MAGNETOSPHERIC VLF LINE RADIATION OBSERVED AT HALLEY, ANTARCTICA

J. P. MATTHEWS and K. YEARBY

Department of Physics, University of Sheffield, Sheffield, U.K.

***Abstract*:** Spectrograms of broad-band ELF/VLF goniometer data obtained from ground based measurements made at Halley, Antarctica ($L=4.3$, conjugate near St. Anthony, Newfoundland) have shown the presence of discrete line radiation of magnetospheric origin, in the frequency range 1–4 kHz. The properties of this radiation are broadly similar to Power Line Harmonic Radiation (PLHR), studied from ground based observations made at Siple, Antarctica ($L=4.1$, conjugate–Roberval, Quebec), although there are some interesting differences. Line radiation observed at Halley, is never regularly spaced in frequency by 120 Hz, as one may expect if signals from the Newfoundland power distribution system (60 Hz fundamental) are entering the magnetosphere, and being amplified. Instead, frequency spacings are widely distributed about mean values between 50 to 90 Hz. The lines are observed to trigger emissions and often exhibit 2 hop amplitude modulation, which demonstrates that they are of magnetospheric origin. Events occur mostly in quiet to moderate geomagnetic conditions, and during the late afternoon period of local time. Arrays of lines are often observed to drift upwards together in frequency. Line bandwidths are 20–30 Hz-much larger than the bandwidths of locally generated induction lines. We show that the line spacing of $\sim$80 Hz is too large to correspond to sideband separation for waves of equatorial field strength $\sim$10 pT, and we investigate the conditions required for effective particle trapping by the wave array, of the type described by NUNN (J. Plasma Phys., **11**, 189, 1974). It is proposed that the line radiation either originates in the signals which enter the magnetosphere from Newfoundland, or is 'naturally' generated, possibly by a linear instability which takes place if the electron distribution is unstable in restricted ranges of wave frequency and wave number.

1. Introduction

VLF radiation from the power distribution systems of industrialised regions can enter the magnetosphere and interact with the ambient particle population. The Power Line Harmonic Radiation (PLHR) is amplified in the magnetosphere, and can influence the growth of other whistler mode waves. As the line radiation observed at Halley is in certain respects similar to PLHR we shall begin by summarizing recent work on this topic.

The pioneer work of HELLIWELL *et al.* (1975) provided direct evidence of harmonic radiation from the Canadian power distribution system entering the magnetosphere and stimulating VLF emissions. The data presented were recorded at Siple, Antarctica and its conjugate at Roberval in Canada. The fundamental frequency of the Canadian power system is 60 Hz, and if odd harmonics are radiated most strongly, one would expect a magnetospheric response consisting of an array of lines spaced by 120 Hz. In fact, the magnetospheric lines observed in one example by HELLIWELL *et al.* (1975) varied in spacing between 70 and 230 Hz with a mean spacing of 129 Hz. Also, the magnetospheric lines were usually shifted by 20–30 Hz with respect to their parent induction line in the northern hemisphere. These workers discussed other PLHR effects such as triggering, entrainment, slope reversals of emissions and echoing phenomena, and observed a line bandwidth of $\sim$30 Hz which is much broader than the bandwidth of locally generated induction lines. Some of their records showed evidence of 'fine structure' *i.e.* line spacings as low as 20 Hz, and on one occasion all the lines were observed to drift upwards together.

PARK (1977) showed that in post storm periods at midlatitudes the strongest waves were often emissions stimulated by PLHR. He concluded that PLHR must have a strong influence on the particle populations in the magnetosphere. PARK and HELLIWELL (1977) suggested that whistler precursors are initiated by PLHR. In PARK and HELLIWELL (1978) the local time and Kp dependence of PLHR induced emissions were discussed. At Siple and the nearby Eights Station, PLHR induced emission events peaked strongly at around 0900 LT and tended to occur during periods of quiet geomagnetic activity ($Kp=1-2$). A recent study of chorus activity between 2 and 4 kHz (PARK and MILLER, 1979) has revealed a minimum in wave intensity on Sundays when electrical power usage is low, in comparison with the rest of the week. The authors attribute this to the lowered ability of weak Sunday PLHR to catalyse wave growth in the magnetosphere.

Satellite studies have provided evidence of enhanced VLF activity over industrialized regions. Low altitude satellite studies (LEFEUVRE and BULLOUGH, 1973; BULLOUGH *et al.*, 1976; TATNALL *et al.*, 1978; BULLOUGH and KAISER, 1979) have revealed a permanent zone of enhanced VLF activity over North America, with strong intensification over the industrial regions in the north east of the continent. The statistical significance of these results, based on 6330 observations over N. America alone, is high. LUETTE *et al.* (1977) examined chorus activity at high L values ($4<L<10$) on the Ogo 3 satellite, and also found that peaks in VLF activity were located over major industrialized centres. The statistical significance of these results have been questioned by TSURUTANI *et al.* (1979). These authors performed a similar study to LUETTE *et al.* (1977) and found no longitudinal localization in chorus activity. However they examined only emissions at ELF frequencies where no localization would be expected, in agreement with earlier work (BULLOUGH *et al.*, 1976; TATNALL *et al.*, 1978). Narrow band VLF signals with a frequency of separation of 100–130 Hz were detected by a receiver aboard the S3–3 satellite (KOONS *et al.*, 1978). The authors suggested that power line harmonic radiation was amplified to detectable levels by a nonlinear interaction involving signals from a transportable VLF transmitter operating in Central Otago, New Zealand. In this case, it is hard to resolve which effects were caused by the transmitter and which by PLHR. LUETTE *et al.* (1979) provide evidence from the Ogo 3 satellite that PLHR in the high altitude regions of the magnetosphere is sufficiently intense to control the starting frequencies of chorus emissions.

Results from controlled experiments, in which VLF signals transmitted from the ground are used to stimulate equatorial wave generation out to several earth radii, have provided new information concerning the wave/particle and wave/wave interactions which govern wave growth (HELLIWELL and KATSUFRAKIS, 1974; MCPHERSON *et al.*, 1974; KOONS and DAZEY, 1974; DOWDEN *et al.*, 1978). These results have given a stimulus to new theoretical work (HELLIWELL and CRYSTAL, 1973; NUNN, 1974; DOWDEN *et al.*, 1978), which in turn has led to a greater understanding of the role that relatively weak coherent waves such as PLHR can play in the growth phase of VLF emissions.

