Terrestrial Kilometric Radiation Observed by Satellite JIKIKEN (EXOS-B)

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The natural plasma wave astronomy mode (NPW-A) on board JIKIKEN (EXOS-B) launched on Sept. 16, 1978, are making observation of the planetary and solar radio waves in the frequency range from 10 kHz to 3 MHz using the long dipole antenna with length of 102 m. The high resolution spectrum obtained by the NPW-A receiver provides important characteristics of the terrestrial kilometric radiation (TKR) that carries the information on the source region where TKR is generated.

When the source mechanism that the electrostatic waves near the upper hybrid frequency generated by auroral precipitating particle is converted in a form of the electromagnetic waves is considered, we can estimate the position of the TKR source from the measured spectrum. The height distribution of the source region derived from the frequency component of the radiation indicates the altitude range that varies in accordance with the geomagnetic activity, and ranging from 3,000 km to 12,000 km above the auroral ionosphere. The fine structure of TKR spectrum shows that the source with the dimension of 100 km is moving down repeatedly toward the polar ionosphere with the average velocity of 5-10 km/sec, and suggests that the source motion is closely related to the formation and the structure of the parallel electric field. The TKR emission sometimes coincides with the intense upper hybrid emission around the satellite position at the inner edge of the dusk side plasmasheet, indicating that TKR has intimate relation to the energetic particle precipitation that generates the UHR waves; the precipitating particles may contribute to the development of the auroral field aligned currents.

1. Introduction

The first observation of intense propagating noise from the earth was reported by BENEDIKTOV *et al.* (1965, 1968). Their observation in the frequency range from 725 kHz to 1.525 MHz showed the sporadic enhancement of the radio noise whose activity is closely related to the geomagnetic disturbances. Using OGO 1 satellite, DUNKEL *et al.* (1970) indicated that there exist two types of low frequency noise desig-

nated as 'broadband' and 'highpass' noises, detected in the distant area from the earth in the nightside magnetosphere. The 'highpass noise' is now identified as the same objectives called the terrestrial kilometric radiation (TKR) in present. They were the first who discovered the high correlation between the occurrence of the radio wave emission and the enhancement of the auroral electrojet index (AE).

Recent satellite observations have revealed two distinctly different nonthermal emissions. One of these types of radiation has a continuous appearance with relatively weak intensity. This radiation has been called the 'nonthermal continuum.' The other type emission has been called 'terrestrial kilometric radiation' by GURNETT (1974) and KAISER and ALEXANDER (1976). The survey of the basic characteristics of TKR was demonstrated by GURNETT (1974) based on the experiments on Imp 6 and 8 satellites. He showed that TKR is the electromagnetic waves that have the linear relation between the electric and magnetic field strength. The terrestrial kilometric radiation is characterized by the frequency band ranging from several tens of kHz to several hundreds of kHz centered at a some frequency in a range from 100 kHz to 400 kHz. After that, the properties of the terrestrial kilometric radiation have been investigated by many workers with respect to the relation to the occurrence of the auroral arcs and substorm phenomena (KAISER and ALEXANDER, 1977; VOOTs *et al.*, 1977), the angular distribution of the radiation (GREEN *et al.*, 1977) and the spacial structure of the source (KRUTH *et al.*, 1975; KAISER and ALEXANDER, 1976; ALEXANDER and KAISER, 1976, 1977). For the next step it is required to study the dynamical behavior in both the intensity and frequency, and detailed structure of the source region; moreover, it is desired to clarify the generation mechanism of this fascinating TKR phenomena.

The purpose of the present paper is to present some initial results of JIKIKEN (EXOS-B) satellite that is equipped with the swept frequency receiver with analog telemetry system that provides the high resolution data on the dynamic spectrum of the TKR phenomena. The analyzed data based on the first 6 months observations of JIKIKEN, provide significant informations on the dynamical behavior of the source location and the relation to the energetic particle distribution in the plasma sheet region of the magnetosphere close to the plasmapause, and contain the important clue for the quest of the generation mechanism.

The JIKIKEN satellite was launched on Sept. 16, 1978 at 14:00 JST being purposed to study the plasma and radio waves and particle phenomena to clarify the wave particle interaction in the plasmasphere and the magnetosphere as one of the series of IMS (International Magnetospheric Study) satellite observations planned in Japan. The satellite was injected into an excentric earth orbit with the initial apogee and perigee of 30,051 km and 227 km, respectively, the inclination of -31.1 degree and the initial period of 524 min. The spacecraft is spin stabilized with the initial spin period of about 94 sec.

The natural plasma wave experiment on JIKIKEN is designed to observe the phe-

nomena such as 1) the plasma waves which are generated as the result of the wave-particle interaction in the magnetosphere, 2) planetary and terrestrial radio waves emitted from the polar region of the planet associated with the planetary and terrestrial magnetospheric disturbances, and 3) hectometric radio bursts from the sun.

The mode of Natural Plasma Wave observation with Radio Astronomy (NPW-A) using the swept frequency receiver in a range from 10 kHz to 3 MHz provides two kinds of data in the magnetosphere. The first is an in situ plasma wave phenomena in the magnetosphere; and the second is the remote radio wave phenomena originated from the earth and the other celestial objects such as the sun and Jupiter. Among these remote radio wave phenomena, TKR is one of the most prominent subject of the JIKIKEN observation.

