic electric field occurs over the epicenter region, terrestrial ions emanating from the active fault can go upward along the electric field lines despite the westerly winds.

4. Anomalous increases of radon ion density observed before the Hyogo-ken Nanbu earthquake

Anomalous radon ion density increases of about 100 times the normal radon ion density were measured at Okayama about 200 km west of the epicenter within 8 days before the Hyogo-ken Nanbu earthquake (Wadazumi, 1999). The chemically inert radon is soluble in the water. Since the radon is a member of the radioactive decay series of uranium existing in crustal rocks, the radon is ionized due to the radioactive decay. The terrestrial gas emanations, such as the radon, helium, hydrogen, mercury, and carbon dioxide with duration of a few hours to a few weeks have been often observed along active faults within epicentral distance of about 500 km before great earthquakes (King, 1986). The terrestrial gas emanations are controlled largely by faults and fissures in the crust and by faulting activities, since active faults are major leaks or paths of least resistance for terrestrial gases generated or stored in the crust to escape to the atmosphere. Thus, the terrestrial gas emanations along active faults are sensitive to tectonic stress changes. The upward tornado-type cloud is an important evidence of the upward rapid air currents which convey upward terrestrial ions emanating from the active faults before the M 7.2 Hyogo-ken Nanbu earthquake. The speed of upward air currents in the tornado-type cloud is 40–80 m/s (Magono, 1972). The emanating radon ions are carried upward by the rapid air currents to cold high altitudes, and become core ions of positively charged ice crystals in the topside cloud. This charge separation process causes negative charges in the bottom-side cloud. An electrostatic field is set up with the accumulation and evolution of thundercloud charges in the lower ionosphere as the positively charged cloud-to-ground lightning discharges lower a part of the cloud charges to the ground.

5. Quasi electrostatic ionization in lower ionosphere by seismic cloud discharges

The air breakdown electric field which is proportional to the atmospheric neutral density, Q falls more rapidly with height than the thundercloud electrostatic field, E since Q decreases exponentially with height, z and the electrostatic field, E decreases with height as $\sim 1/z^3$. Consequently, there should be a height above which the thundercloud electrostatic field exceeds the sparking limit of the atmosphere (Wilson, 1925).

Pasko *et al.* (1997) have investigated the quasi-electrostatic heating, ionization, and excitation of optical emissions in the mesosphere and lower ionosphere to interpret sprites. The temporal electrostatic field at high altitudes due to a sudden removal of thundercloud charges by lightning discharges causes ambient electron heating and neutral particle ionization in the lower ionosphere. We apply this process to explain the anomalous increases of the sporadic E ionization at altitude of 100 km as shown by Table 1 and Fig. 2. The electron mobility, $\mu = e/(\nu \mathrm{m})$ which is computed from the effective electron collision frequency, $\nu = 1.75\times10^3/\mathrm{s}$ at 100 km and $e/m = 1.759\times10^{11}$, is 1.005×10^8 at altitude of 100 km. The air breakdown electric field of $E_k = 3.2\times10^6 Q/Q_o$ V/m at altitude of 100 km is 43 mV/m for the neutral partricle density, $Q_o = 7.8\times10^{18}/\mathrm{m}^3$ at altitude of 100 km (Davies, 1965). The ionization coefficient is given by

$$P = 7.6\times10^{-13} Q x^2 f(x) \exp[-4.7(1/x-1)], \tag{4}$$

where $f(x) = [1+6.3\exp(-2.6/x)]/1.5$ and $x = E/E_k$ (Papadopoulos *et al.*, 1993). The effective attachment coefficient in the quasi-electrostatic heating reaction, $e^- + O_2 \rightarrow O + O^-$ is given by

$$L = (-2.41\times10^8 + 211.92y - 3.545\times10^{-5}y^2)Q/Q_o, \tag{5}$$

where $y = EQ_o/Q$ and $Q_o/Q = \mu/1.36$ (Davies, 1983). The expressions of P and L are numerically given by

$$P = 3135.7E^2[\exp(-0.2035/E) + 6.3\exp(-0.3161/E)], \tag{6}$$

and

$$L = -2612.3E^2 + 211.92E - 3.27, \tag{7}$$

at altitude of 100 km, respectively, where E is the electrostatic field at 100 km due to the sudden removal of thundercloud charges by lightning discharges. The time variation of electron density, N produced by the quasi-electrostatic heating and ionization (Pasko *et al.*, 1997) is given by