This paper aims to present new evidence of VLF line radiation similar in certain respects to PLHR observed by HELLIWELL *et al.* (1975). As far as we are aware, these are the only examples of well developed magnetospheric line arrays, other than those reported at the Siple/Roberval longitude. PARK and MILLER (1979) pointed out the importance of investigating PLHR activity at other longitudes—especially where power usage is low in comparison to the Roberval region of Quebec. We confirm that structured line radiation can be observed at Halley on rare occasions, but we have insufficient evidence from the conjugate point in Newfoundland to conclude that this radiation is definitely PLHR.

2. Experimental Results

The VLF goniometer system employed at Halley, Antarctica has been described elsewhere (BULLOUGH and SAGREDO, 1973). Briefly, this consists of a wideband (0.5–20 kHz) receiver connected to two vertical loop aerials mounted at right angles to each other. From these two loops, a single loop rotating about the vertical axis at 25 Hz is synthesized electronically, so that an incoming signal is modulated in amplitude by the system. Signals which are plane polarized and propagating essentially horizontally in the earth/ionosphere waveguide are observed to be split by the goniometer into two components separated by 50 Hz. Each component is shifted ± 25 Hz away from the true frequency of the incident wave. Waves which are circularly polarized and incident vertically on the aerials produce only one component whose frequency is shifted 25 Hz up or down depending on the apparent sense of rotation of the aerials, with respect to the incident wave polarization. Signals having intermediate angles of incidence and/or elliptical polarizations will produce line doublets with one component dominating. This system is well suited to bearing determination of incident signals (*e.g.* whistlers), and has been used as such for a number of years (SAGREDO and BULLOUGH, 1973; MATTHEWS *et al.*, 1979).

The data to be presented were recorded on magnetic tape in Antarctica and returned to the U.K. for analysis. Line radiation events can be detected by visual inspection of film spectrograms in the range 0–5 kHz, made using slow film speeds (0.04 cm per s), and a 512 line Fast Fourier Transform (FFT) analyser having a 10 Hz resolution on the 0–5 kHz range. Long periods of Halley data must be filmed in order to observe the rare occasions when the type of line radiation activity described in this paper is clearly identifiable. On other occasions, however, the wave activity may still be influenced by magnetospheric lines even though the latter are not clearly identifiable on film spectrograms. This is likely to be the case, for example, when trains of emissions are observed to start at the same frequency. The criteria we have used for selecting our line radiation events is that two or more well defined lines should be visible on the spectrogram and should exhibit triggering behaviour, two hop whistler mode amplitude modulation (Fig. 4) or other behaviour which clearly indicates their magnetospheric origin. These criteria may be more restrictive than those used by the Stanford workers, since no general agreement exists as yet on the problem of defining a PLHR event.

Data recorded on 24 June 1977 are presented in Fig. 1. This spectrogram shows a well defined array of magnetospheric lines which are gradually drifting upwards in frequency at $\sim$80 Hz/min, and lie in the frequency range 1.75–2.5 kHz. Power system frequencies do not exhibit sustained drifts as large as this (HELLIWELL

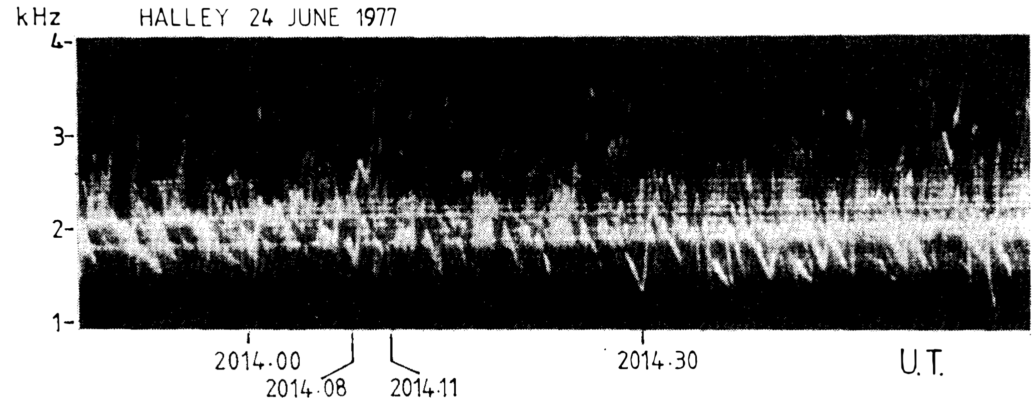

Fig. 1. The spectrogram shows a well defined array of magnetospheric lines which are gradually drifting up in frequency at $\sim$80 Hz/min, and lie in the frequency range 1.75–2.5 kHz. The lines trigger emission activity and show some evidence of a two hop modulation in the envelop of the wave spectrum. Local induction lines from Halley station are just visible between 1–1.5 kHz, and are regularly spaced lines of constant frequency.

et al., 1975). The fact that lines observed at Halley usually drift steadily upwards means that one cannot relate their frequencies to possible parent induction lines in the northern hemisphere. The lines trigger emission activity and show some evidence of a two hop modulation in the envelope of the wave spectrum. The bandwidths of the lines are ~30 Hz, which is much broader than the bandwidths of the local Halley induction lines. These latter appear between 1–1.5 kHz, and are regularly spaced lines of constant frequency. In this example, the frequency spacings of the magnetospheric lines are widely spread about the most common value of 80 Hz (Fig. 8).

In Fig. 2, the 3 s portion of data between 2014.08 and 2014.11 UT on 24 June 1977 is presented as a plot of amplitude (log. scale) versus frequency, obtained using a FFT analyser. Interference from the local power system at Halley appears as a series of well defined spikes near 1.2 kHz. At 1.89 kHz the first of the magnetospheric lines appear and these have larger signal intensity and broader bandwidths, although some line broadening (~4 Hz) results from the upward line drift in the 3 s interval chosen for display. In calculating signal strength in the 10 Hz bandwidth some allowance must be made for the frequency response of the preamplifier used in the goniometer system. This has a resonant peak at ~1.6 kHz. Corrected received field strengths are given next to each line in Fig. 2—the values lying between .04 and .16 pT RMS.