2. Instrumentation

JIKIKEN is equipped with the two sets of long dipole antenna which are arranged orthogonally each other in the perpendicular plane to the spacecraft spin axis with the

Fig. 1. Block diagram of NPW-A system. Wave Common Tx(WCM Tx) and Wave Common Rx(WCM Rx) which are utilized as the common subsystems of the wave observation systems, are shown in focusing on the essential parts working for NPW-A mode.

length of 102 m (tip to tip) and 72 m (tip to tip). The 102 m dipole antenna is used mainly for the plasma and radio wave reception, while the other set (72 m antenna) is used for the plasma relaxation sounder and the impedance probe. The signals picked up by this receiving antenna is fed to the low noise wide band pre-amplifier, then analyzed by onboard swept frequency spectrometer that consists of a double superheterodyne receiving system.

The block diagram of the receiver is indicated in Fig. 1. At the pre-amplifier the signal is amplified by 40 dB in a full frequency range from 10 kHz to 3 MHz. Monolithic wide band operational amplifier is used for this purpose. Through the first mixer the signal frequency is converted to the fixed frequency of 10.700 MHz using a local signal whose frequency is swept from 10.710 MHz to 13.700 MHz. Thus, the receiver works as a spectrum analyzer for the observation of the dynamic spectrum of the phenomena ranging from 10 kHz to 3 MHz. The NPW-A mode is designed to take the 1 kHz band width at the first IF (inter mediate frequency) using a crystal filter. In the second stage the signal is amplified with center frequency of 200 kHz. The signal is compressed through the logarithmic amplifier after detected by the precision detector circuit.

The threshold of the receiver is estimated to be 0.1 μ Volt. At 1.47 MHz, the 102 m dipole antenna from tip to tip works as a quarter wavelength antenna where we can estimate the effective height as $(\lambda/\pi)=64.9$ m which give us a threshold value 1.54×10^{-9} Volt/m. The threshold power is then obtained as 1.0×10^{-28} Watt/m²Hz.

3. Example of Terrestrial Kilometric Radio Waves

The location of the apogee of JIKIKEN satellite was in the midnight sector (02 hLT) at the launched stage and has made shift westward with the rate of about 15°/month. So that we can obtain the various wave phenomena distributed in wide range of the local time of the magnetosphere from the midnight to dusk region during the first 6 months after the launch. The typical example of the dynamic spectrum of the wave phenomena observed in the dusk side magnetosphere on Feb. 2, 1979 is shown in Fig. 2 (and also in the lower panel of Fig. 4), along the trajectory shown in Fig. 3. Two remarkable banded emissions are observed in the frequency range from 150 kHz to 75 kHz through the entire orbit. The higher frequency emission with the narrower bandwidth in Fig. 2 is near the local upper hybrid frequency, $f_{\text{UHR}} = \sqrt{f_p^2 + f_c^2}$, where f_p and f_c are the plasma frequency and the electron cyclotron frequency, respectively. This upper hybrid resonance emission is attributed to the plasma waves associated with the beam wave instability generated in the ambient plasma. From the upper hybrid resonance frequency, then, we can obtain the profile of the plasma density. The structure of the plasmapause on this day at the dusk side shows the gradual decrease of the plasma density with the distance from the earth. Though it is difficult to point out the distinct plasmapause position, the L value of the plasma-

Fig. 2. Dynamic spectrum of the wave phenomena observed in the dusk side magnetosphere on Feb. 2, 1979. The terrestrial kilometric radiation is detected from about 12:10 UT and faded out at about 15:10 UT in the frequency range from 120 kHz to 500 kHz. The emissions between the local upper hybrid resonance frequency and the local electron plasma frequency is continuously observed through out the entire orbit. Around 14:50 UT and 15:10 UT, the radio wave emissions of the celestial origin, which have the pure falling tone, are observed.

pause is detected to be about 5.0 taking account of the change of the frequency of UHR emission.

Another banded emission that follows the UHR emission with the frequency difference of nf_c , where n is the integer, is attributed to the plasma waves as the result of the nonlinear wave particle interaction between the upper hybrid emission and the electrostatic electron cyclotron harmonic wave. This emission is named as the subsidiary UHR emission (see the paper in this issue by OYA and MORIOKA).

In the frequency range above the local upper hybrid resonance frequency, a group of emission is observed covering the frequency range from 120 kHz to 500 kHz. The wavelength of this emission covers from 0.6 km to 2.5 km, especially, main portion of the emission has the wavelength of 1.7 km. This is identical as will be discussed in the following sections to the earth's kilometric radio waves discovered by GURNETT (1974). Starting from 12:10 UT (see Fig. 2), the emission gradually makes growth with quick

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Fig. 3. Trajectory of JIKIKEN satellite on revolution 393, Feb. 2, 1979, corresponding to Fig. 2. The thick line on the trajectory shows the interval when the terrestrial kilometric radiation is detected.

variation of the intensity and frequency band width and gradually fades out at about 15:10 UT. The starting position and the end position for the JIKIKEN observations of TKR have been plotted with thick line in Fig. 3. It is evident that the reception of the terrestrial kilometric radio waves are located outside the plasmasphere.