$$\mathrm{d}N/\mathrm{d}t = (P-L)N. \tag{8}$$

Therefore, the time required for producing the anomalous increase of sporadic-E electron density, N in the quasi-electrostatic heating and ionization process is given by

$$t = \ln(N/N_o)/(P-L), \tag{9}$$

where N_o is an initial ambient electron density. Table 3 indicates computed times which are necessary to produce the anomalous sporadic-E electron density, $N = 10^6/\mathrm{cm}^3$ ($f_oE_s = 9$ MHz at 1345 JST, Jan. 15) in the ambient sporadic-E layer with $N_o = 2.2\times10^5/\mathrm{cm}^3$ ($f_oE_s = 4.2$ MHz at 1230 JST, Jan. 15) for typical electrostatic fields at altitude of 100 km. As for the seismic flash, only eye measurement data are now available. If the seismic flash results from the positively charged cloud-to-ground discharges as discussed

Table 3. Times for producing the anomalous increase of sporadic-E electron density, $10^6/cm^3$ at 100 km height before the M 7.2 Hyogo-ken Nanbu earthquake in typical electrostatic fields computed by the quasi-electrostatic ionization process.

E	$P-L$	t
1 V/m	19362	78 μs
500 mV/m	3697	0.41 ms
100 mV/m	20.67	73 ms
60 mV/m	0.7872	1.9 s

in Section 4, some seismic flashes with duration of 0.01–0.4 s will repeatedly occur for about one second (Magono, 1972). So, the computed times for $E=60$–100 mV/m in Table 3 are comparable with duration of seismic flashes which appear before great earthquakes. A stable sporadic-E layer with the enhanced electron density of $10^6/\mathrm{cm}^3$ ($f_0E_s=9$ MHz) will be formed at altitudes around 100 km by the wind-shear mechanism (Whitehead, 1967; Axford, 1967) which has produced the pre-existing weak sporadic-E layer in the winter daytime. The quasi-electrostatic heating and ionization process may be applied to tropical sporadic-E layers associated with strong thunderstorms (Mitra and Kundu, 1954). Since positive charges produced by upward air currents with speed of 40–80 m/s are accumulated in the topside thundercloud at altitudes of 5–7 km, the quasi electrostatic ionization at altitude of 100 km may occur at about 100 s after the terrestrial gas emanation from the active faults.

6. Conclusion

The anomalous f_0E_s increases above 7 MHz were observed at Shigaraki about 120 km northeast of the epicenter and at Kokubunji about 500 km east of it in the daytime on a geomagnetic quiet day of January 15, 1995 before the M 7.2 Hyogo-ken Nanbu earthquake of January 17, 1995. A tornado-type upward seismic cloud with rapid air currents over the epicenter region and the anomalous increases of radon ion density at epicentral distance of about 200 km were observed within 8 days before this earthquake onset. So, these anomalous phenomena are investigated from a viewpoint of the lithosphere-atmosphere-ionosphere coupling. Since the anomalous phenomena prior to the Hyogo-ken Nanbu earthquake onset occurred in a period of geomagnetic quiet and no solar event, they indeed seem to be seismic precursors. The occurrence area of the anomalous f_0E_s increases in epicentral distance before this earthquake is about the same as that of terrestrial gas, such as the radon ions emanating from active faults before great earthquakes (King, 1986). The upward movement of radon ions to cold high altitudes by the rapid air currents produces positively charged ice crystals in the topside-cloud and negative charges in the bottom-side cloud, and this process causes the positively charged cloud-to-ground lightning discharges to generate an electrostatic field above the air breakdown electric field in the lower ionosphere. The times for producing the anomalous sporadic-E ionization in typical electrostatic fields computed by the quasi-electrostatic ionization process are comparable with the seismic flash duration before great earthquakes. Therefore, the anomalous f_0E_s increases and seismic flashes seem to occur about 100 s later after the anomalous radon-ion emanations from the active faults before the M 7.2 Hyogo-ken Nanbu earthquake onset.

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