A spectrogram on an expanded frequency scale is shown in Fig. 3. These data show the lines of Fig. 1 in greater detail, (resolution = 2 Hz) exhibiting line

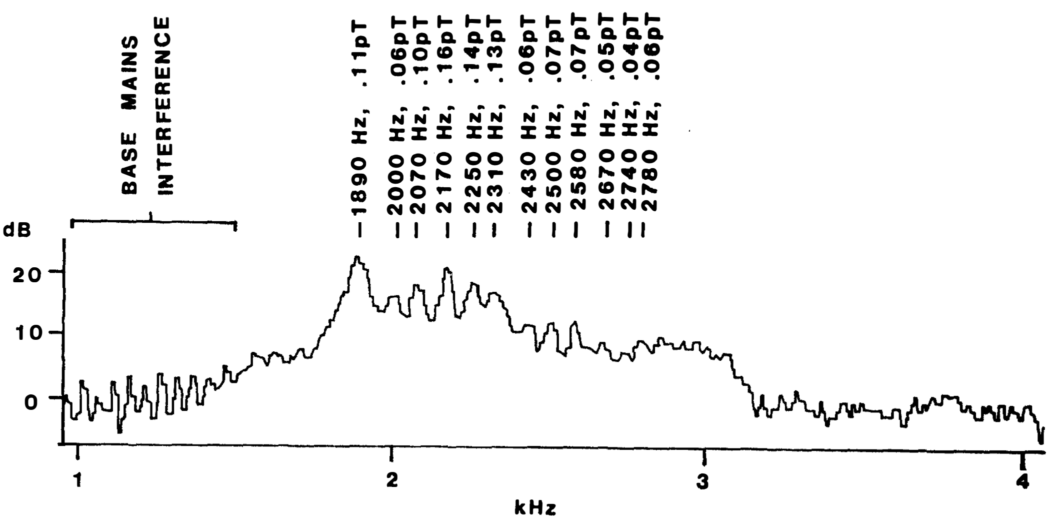

Fig. 2. Amplitude (log. scale) versus frequency plot of the 3 second portion of data between 2014.08 and 2014.11 UT on 24 June 1977 (see Fig. 1). Interference from the local power system at Halley appears as a series of well defined spikes near 1.2 kHz. The magnetospheric lines starting at 1.89 kHz are of broader bandwidth (~30 Hz), and greater signal intensity (.16 pT max).

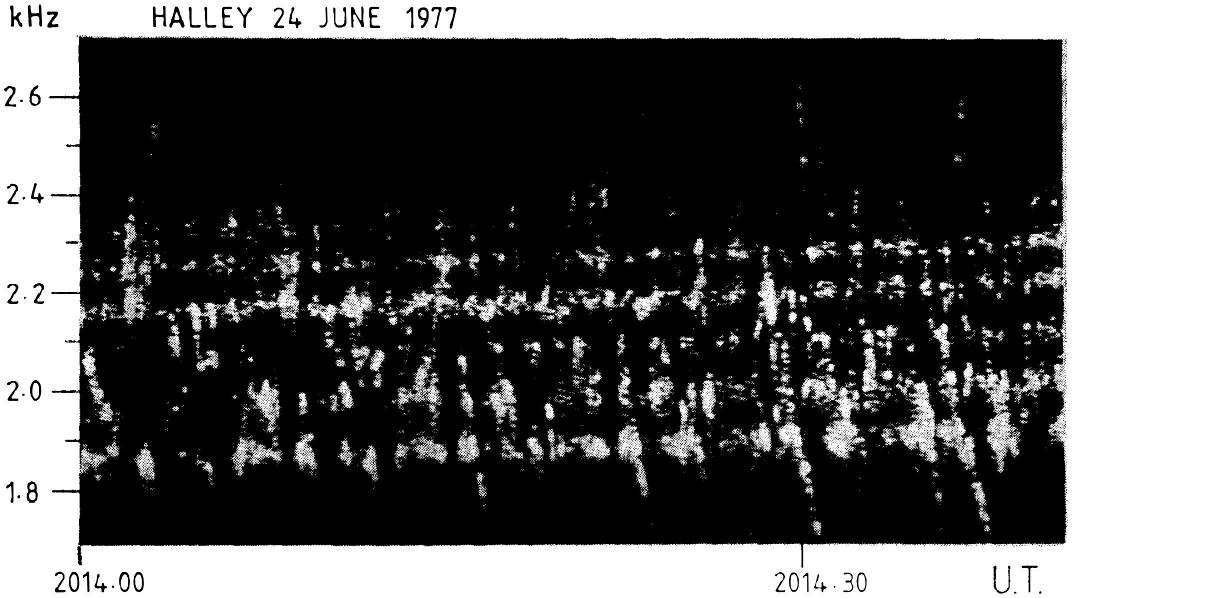

Fig. 3. *Spectrogram on an expanded frequency scale showing magnetospheric lines in greater detail (resolution —2 Hz). Line frequency drifts, small scale amplitude fluctuations, and triggering of risers and fallers are exhibited.*

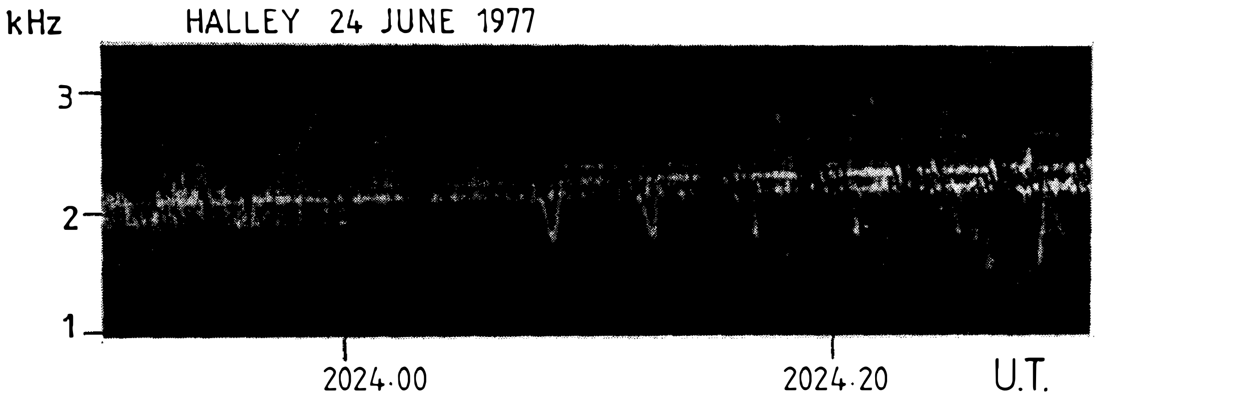

Fig. 4. *The three magnetospheric lines illustrated here all drift at different rates. The lower line triggers several well defined hooks, and a clear two hop amplitude modulation is visible.*