In the spectrum given in Fig. 2, there is also record of the emission that covers the frequency range above 500 kHz with falling tone structure as seen at about 14:29

UT, 14: 51 UT, 15: 08 UT, and 15: 13 UT. The source of this type emission is identified to be the celestial origin. As the situation of the sun and Jupiter in the sky is, however, in the relation of antipode with respect to the spin axis of the satellite, separation of the solar origin from the Jovian origin is impossible for the present case. The spectrum of the emission of the terrestrial and celestial origin thus has the wide variety of the feature. The study of the present paper concentrates to the terrestrial kilometric radio waves (TKR) out of the wide variety of the spectrum observed in the magnetosphere.

4. Occurrence Characteristics of TKR Emissions

For the case observed on Feb. 2, 1979, the relation between the TKR activity and the development of the substorm is examined using the ground-based geomagnetic data. The ground-based data of the magnetic field and the geomagnetic pulsation were available from Onagawa magnetic observatory, Tohoku University (28.45°, geomagnetic latitude). The local time of Onagawa was in the evening to the midnight, when TKR observation of JIKIKEN was performed around the dusk side in the magnetosphere on Feb. 2, 1979. The ordinary magnetogram observed on Feb. 2, 1979 is shown in the upper panel of Fig. 4. The midlatitude positive bay phenomena associated with the polar magnetic substorms appear at about 10: 42 UT, 11: 43 UT, and 12: 56 UT. The Pi 2 pulsations that are the good indicators of the onsets of the polar magnetic substorms (SAITO *et al.*, 1976) are indicated by arrows in the

Fig. 4. Ordinary magnetogram observed on the ground (Onagawa) and dynamic spectrum of the wave phenomena in the magnetosphere observed by JIKIKEN. Arrows in the upper panel show the onsets of Pi 2 pulsations. TKR is detected from about 12: 10 UT in the frequency range from 120 kHz to 500 kHz and faded out at about 15: 10 UT. Midlatitude positive bays are coincident with the development of TKR activity when the satellite is located outside the plasmasphere.

Fig. 5. Relationship between the polar magnetic substorm observed at Tixie Bay and TKR observed on JIKIKEN. Associated with the onset of the substorm, the bandwidth of TKR is expanded suddenly. It is also apparent that the center frequency of TKR varies according to the evolution of the polar magnetic disturbance.

figure. The dynamic spectrum of TKR on Feb. 2 is again shown in the lower panel of Fig. 4. After JIKIKEN satellite passes through the plasmasphere (about 12:00 UT) the TKR waves are observed. It is noticed that the observed TKR activity is correlated with the development of the substorm (shaded portion in the magnetogram). The detailed relationship between the development of the magnetospheric substorm and the spectral behavior of TKR investigated by means of the expanded dynamic spectrum. In Fig. 5, ordinary magnetogram at Tixie Bay (60.5° geomagnetic latitude, 191.9° geomagnetic longitude) and the dynamic spectrum of TKR observed by JIKIKEN is indicated for the case of the severe magnetospheric substorm on Mar. 3, 1979. At the onset of substorm at 14:10 UT, the quick broadening of the emission bandwidth is observed in a frequency range from 120 kHz to 300 kHz. The time scale of this quick response to attain to the widest frequency bandwidth is within 40 sec, and the power flux density varies, at 250 kHz, from 2.0×10^{-16} Watt/m²Hz

to 3.2×10^{-15} Watt/m²Hz. This evidence suggests that the generation of TKR is taking place in the wide range of altitude along the magnetic field lines in the auroral region within a very short time associated with auroral breakup.

It is also indicated from Fig. 5 that the frequency of the maximum power flux of the dynamic spectrum varies according to the evolution of the magnetospheric fields and particles activity. At the beginning of the dynamic spectrum, 13:55 UT, the center frequency of TKR is about 280 kHz, the center frequency, then, gradually decreases with the average frequency drift rate of 46 kHz/min, till the onset of the large substorm. In this phase, until the onset of the substorm, the magnetogram shows small positive variation that is thought to be some sort of the energy accumulation of the fields and particles in the magnetosphere. This period can also be interpreted as the sequential occurrence of the small scale substorms following the idea invoked by AKASOFU (1973). At the onset of the large magnetospheric substorm, the center frequency of TKR changes suddenly from 210 kHz to 190 kHz. Thereafter, the center frequency was rather constant for 10 min, and then turned to the increase with time. This evidence suggests that the center frequency of the TKR emission decreases associated with enhancement of the magnetospheric fields and particles activity. These features of the center frequency variation of TKR with respect to the magnetospheric activity indicates that the displacement of the source region of TKR emission takes place in upward direction along the magnetic field line, in the auroral region, in the initial phase of the substorm; the initial phase is here defined as the period of the increment of the activity of the magnetospheric fields and particles.