frequency drifts, small scale amplitude fluctuations and triggering of risers and fallers. Magnetospheric line drifts at Halley can be as high as 200 Hz/min but are frequently about 100 Hz/min. This effect has been observed at Siple (see Introduction), but appears to be a rarer phenomenon there. Assuming a power line source in both cases, this may be related to the stronger input signal which enters the magnetosphere from Roberval as compared to Newfoundland. It follows that to observe an event at Halley a large magnetospheric amplification would be required, perhaps a non-linear interaction in which frequency stability is lost. Moreover, lines do not always drift together to preserve a roughly constant frequency spacing. In Fig. 4 three lines are present which all drift upwards at different rates. The middle line gradually moves away from the lower line (frequency 2.05 kHz at the start of the record), and approaches the frequency of the upper line. Several well defined hooks are triggered from the lower line, and a clear two hop modulation envelope is visible.

The data presented in Fig. 5 show line radiation recorded on 15 July 1977. Two hop amplitude modulation is again visible here, but after 1655.22 UT the event dies out and emissions are triggered from the frequencies previously occupied by line radiation. Two very loud whistlers—one at 1655.05 UT, and the other at 1655.20 UT—overload the receiving apparatus and cause a data drop out at lower frequencies.

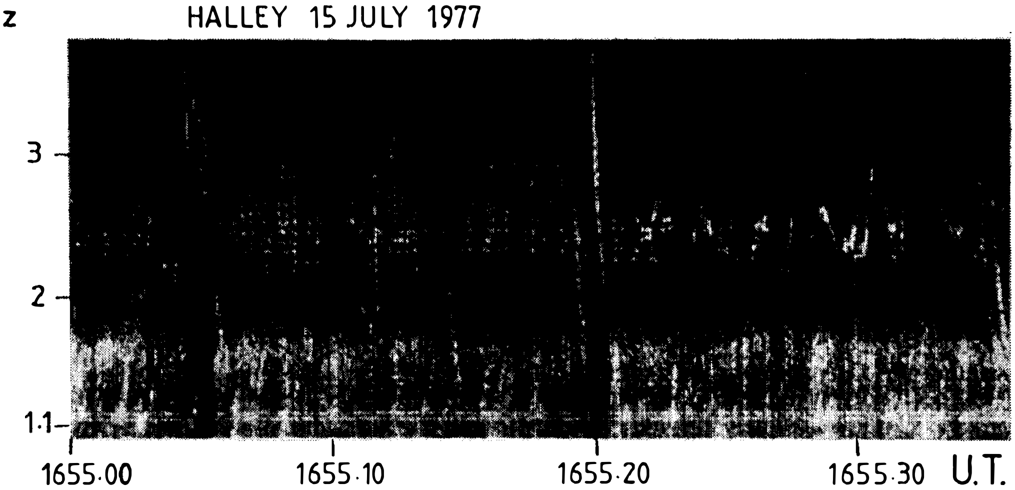

Fig. 5. Magnetospheric line array centred on ~2.5 kHz. Two hop amplitude modulation is visible. At 1655.05 UT and 1655.20 UT two very loud whistlers overload the receiving apparatus and cause a data drop out at lower frequencies. After 1655.22 UT the line radiation event dies out and emissions are triggered from the frequencies previously occupied by the lines.

Further examples of line radiation events are shown in Figs. 6 and 7. In Fig. 6 a very intense band of line radiation exists between ~1.7–2.8 kHz. Many long enduring risers are triggered. In Fig. 7 data recorded on a sampling basis of one minute in five are presented and show how line arrays can develop over the period of minutes. Between 2235.00 and 2236.00 the line radiation is split into two distinct bands (centred on ~2.8 and 3.2 kHz), whereas at the start of the 2240–41 run these bands have apparently merged together.

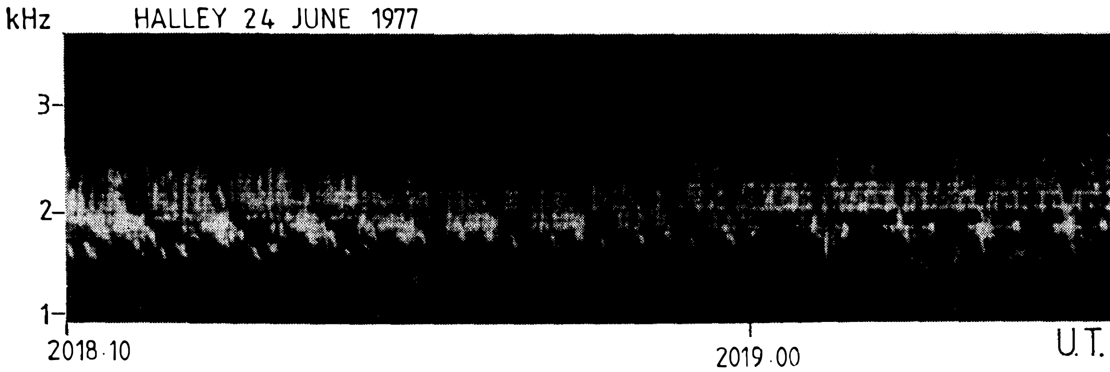

Fig. 6. Well defined and intense band of line radiation exhibiting extensive triggering of emissions.

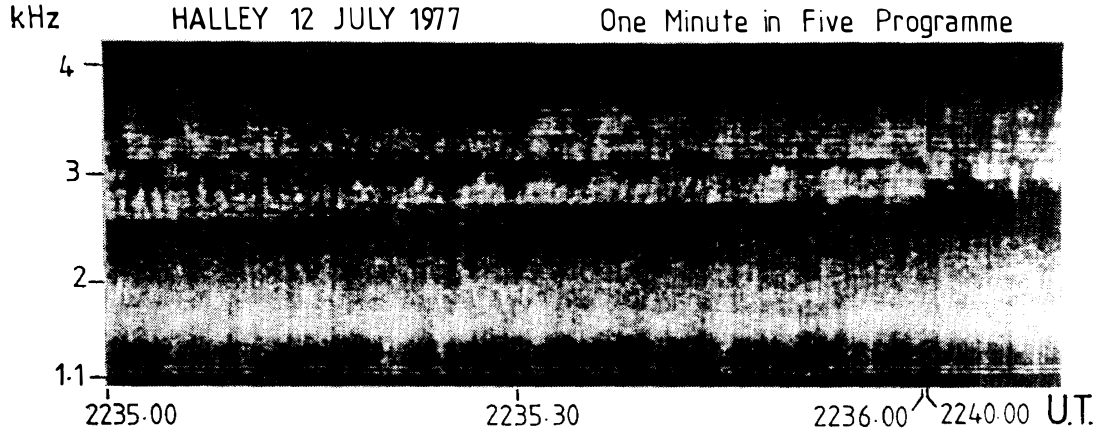

Fig. 7. Data recorded on a one minute in five sampling program, showing how line arrays can develop over the time period of minutes. Between 2235.00 and 2236.00 the line radiation is split into two distinct bands (centred on ~2.8 and 3.2 kHz), whereas at the start of the 2240–41 run these bands have apparently merged together.

In Fig. 8 we present histograms showing the distribution in frequency of separation between adjacent magnetospheric lines. The best defined lines having a field strength 6 dB greater than the troughs on either side are marked by cross hatching. Similarly the hatched and unhatched areas refer to lines 4 dB and 2 dB greater than the troughs on either side respectively. To obtain these data we have selected four 30 s periods of well defined line radiation activity, and have subsequently broken each of these down into 3 s intervals. Successive FFT spectra (calculated every 42 ms) were averaged over each 3 s interval to give an amplitude/frequency plot of the type presented in Fig. 2, and from this we measured frequency spacing and relative amplitudes.

The two histograms at the top of Fig. 8 are from a period of strong line radia-

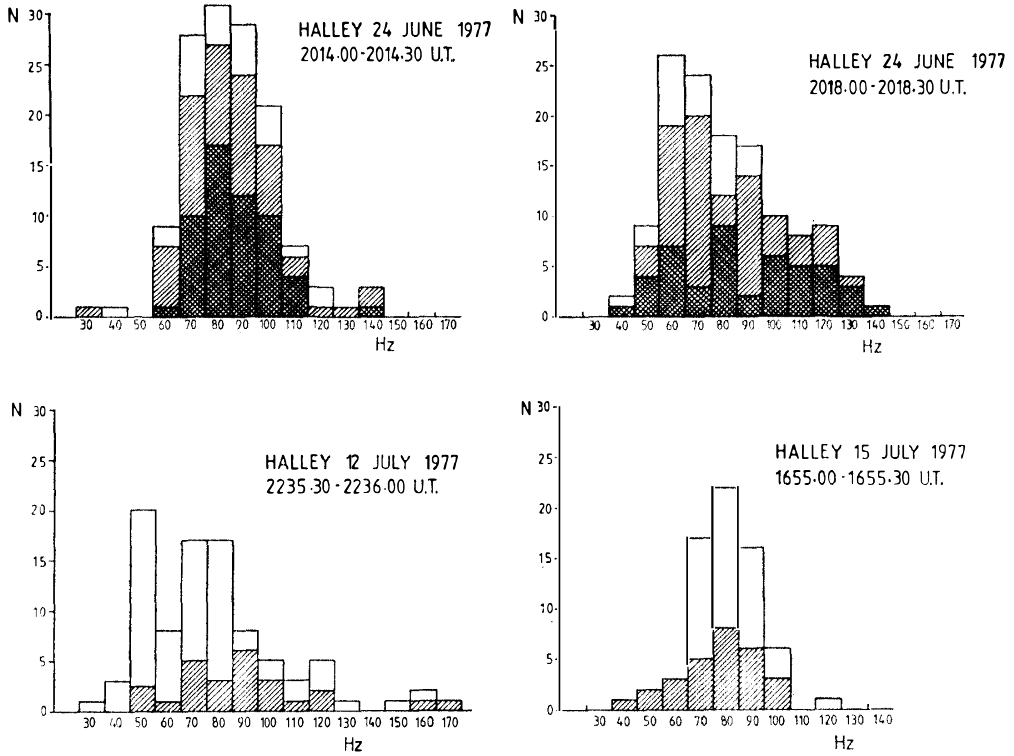

Fig. 8. Histograms showing the distribution in frequency of separation between adjacent magnetospheric lines. Key:—

: Line amplitudes 6 dB or greater than the troughs on either side.

: Line amplitudes 4 or 5 dB greater than the troughs on either side.

Unhatched: Line amplitudes 2 or 3 dB greater than the troughs on either side.

Frequency spacing measurements were made on 3 s data intervals.

tion activity which occurred in the early evening of 24 June 1977 (LT Halley= UT−2 hr). Spectrograms of activity in this period have been described earlier (see Figs. 1, 6). The histogram for the period 2014.00–2014.30 UT (top left) shows a line spacing distribution centred on 80 Hz, at all three stages of line definition. Four minutes later the distribution from 2018.30 UT (top right) shows the less well defined peaks spaced mostly at 60 Hz, the best defined being broadly spread between 50–130 Hz. In both histograms there is little or no component from the 50 Hz goniometric splitting which indicates that the radiation is propagating nearly vertically downwards to Halley. For the histogram shown in the bottom left (see Fig. 7 for spectrogram) there may be some contribution to the 50 Hz interval from goniometric splitting, though this is not large since alternate spacings of 50 Hz were not measured. For example, if lines were originally spaced at 120 Hz one would expect a 50 Hz–70 Hz–50 Hz etc. system if goniometric splitting was present. In the bottom right (see Fig. 5) line spacings again peak at 80 Hz. In none of these cases do we observe a distribution centred on about 120 Hz as observed by HELLIWELL *et al.* (1975). The reason for this is difficult to understand if a power line source is assumed. However, an extra complication arises from the fact that a mixed 50 Hz and 60 Hz system is in operation in Newfoundland (M. K. SEN, private communication).