The case study for the occurrence of TKR and its relation to the substorm activity has been made. The results indicate that a clear dependency exists between the emission intensity and the substorm activity. The bandwidth of the TKR dynamic spectrum has also a close relation with the geomagnetic activity. These evidence are again identical to the results of relation with the magnetospheric substorm activity, as has been pointed out by GURNETT (1974), VOOTS *et al.* (1977), and KAISER and ALEXANDER (1977). In Fig. 6, the dynamic spectra observed both on the magnetically quiet and active days are shown with respect to the observing positions outside of the plasmapause. In data of TKR on a geomagnetically quiet day (the upper panel of the figure) a weak emission is observed with the narrow band width centered around 200 kHz though ΣK_p is only 7₀ on this day. It is very important that TKR is observed even on the geomagnetically quiet day at the night side magnetosphere though the emission has only weak intensity and the spectrum is limited into a relatively narrow frequency band. The result implies that TKR is radiated almost all the night-hours in the upper ionosphere above the auroral oval where TKR can be observable mainly from the outside of the plasmapause. In the lower panel of Fig. 6, the dynamic spectrum of TKR emission under the relatively high geomagnetic disturbance condition has been indicated. The observation has also been made outside region of the plasmasphere. Both intensity and band width of the TKR emission on a magnetically

Fig. 6. The occurrence characteristics of TKR depending on the geomagnetic activity. Even on a magnetically quiet day, TKR appears with low intensity and narrow band width (upper panel).

disturbed day increases compared with those on a quiet day. It is also remarkable that the intensity and band width reveals very rapid variation suggesting the variation of the spacial and time dependent auroral activity. The study for the correlation between the rapid change of TKR observed in the magnetosphere and the substorm development associated with rapidly changing phenomena such as particle precipitation, generation of VLF hiss and microstructure of aurora is required as future works.

5. Source Location of TKR

The source region of TKR can be deduced from the observed modulation pattern due to the rotation of the dipole antenna caused by the spacecraft spin motion. The spin modulation effect of the observed TKR is shown in Fig. 7 in the frequency range from 100 kHz to 1,000 kHz. As the receiving swept frequency is divided into two ranges, that is from 10 kHz to 200 kHz in LF range, and from 120 kHz to 3 MHz in HF range of the receiver, there is an overlap of the spectrum in a range from 120 kHz to 200 kHz in HF range as seen in the top and bottom panels in Fig. 7. When we select the HF range for the observed TKR, then, compressed dynamic spectra in their frequency coordinate is obtained. This compressed dynamic spectra are useful for the study of the macroscopic feature of TKR as shown in the second and the third panels of Fig. 7. It is clearly indicated in this dynamic spectra that the observed TKR shows positive frequency shift during the one half spin modulation when the satellite is located in the northern hemisphere, while an opposite frequency shift reveals when satellite is located in the southern hemisphere. This frequency shift in the spin modulation pattern is explained as follows. As the spin axis of the spacecraft is oriented to the direction of the sun with counter clockwise rotation during the period of the present observation, the direction of the maximum gain of the dipole

Fig. 7. Frequency shift of TKR caused by both the spin modulated directivity of the dipole antenna and the location of the spacecraft in the magnetosphere. The frequency shift is positive when the spacecraft is in the northern hemisphere (upper two panels), and negative in the southern hemisphere (lower two panels).

Fig. 8. Schematic illustration of the source region of TKR, plasmasphere and satellite location, viewed from the sun. When satellite is located in the northern hemisphere of the dusk side magnetosphere, TKR generated above the northern polar ionosphere is detected sequentially from the lower frequency component to the higher frequency component due to the rotation of the dipole antenna.

antenna sweeps the earth's polar region from higher to lower altitudes in the northern hemisphere, and then sweeps from lower to higher altitudes in the southern hemisphere. These relation are shown schematically in Fig. 8. In the period of the observation when JIKIKEN is located in the northern hemisphere, only TKR generated in the northern polar region can arrive at the satellite, because the southern source is hidden by the plasmasphere, and vice versa. It is evident from above mentioned mechanism that the observed frequency shift shows that the lower frequency component of TKR is generated at relatively higher altitude and the higher frequency component, at lower altitude. This result reveals that the frequency of the generated TKR is determined as a function of altitude above the auroral latitude.

Fig. 9. Schematic illustration of the scan of the radio source by dipole antenna (upper panel), and the resultant dynamic spectrum. When the dipole antenna that has broad directivity scans the radio source whose frequency varies linearly with respect to the direction of the antenna scanning, the observed dynamic spectrum should show the broad expansion in time axis.

In the dynamic spectrum of Fig. 7, the width of a spin modulated spectral pattern has by no means the information on the distribution of the source region. When we observed the small radio source where the emitted frequency varies linearly between both ends of the radio source (see upper panel of Fig. 9), using the rotating dipole antenna whose beam width of the directivity has broad coverage ($\sim 78^\circ$) compared with the visual angle of the source, the observed dynamic spectrum shows widely distributed pattern in time axis as illustrated in the lower panel of Fig. 9. Therefore, only the gradient of the frequency shift observed in the spin modulated dynamic spectrum is meaningful.

The amplitude variation at a frequency of 130 kHz is plotted in the lower panel of Fig. 10. Though the modulation pattern is not so much typical due to the fast variation of the original TKR intensity, the null point of the rotating antenna can be identified without difficulty as shown by arrows in the figure. The abscissa of upper

Fig. 10. Amplitude variation of TKR at 130 kHz with respect to the spin rotation of the satellite (lower panel). When null point of the signal (indicated by arrows) is detected, the antenna is pointed to the polar ionosphere where the altitude along the field line of 70° is about 8,000 km (upper panel). This indicates that the source altitude of TKR at 130 kHz is about 8,000 km.

panel of Fig. 10 shows the elevation angle between the direction of the earth center viewed from the satellite and the direction of the cross point of the antenna axis direction with the magnetic field line of 70° invariant latitude. The ordinate of the figure shows the altitude of the above mentioned cross point measured along the field line of 70° invariant latitude. As shown in this figure, at the time when the antenna detects the null point for the source, the altitude of the cross point is about 8,000 km along the 70° field line. From this analysis, the source altitude of TKR at the frequency of 130 kHz is determined to be about 8,000 km assuming that TKR is generated at the upper ionosphere of the polar region near 70° invariant latitude. The electron cyclotron frequency at the 8,000 km altitude along 70° field line deduced from the dipole field model is 136 kHz. This value is very close to 130 kHz of the present observation frequency. This suggests that the frequency of TKR is closely related to the local electron cyclotron frequency at the source region. In the previous studies on TKR using the far distant satellites such as Imp 6, Hawkeye 1, and RAE 1 and 2 satellites, the source location of TKR has been inferred to be $1-2 R_E$ above the polar ionosphere by means of the direction finding (KURTH *et al.*, 1975), the angular distribution of TKR in the magnetosphere (GREEN *et al.*, 1977) and the lunar occultation of TKR (KAISER and ALEXANDER, 1976). In the current works on TKR source position, the observation of JIKIKEN satellite is the first that directly has

identified the source location of TKR.

The theory of the TKR was initially proposed by BENSON (1975) based on the electrostatic conversion theory proposed by OYA (1971, 1974). Recently the more elaborated theory has been produced and will appear near future (Oya, 1979, private communication) on the conversion from the electrostatic plasma wave or hybrid mode of the plasma wave to the electromagnetic waves. That is, the most probable source mechanism is that the electrostatic waves near the upper hybrid resonance frequency excited by precipitating auroral energetic particles escapes in a form of the electromagnetic waves. Therefore, the observed TKR frequency will reflect the characteristic frequency, f_{UHR} , at the source region. Thus, the frequency of TKR contains the informations on the local plasma parameter, that is an electron cyclotron frequency and plasma frequency of the generation region above the auroral latitude.

The dynamic spectrum of a typical TKR event shows vivid time-dependent variation in both the intensity and frequency band width as has already been mentioned in the previous section. The enhancement of the intensity is well correlated with the broadening of the frequency band width as shown in dynamic ampligram of TKR in Fig. 11. This correlation between the enhancement of TKR intensity and frequency band width suggests that the generation region of TKR expands with the increment of the activity of TKR emission.

The observed frequency of TKR with the power flux more than about 1×10^{-19} Watt/m²Hz is investigated with respect to the geomagnetic activity, ΣK_p , during the period from Feb. 1 to Mar. 14, 1979, as shown in Fig. 12. It is evident that the lower

Fig. 11. Ampligram of TKR. The enhancement of the intensity and expansion of the band width are well correlated each other. The emissions with the falling tone structure as seen at 13: 52 UT on Feb. 8, 14: 28 UT, 14: 50 UT and 15: 07 UT on Feb. 2 are the radio waves from the celestial body.

Fig. 12. ΣK_p dependence of the band width of TKR. The lower border frequency of TKR decreases monotonously as the geomagnetic activity increases. The higher frequency border increases up to 900 kHz, with the increase of ΣK_p , then frequency is kept rather constant nevertheless ΣK_p increases. On the right ordinate, the altitude of the source region is shown, assuming that TKR frequency is reflecting the upper hybrid frequency at the source, of which location is on the field line of 70° invariant latitude.

limit of TKR frequency extends monotonously towards lower frequency side with the increment of the geomagnetic activity. On the most disturbed day during the analyzed period, i.e. $\Sigma K_p = 34$, the lowest frequency of TKR was about 70 kHz, and on the most quiet day ($\Sigma K_p = 4_0$), the lowest frequency of TKR was 150 kHz. The higher limit of TKR frequency also increases on the geomagnetically disturbed day; there is, however, the portion of the leveling off with increment of the geomagnetic activity. That is, during a moderately disturbed condition, the higher limit frequency increases with the geomagnetic activity, and approaches to about 900 kHz when ΣK_p is about 25, while the higher limit frequency does not increase with the geomagnetic activity, and seems to be rather constant, in the range of ΣK_p that exceeds 25.

Based on the theory of the hybrid mode plasma wave origin (OYA, 1971, 1974; BENSON, 1975), the source location can be identified from the emission frequency f , i.e. the altitude r , along the field is given from the relation

$$f = f_p^2(r) + f_c^2(r) \quad (1)$$

where $f_p(r)$ and $f_c(r)$ are the plasma frequency and the electron cyclotron frequencies at the point r .