PARK (1977) has suggested that spacings which are not multiples of 60 Hz may be generated by uncoupled power systems operating at slightly different frequencies. For the most part, the Newfoundland and Labrador Hydro system is 60 Hz, but near the Halley conjugate there are some paper mills which use 50 Hz systems.

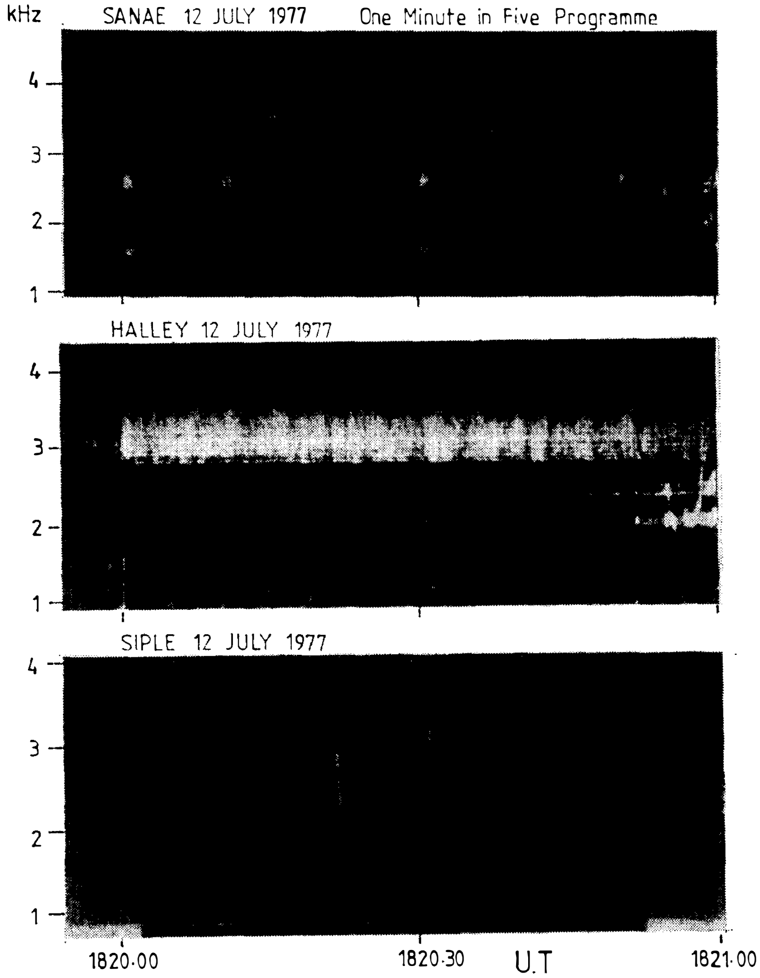

Fig. 9. Spectrograms from Halley ($L=4.3$), Sanae ($L=4.1$) and Siple ($L=4.0$). On the Halley record an intense hiss band is visible at around 3 kHz. Line structure is present in this band. Two whistlers are recorded at ~1820.22 and ~1820.31 UT. On the Sanae record the line structured hiss band is visible, though less intense than at Halley, but the two whistlers are not visible. The Siple data show these two whistlers quite clearly but the structured hiss band is barely visible.

The 50 Hz and 60 Hz systems are interconnected through rotating type frequency converters, which are probably rich sources of mains harmonics.

In Fig. 9 we present spectrograms from three Antarctic VLF receiving stations; Halley (L=4.3), Sanae (L=4.1) and Siple (L=4.1). The data are from 12 July 1977 when all three stations were recording on a one minute in five basis, as recommended during the International Magnetospheric Survey. Data from Sanae and Siple are not goniometric and our comparison assumes similar equipment sensitivities.

On the Halley record an intense hiss band is visible at around 3 kHz. Line structure is evident in this hiss band, which was already developed in the previous run (1815–1816 UT). Lines also develop at 2035±10 Hz, 2425±10 Hz and 2535±10 Hz (all three are split into 50 Hz doublets by the goniometer). The lines trigger strong emissions as they grow in amplitude towards the end of the run. Note that two whistlers are recorded at 1820.22 and 1820.31 UT. On the Sanae record (A. HUGHES, private communication) the line structured hiss band is visible although less intense than at Halley and the triggered emissions are present at the end of the run; however, the two whistlers are not visible. The Siple data (D. CARPENTER, private communication) show these two whistlers quite clearly but the structured hiss band is barely visible. Some local interference lines are present on this record. The fact that goniometric splitting is present on the lines observed at Halley indicates that the line radiation is propagating in a duct whose ionospheric end point probably lies in the region between Halley and Sanae.

3. Discussion

The effect of magnetospheric line radiation on the pitch angle diffusion of energetic electrons can be estimated using the quasilinear theory (HELLIWELL *et al.*, 1975). This assumes that the frequency band occupied by the line radiation is white noise so that the line structure is effectively ignored. Pitch angle diffusion coefficients can then be calculated in the usual manner (ROBERTS, 1968), given an estimate for the equatorial wave field strength. This idea has been developed in TATNALL *et al.* (1978) and here it is shown that magnetospheric line radiation complements the pitch angle diffusion caused by ELF hiss, and becomes relatively more important at lower particle energies (10–100 keV). However, this approach cannot provide an insight into the mechanism responsible for the formation of line elements.