To calculate $f_p(r)$, in this paper, the polar wind model (BANKS and HOLTZER, 1969) is used; and $f_c(r)$ is calculated from the geomagnetic dipole model. The result indicate that in the trough region $r > 2,000$ km, $f_p^2 \ll f_c^2$ and we can approximate as

$$r = r_0 \cdot \sqrt[3]{f_{0c}/f} \quad (2)$$

where f_{0c} is the electron cyclotron frequency at the earth's surface $r = r_0$.

On the right ordinate in Fig. 12, the calculated altitude is indicated. From the figure, it is evident that the source altitude of TKR expands in the range from 12,000

km to 2,500 km along the auroral field line on the disturbed day. In the quiet condition the source altitude ranges from 7,000 km to 6,000 km.

From the above investigation it is summarized that 1) the generation region of TKR expands toward both the higher and the lower altitudes as the geomagnetic activity increases, 2) the lowest altitude of the generation region is, however, limited at around 2,500 km even when the geomagnetic indices ΣK_p exceeds 25.

6. Movement of the Source Region

In the dynamic spectrum, the intense portion of TKR indicates the patch which is characterized by the rising tone. The examples of the patch are illustrated in Figs. 13 and 14 with the schematic illustration to interpret the characteristic patch. The patch appears frequently with the duration of 1 to several minutes and band width of 5 to 10 kHz. Sometimes, it seems that TKR is composed of the cluster of this fine

Fig. 13. Example of the fine structure of TKR. The cross sections of the dynamic spectrum at point A and B are shown in the lower panel. The band width of the fine structure is about 2-5 kHz.

Fig. 14. Fine patch structure of TKR (top panel) and schematic illustration (middle panel). The frequency drift of the fine patch structure is nearly in proportion to cubic power law with time (bottom panel).

patch structure. The features of the fine patch structure, in terms of the frequency drift rate, band width and characteristic duration time, provide the information of the source mechanism of TKR. The positive drift of frequency (rising tone) shows that the most intense portion of the TKR source is moving down towards the earth's polar ionosphere. When we suppose that the frequency of TKR is determined by the local upper hybrid resonance frequency as described in Sec. 5, the average velocity of the portion of the most intense source region is estimated from the drift rate of the fine patch structure. When it is assumed that TKR is radiated along the field line of 70° invariant latitude, the detected frequency can be translated to the altitude of the emitting region as shown on the right ordinate of the middle panel of Fig. 14. The average velocity of the emitting region is estimated to be about 5 to 10 km/sec. This result is consistent with observation of TKR source by ISEE-1 and 2 (GURNETT *et al.*, 1978). Since the obtained source motion is apparently very slow compared with velocity of the auroral precipitating particles which are moving along the auroral field line, it is suggested that the source portion is moving or propagating down to the auroral region with the speed independent to the particle velocity.

One possible mechanism of the emission source is the particle acceleration due to the electric field along the magnetic field. The accelerated particles can produce the hybrid mode waves due to Cernkov radiation mechanism (OYA, 1971) as a result of the beam wave interaction. The electric field parallel to the magnetic field has currently been investigated, the most topical subject for the present is the existing double layer (BLOCK, 1975).

The drift rate of a fine patch structure varies with time as seen in Fig. 14; i.e., the frequency drift is taking place nearly in proportion to cubic power law with time. From the linear relation between the cubed frequency value and time, the frequency drift is expressed as

$$f_{\text{obs}}^3 = \alpha t \quad (3)$$

where α is obtained from a gradient of the empirical linear relation between the cubed frequency value and the time as has already been given in Figs. 14 and 15. From Eq. (2), then, it follows, taking $f = f_{\text{obs}}$, that

$$r = r_0 f_{\text{oc}}^{1/3} (\alpha t)^{-1/9} \quad (4)$$

Fig. 15. Plot of the cubed frequency value of TKR fine patch structure showing that the frequency drift of the fine patch structure is well-fitted to the cubic power law with time.

or

$$\frac{dr}{dt} = A(r/r_0)^{10} \quad (5)$$

where

$$A = -(\alpha r_0 / 9 f_{oc}^3).$$

As has been indicated in Fig. 16, where the velocity profile of the source is shown versus the distance along the field line of 70° invariant latitude, the velocity of the source region motion steeply decrease when the source moves towards earth's surface. In Fig. 16, the hatched area shows the actual velocity range. The initial velocity is a few tens of kilometer per second and decreases sharply as the source coming down to the auroral ionosphere, then almost becomes $1/1,000$ at the altitude of 3,000 km. It is inferred that this feature of the source motion may be closely related to the electric field parallel to the auroral field line.

Fig. 16. Source velocity profile deduced from the frequency shift of the TKR fine patch structure, illustrating that the source velocity is steeply decelerated with decreasing the radial distance from the earth.