Line frequency spacings of ~80 Hz (see Fig. 8) are too large to be explained in terms of successive sideband generation. To show this, we assume optimum wave growth for a dimensionless resonant frequency separation between parent wave and sideband in the inhomogeneous case (NUNN, 1973) of

$$\delta\omega_0 \sim \left[\frac{R_0 k_0^2 V_\perp \sin P_0}{\omega_0(3/2+\beta/2k_0^2)}\right]^{1/2}. \tag{1}$$

P_0 is the phase difference between the perpendicular velocity and the wave electric field at which stable trapping occurs in an inhomogeneous medium. We define $k_0=k/\bar{k}$ where k is the wave vector and $\bar{k}$ is equal to π_{eq}/c with π_{eq}=equatorial plasma frequency and c=speed of light. $V_\perp$ is the dimensionless perpendicular velocity given by $V_\perp=2v_\perp\pi_{eq}/c\Omega_{eq}$, with $v_\perp$=actual perpendicular velocity of the resonant particle and Ω_{eq} the equatorial electron gyrofrequency. The gyrofrequency variation along a field line in the vicinity of the equator is

$$\Omega(z)=\beta\Omega_{eq}=\left(1+\frac{1}{2}dz^2\right)\Omega_{eq}$$

and thus exhibits a parabolic dependence on z, with d=constant and z the co-ordinate in the magnetic field direction. We take $\omega_0=2\omega/\Omega_{eq}$, where ω is the actual wave frequency and finally R_0 is the dimensionless parent wave amplitude given by

$$R_0=4e\pi_{eq}E/mc(\Omega_{eq})^2 \quad \text{(c.g.s. Gaussian)}$$

with e and m the electronic charge and mass respectively, and E=wave electric field. For a 10 pT wave we obtain $R_0=5.8\times10^{-5}$, and for the other quantities at $L=4.3$ we have calculated $k_0=.55$, $\omega_0=.46$, and with a particle perpendicular velocity $v_\perp=4\times10^7$ m/s (corresponding to a particle $\sim$10 keV in total energy) $V_\perp=.42$. Further $\beta\approx1$, and $\sin P_0\sim1/2$, yielding from eq. (1)

$$\delta\omega_0=2\times10^{-3}$$

corresponding to an actual frequency spacing of $\delta\omega\sim10$ Hz. Wave-wave interaction via non-linear resonant particles will be significant for spacings less than $\sim3\delta\omega$, falling off for greater separations. Thus nearly all observed frequency separations correspond to independent waves. A wave field strength of 10 pT is a reasonable upper limit since at Halley the received signal intensities of individual lines varied between .03 and .3 pT in a 10 Hz band width. We estimate a corresponding equatorial wave field of between .6 and 6 pT (HELLIWELL, 1965). These waves are of roughly the same intensity as PLHR reported by HELLIWELL *et al.* (1975) and are somewhat weaker than estimates made by DOWDEN *et al.* (1978) for signal strengths during non-linear amplification events. The particles involved in the generation of line radiation are probably of a few keV in energy. In particular, such particles satisfy the first order gyroresonance equation at 45° pitch angle if a wave frequency of 2–3 kHz and typical electron densities at $L=4.3$ are used.

The calculated sideband frequency spacing of $\sim$10 Hz is in accord with the observations discussed in HELLIWELL *et al.* (1975). Here, emissions stimulated by power line harmonic radiation were able to drift upwards in frequency and stop roughly 20 Hz below the next line higher up. These 'fine structure' lines then became the salient spectral feature.

In a whistler wave field consisting of an array of discrete modes NUNN (1974) found that a very efficient non-linear particle trapping effect could be produced by the wave array if the wave frequency spacings and wave amplitudes were correctly chosen. To investigate the relevance of this theory to the present problem, we start from the basic conditions for non-linear particle trapping by a wave array

$$C^2/A_n \sim 1$$

where

$$C = \frac{\delta\omega_a}{2}(3+\beta/k_0^2)$$

and

$$A_n \approx k_0^2 F R_0 V_\perp/\omega_0 .$$

The term $\delta\omega_a$ represents the dimensionless resonant wave frequency spacing, and F is a function which describes the envelope of the whistler wave pulse and is assumed to be a slowly varying function of position and time—clearly the case for line radiation events. We take $F=1$. The terms k_0, ω_0, β, R_0 and $V_\perp$ are defined as before.

With $R_0=5.8\times10^{-5}$, $k_0=.55$, $\omega_0=.46$, $\beta=1$ and $\delta\omega_a=1.86\times10^{-2}$, we obtain, for $C^2/A_n \sim 1$, $V_\perp \simeq 300$, which is unacceptably high, since it corresponds to $v_\perp > c$.

From the above calculation we conclude that non-linear particle trapping by a wave array of the type described by NUNN (1974) is not taking place. For electrostatic waves NUNN (1974) shows how spectral structure can develop from a band of hiss by non-linear resonant particle excitation. This type of process could explain some of the line structures observed at Halley, although intense hiss bands are not often observed on spectrograms made prior to magnetospheric line radiation events. Sometimes, however, there does appear to be a close association between line radiation and hiss bands (see Fig. 9). High particle energies are also required for this mechanism, and so it is an unlikely explanation of our data.

The line radiation may originate from unamplified input signals which are produced in the mixed 50 Hz and 60 Hz power distribution system of Newfoundland. Without simultaneous recordings from the Halley conjugate, it is difficult to understand how a broad distribution of frequency spacings centred on, say, 80 Hz, can arise. Perhaps selective amplification of lines from two or more uncoupled systems, followed by line frequency drifting takes place. According to DOWDEN *et al.* (1978), a relatively weak input signal such as an unamplified Power Line Harmonic can act as a source of embryonic emission under favourable conditions. The input wave will control the embryo emission as long as the frequency offset δf of the embryo emission from the input wave is less than F_c, the control frequency, where, for a wave magnetic field B_w

$$F_c = \frac{4\omega((e/m)B_w(\Omega-\omega))^{1/2}}{\beta(\Omega+2\omega)\pi}$$

and

$$\beta = \frac{1}{2}\left[1 + \Delta v_\parallel(IW)/\Delta v_\parallel(EE)\right].$$

If v_0 is the cyclotron resonance velocity, the range of parallel electron velocities trapped by the wave is $v_0 \pm (1/2)\Delta v_\parallel$. The quantities $\Delta v_\parallel(IW)$ and $\Delta v_\parallel(EE)$ refer to the input wave and embryo emissions respectively. A typical plasmaspheric value of F_c would be ~ 100 Hz. If $\delta f > F_c$ the embryo emission would presumably drift freely upwards in frequency to avoid recapture by the input wave. Frequency drift rates of ~ 80 Hz/min would indicate that $\delta f > F_c$ in our case, and that the magnetospheric lines are therefore no longer coupled to their parent signals. The differential drift rates illustrated for example in Fig. 4, lead us to suggest that the lines are acting independently of one another.