The existence of this field has been recently confirmed by means of the rocket observation (for example, WHALEN and MCDIARMID, 1972; ARNOLDY and CHOY, 1973) and satellite observation (for example, FRANK and GURNETT, 1971; SCHELLY *et al.*, 1976 and MOZER *et al.*, 1977). The altitude of the parallel electric field, derived from the particle observation and direct measurement of $E_{\parallel}$, is also consistent with the generation region of TKR deduced from this work. The source motion deduced from the fine patch structure may be reflecting the microstructure or dynamical behavior of the parallel electric field, $E_{\parallel}$.

7. Correlation with the Intense UHR Emissions

The emission between the upper hybrid resonance (UHR frequency) and the plasma frequency surrounding the satellite indicate the enhancement of the intensity which builds up, sometimes, to the saturation level of the pre-amplifier of the instrument (OYA *et al.*, 1980). The enhanced upper hybrid emissions are detected outside the plas-

Fig. 17. Distribution of the enhanced UHR emissions in the magnetosphere. The lines marked by dark circles show where TKR and enhanced UHR emission are simultaneously observed.

Fig. 18. Plot of the L value where intense UHR emission is observed, versus K_p indices. The region of the intense UHR emission moves toward the earth as the magnetic activity increases. All the events are located between the plasmopause (L_{pp}) (BINSACK, 1967) and the inner edge of the plasma sheet (L_b) (MAUK and MCLWAIN, 1974).

masphere ranging from $L=4$ to $L=6.5$ as has been given in Fig. 17. The L value of the satellite position where intense UHR emission is observed is dependent on K_p index (see Fig. 18). It is also remarkable that this type of the emission is associated with the enhancement of the soft electron flux (OYA *et al.*, 1980), indicating that UHR emission is generated by the wave particle interaction in the ambient plasma.

This peculiar emission sometimes corresponds to the occurrence or enhancement of TKR emissions in the dusk side magnetosphere. As has been indicated in the top panel of Fig. 19, the intense UHR emissions are observed at about 14:01 UT, and a narrow band TKR emission occurred almost simultaneously. The examples in the middle and bottom panels of Fig. 19 show that TKR emission is enhanced being associated with the intense UHR emissions. The L value of the satellite position where the observations have been carried out is rather smaller than that of the auroral region in all cases, so the area of occurrence of the intense UHR (in situ observation) and TKR (propagation from the auroral latitude) are not directly connected with the same

Fig. 19. Relationship between the intense UHR emissions and enhancements of TKR. Simultaneous occurrence of the both events (top panel) and the enhancement of TKR associated with the intense UHR emission (middle and bottom panels).

field line. But it should be noted that the intense UHR emission are detected near the inner edge of the dusk side plasmasheet. In Fig. 17, the intense UHR emission events associated with the TKR enhancements are marked by dots. The result is suggestive that the simultaneous occurrence of both the intense UHR emission and TKR is closely related to the development of the auroral field aligned current systems in the dusk side magnetosphere.

8. Discussion and Conclusion

The natural plasma wave experiment onboard JIKIKEN is successfully carrying out and has revealed some important characteristics of the terrestrial kilometric radiation by means of the high resolution spectrum analysis.

The theoretical models proposed for the generation of TKR are divided into two categories. The first is the direct emission of the escaping electromagnetic waves

through the wave particle interaction, which is taking place at the extraordinary mode branch in the small wave number region of dispersion curve. The models of the generation of TKR in this category have been proposed by FRANKEL (1973), MELROSE (1976), and WU and LEE (1979). The second is the mode conversion from longitudinal plasma waves generated by interaction with the relatively low energy particles to the escaping electromagnetic radio waves. OYA (1971, 1974) is the first who showed that the conversion of the longitudinal plasma waves into the escaping electromagnetic waves can take place with high efficiency. It is necessary for the explanation of the TKR as the result of the direct electromagnetic radiation that the particles are precipitating with the very large flux in the high energy component or with the anomalous temperature anisotropy, which are unreasonable for the actual auroral particles. On the other hand, the electrostatic waves or the hybrid mode between the electrostatic and the electromagnetic waves can be generated in the frequency range between the upper hybrid frequency and the electron cyclotron frequency by the relatively low energy plasma beam which is reasonable for the auroral precipitating particles (OYA, 1971, 1974). The plasma waves near the upper hybrid frequency is generated by the precipitating auroral particles, then converted with high conversion efficiency from the longitudinal or the hybrid mode electrostatic plasma waves to the transverse electromagnetic waves when the waves travel the slightly inhomogeneous plasma. Based on this theory, the source position of the TKR has been identified with the assumed plasma density and magnetic field model. Since the plasma frequency is much smaller than the electron cyclotron frequency in the generation region the source situation is mainly fixed by the magnetic field model that is well established as geomagnetic dipole model.

The rapid variation of the frequency band width shows the expansion of the source region of TKR. In the case of the data observed on Feb. 8, 1979, for an example, the TKR emissions appear with the frequency band that covers between about 200 kHz and 400 kHz before 13: 50 UT, and suddenly its frequency band is expanded to cover a range between 150 kHz and 700 kHz in about 20 sec (see Fig. 11). This frequency change corresponds to the expansion of source region from 5,000 km to 3,500 km for the lower limit of the source region and from 7,500 km to 9,000 km for the higher limit of the source region. These rapid expansions of the source region (order of 100 km/sec) is indicating vertical motion of the source region where the acceleration of the auroral particles is taking place. The center of the generation region of TKR is about 6,000 km height; this is consistent with the height distribution of $E_{\parallel}$ region obtained by GHIEMMETTI *et al.* (1978). They studied statistically the spacial distribution of the effective acceleration region using the upward flowing ion events, and showed that the probability of the acceleration is maximum at the altitude of 6,000–7,000 km.

The lower limit of the source altitude decreases with the increment of the geomagnetic activity; the lowest limit is, however, restricted at the altitude of about 2,500 km

even for the higher $\sum K_p$ indices than 25. Whereas the higher limit of the source altitude increases with the increment of the geomagnetic activity. In a magnetically quiet condition, the altitude range of the source region ranges from 6,000 km to 7,000 km.

The altitude variation of the source region with respect to the geomagnetic disturbance shows the similar tendency with K_p dependence of the plasmapause position. There may remain duplicated effects on the expansion of the frequency band with geomagnetic activity; i.e., the compressed plasmasphere on the disturbed day makes the visible frequency range wide due to the decrement of the cutoff frequency at the plasmapause in addition to the widening of the frequency band due to the expansion of the source region on the geomagnetically active day. The cases where the observed dynamic spectrum indicates clear cutoff at the upper limit frequency is, here, excluded from the present analysis to discriminate the plasmapause cutoff effect from the source region effects.

In addition to the macroscopic behavior that is substantially associated with the auroral substorm development, the TKR emission shows the fast variation of both the intensity and frequency band width. These fast variations may be indicating the microscopic structure of the enhancement of the precipitating particle flux and the development and decay of the electric field for the particle acceleration along the auroral field line.

The motion of TKR source region is deduced from the fine patch structure of the dynamic spectrum of the TKR emission. Sometimes the feature of the whole TKR emission consists of the cluster of these patch structures. The fine patch structure suggests that the source agency is repeatedly moving down towards the auroral ionosphere starting from the same area around from 6,000 km to 7,000 km above the ionosphere, with the duration from one to several minutes and with the initial velocity of few tens of kilometer per second and rapidly decelerated as the radial distance approach to down side limit of the source region. The band width of the fine patch structure, that has about 5 to 10 kHz, brings us the information for the unit of the emission size. Two categories of the expansion can be considered for the present time, pertaining to the interpretation of the band width of the fine patch structure; the first is the spacial distribution and the second is the time dependent variation of the electron density. The spacial distribution has also two different possibilities, i. e., i) latitudinal distribution of the source and ii) the height distribution of the source along the field lines that are connected to the polar ionosphere. When the band width of the fine patch structure, ± 5 kHz, is attributed to the latitudinal distribution of the source region, the source region has the dimension of ± 3 degrees in latitude at the height of 6,000 km, which seems to be rather too wide compared with the distribution of the typical dusk side auroral events, such as the visible discrete aurora region, the field aligned current region and the inverted V event region. On the other hand, when the band width is attributed to the field aligned range, the source region is thought to be

expanded about ± 100 km at the altitude of 6,000 km. From these simple estimation, it is suggested that source of the fine patch structure has the relatively small scale size, at most of the order of 100 km in the direction of the field line.

The possibility of the temporal variation of the electron density still remain for the interpretation of the fine patch structure. In the trough region the particle acceleration is expected for the production of the beam that becomes the origin of the plasma instability to excite the upper hybrid resonance waves. Considering the background plasma density, it can be estimated as the increment of 28% of the electron density in a form of the irregularity can give the fine patch structure with the band width of 5 kHz.

Several theoretical mechanism for auroral electric field are proposed such as double layers (BLOCK, 1975), different pitch angle anisotropy (ALFVEN and FALTHAMMAR, 1963; LENNARTSSON, 1976), thermoelectric effect (HULTQVIST, 1971) and anomalous resistivity (HASEGAWA, 1974). To explain the present results, the minimum scale size of the parallel electric field region must be the order of 100 km. Above models except for the double layers model request the large scale configuration of the electric field, with order of a few earth radii, whereas the double layers model requires the small scale size, with order of Debye length or ion gyro-radius. Although there remain problems to be solved between the difference in the laboratory model and the actual geophysical state, it seems that the some sight of double layers type model is more advantageous to explain the auroral parallel electric field that is confined in a restricted region.

The simultaneous detection of the intense UHR emission near the dusk side region at the inner edge of the plasmasheet and the enhanced TKR emission generated near earth position about the altitude of 6,000 km along the field lines on the auroral latitude is considered to be the result of the coupling between the polar ionosphere and the magnetosphere by the precipitating particles carrying the field aligned currents. IJIMA and POTEMURA (1976) and POTEMURA (1977) showed that in the dusk side magnetosphere the upward and downward field aligned currents are bounded near the inner edge of the plasmasheet, and the position of the current that flows into the ionosphere is located in a region of the earthward side of the plasmasheet boundary. The development of the auroral field aligned currents in the dusk side magnetosphere may closely be correlated to the occurrence of both the intense UHR emission at the position of the downward current region due to upgoing high energy electron and the TKR emissions at the upward current region where the energetic electrons making downward precipitation.

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