If the particle distribution function has several sharp local gradients in pitch angle, then in the linear theory only narrow ranges in electron parallel velocity will be resonantly unstable, so wave growth rates will be largest for discrete frequencies. Following the treatment of CORONITI *et al.* (1971) the time Δt required for quasi-linear particle diffusion to smooth out such velocity space pitch angle gradients is

$$\Delta t \sim \frac{(\Delta\alpha)^2}{D} = \frac{(\Delta\alpha)^2}{\Omega}\left(\frac{B}{B_w}\right)^2$$

where $\Delta\alpha$ is the change in pitch angle in time Δt, and B the equatorial magnetic field strength. $\Delta\alpha$ is taken to be a few degrees—roughly the size of the equatorial loss cone (CORONITI *et al.*, 1971) and $B_w \sim 6$ pT. With $B = 300$ nT we obtain $\Delta t \sim$ 2 min. In general magnetospheric line radiation activity takes place over the time period of minutes, so there is good agreement here. Weak power line harmonic waves may be selectively amplified by this process.

ASHOUR-ABDALLA (1972) used linear theory to study the effect of low amplitude (~ 10 pT) whistler mode signals on the steady state electron distribution function. Pitch angle diffusion coefficients and wave growth rates were computed as a function of both time and frequency. The growth rates increased with time and the frequency of maximum growth also increased with time. From Fig. 15 of ASHOUR-ABDALLA (1972) we deduce a decrease in dimensionless parallel particle velocity of $\sim .0012$ in 400 s. Using the parameters relevant to the present problem, *i.e.* $v_\parallel \sim 4 \times 10^7$ m s^{-1}, $k = 2 \times 10^{-3}$ m^{-1} and $\Omega_{eq} = 5.4 \times 10^4$ rad s^{-1}, we obtain an upwards frequency drift rate of ~ 10 Hz/min, which is in rough agreement with our measurements. Doppler shifts produced by duct motions give drift rates of ~ 1 Hz/min for quiet-moderate geomagnetic conditions (MCNEILL, 1967).

Non-linear effects can also cause wave frequency variations. For example, MATSUMOTO (1979) gives the following condition for electrons to stay in resonance with a wave of frequency variation $d\omega/dt$

$$\frac{d\omega}{dt}=\frac{3\omega}{2\omega+\Omega}V_R\left(1+\frac{\Omega-\omega}{3\Omega}\tan^2\alpha\right)\frac{\partial\Omega}{\partial z}+\Delta n \tag{2}$$

and

$$-\frac{3\omega}{2\omega+\Omega}\omega_t^2\leq\Delta_n\leq\frac{3\omega}{2\omega+\Omega}\omega_t^2$$

where V_R is the resonant particle velocity, α the particle pitch angle and ω_t a wave trapping frequency defined by $\omega_t=(kv_\perp eB/m)^{1/2}$. The first term of eq. (2) is due to the field inhomogeneity and the term Δn represents the non linear effect, resulting from particle trapping in phase potential wells. Frequency variations predicted by eq. (2) may explain the complicated frequency spectra of triggered emissions, since for a 6 pT wave $\Delta_{n_{\max}}\sim720$ Hz/s—but this is much larger than the line frequency drifts we have observed.

It has been noted (HELLIWELL *et al.*, 1975) that the line frequency drifts may be related to the initial positive offset in the frequency of emissions triggered by the Omega VLF transmissions (STILES and HELLIWELL, 1975). By repeated passage through the interaction region at the equator, a line may steadily drift upwards in frequency, each time receiving a small positive frequency shift. These frequency drifts are much slower than upward drifts observed with Quasi Periodic emissions (HO, 1974), (of order 100 Hz/s) which are caused by the faster longitudinal drifts experienced by particles of higher energy.

The periods of line radiation activity observed so far at Halley occur predominantly during quiet geomagnetic conditions ($Kp=1-2$). Over the preceding 24 hours activity is usually moderate ($Kp=2-3$). This dependence on geomagnetic activity is similar to that observed at Siple (PARK and HELLIWELL, 1978) for PLHR events. Very disturbed conditions are not conducive to the good whistler mode echoing and well ordered wave growth required in the generation of line radiation. Also, for ground based observations, high *D* region absorption during these times may prevent observation of line activity. Moderate geomagnetic activity is favoured in the preceding 24 hours since particles required for gyro-resonant interactions are then present in sufficient numbers.

Line radiation events at Halley occur mostly between 1500 and 1800 LT. This is in contrast to the PLHR results from Siple which peak in the morning hours between ~0500 and ~1500 LT, although there are still events occurring between 1500 and 1800 LT. Siple PLHR activity may cause precipitation of electrons which otherwise would have drifted to the Halley longitude, and so may indirectly control the Halley diurnal variation. PARK and HELLIWELL (1978) suggested that the sharp increase in PLHR activity at 0500 MLT was due to the sudden increase in power consumption in the Roberval area of Quebec at that time. The afternoon decrease in PLHR events was thought to be due to the relative inaccessibility of the afternoon-evening sector to energetic particles of a few tens of keV (PARK, 1977) which are responsible for wave growth. We need more information on the local time variation of electrical power usage in Newfoundland, and a greater understanding of factors affecting duct formation and ionospheric absorption before attempting to explain this difference in behaviour at the two longitudes.

One should note that the Halley results are statistically much less significant than those from Siple. The analysis of Halley data is still in its infancy, and moreover line activity appears a rarer phenomenon at Halley than is PLHR at Siple, making events more difficult to find. From data recorded between 24 June 1977 and 17 July 1977, PLHR activity was detected at Siple on at least 14 separate occasions (SONWALKAR, private communication) and line radiation at Halley on 6 occasions. The Siple activity was generally much longer lived, and occurred on different days to the activity at Halley.

4. Conclusion

VLF line radiation of magnetospheric origin has been observed at Halley. Its properties are broadly similar to the PLHR observed at Siple, although line spacings, frequency of occurrence and diurnal variation appear different. Line frequency spacings are widely spread about mean values between 50 and 90 Hz, too large to correspond to wave sideband separation. Calculations suggest that the strongly non-linear wave particle interaction which would naturally generate line structuring is unlikely. The line radiation may be generated from PLHR input signals from the Northern hemisphere, although we do not have sufficient evidence from the Halley conjugate to substantiate this claim. Alternatively, the lines could be generated 'naturally' by a linear process if sufficient structure existed in the electron distribution function.

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