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LOWER HYBRID RESONANCE EMISSIONS

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ABSTRACT

Examination of very low frequency records of the Alouette I satellite has revealed the presence of an unusual band of noise. This band shows several features which distinguish it from other VLF emissions which are observed both in the satellite and on the ground. It is suggested that this noise is generated in the immediate vicinity of the satellite, as a result of a resonance in the plasma surrounding the satellite. From a knowledge of the resonance frequency and the ambient plasma and gyrofrequencies, an inverse mean of the ionic mass may be determined.

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INTRODUCTION

An unusual band of noise observed at mid-latitudes in the VLF recordings of the Alouette satellite has been reported by Barrington and Belrose [1963] who noted that this hiss band had a sharp lower frequency cutoff which increased in frequency with decreasing latitude of the satellite. Brice et al [1964] reported that the generation of this noise could be enhanced or triggered by whistlers and atmospherics. Brice and Smith [1964] noted that since the lower frequency cutoff of this hiss band varied consistently with latitude of the satellite the variation must be spatial rather than temporal. They also suggested that these emissions were related to the lower hybrid resonance for propagation transverse to the earth's magnetic field.

A noise band with characteristics similar to those described above was found in the Injun III VLF recordings by Gurnett*. Subsequently other examples of this noise band have been found in the Injun III data [Gurnett, private communication]. Thus the name "Alouette hiss band" tentatively suggested by Brice et al [1964] and Brice and Smith [1964] seems somewhat inappropriate. Further, as is shown below, there is much evidence to support the suggestion of Brice and Smith [1964] that this band is related to the lower hybrid resonance and therefore this noise will be referred to as the LHR hiss band.

*Paper presented at URSI Meeting, May 1963, Washington, D. C.

OBSERVATIONS

The LHR hiss band is more commonly observed in the Alouette I VLF recordings than those of Injun III and all the examples of this noise band shown below were obtained from Alouette.

An example of the spectra of the LHR hiss band is shown in the upper record of Figure 1, recorded during a north to south pass of Alouette over the South Atlantic*. Also shown in Figure 1 (below) are spectra of simultaneous ground based recordings made at Eights Station, Antarctica. The LHR hiss band in the Alouette spectra shows the characteristic sharp lower frequency cutoff and decrease of frequency (from about 10 to about 5 kc in this example) as the satellite moves to higher latitudes. Also seen in Figure 1 are two rising frequency bands of emissions recorded by both the satellite and the ground based station. This figure illustrates the conclusion drawn after examination of many simultaneous satellite and ground based recordings, namely that the LHR hiss band has never been observed on the ground. Because of the A.G.C, action of the Alouette receiver the noise bands shown on the Alouette spectra must be of comparable amplitude at the satellite. Obviously the same cannot be said of the ground based recordings. It is apparent that the frequency variation of the individual rising bands must be a temporal effect, while, as noted above, the variation in LHR hiss band frequency must be spatial. On

*This spectrogram was obtained from tape recordings kindly loaned by D.R.T.E. in Ottawa.

this occasion the satellite passed close to Eights Station and rising bands of emissions similar to those shown in Figure 1 were observed at Eights before, during, and after the satellite pass. Only three such bands were observed by the satellite over a period of about $3\frac{1}{2}$ minutes, the latter two bands appearing in Figure 1. If these rising bands consist of a number of overlapping periodic emissions (and there is evidence to support this in Figure 1) then it may be deduced that these emissions were propagating along a single whistler-mode path in the outer magnetosphere [Helliwell, 1963b; Helliwell and Brice, 1964]. This point will be further discussed below.

Triggering of the LHR hiss band by atmospherics and whistlers as reported by Brice et al [1964] is illustrated in Figure 2. This figure shows spectra recorded during a north-south pass over Stanford. The lower record is the section of the upper record from 17 to 33 seconds shown with an expanded time scale. In the former, the emission triggered by the first atmospheric shows initially a rapid decrease in lower cutoff frequency, following which this frequency becomes nearly constant. The emissions triggered by whistlers indicate that frequencies near the low frequency cutoff are enhanced for longer periods than the higher frequencies. Also, the sharp lower frequency cutoff increases measureably within these emissions. The whistler triggered emissions have durations of the order of a few seconds. Such triggering of LHR emissions by atmospherics and/or whistlers is relatively common in Alouette recordings.

Of 94 ten-minute recordings examined, 18 showed triggering of the hiss band by atmospherics, while in 20 cases it was triggered by whistlers. As was noted above, this hiss band, triggered or otherwise, has never been observed on ground based recordings. The LHR emissions, either continuous or triggered, were observed in 55% of the recordings examined. The seasonal-diurnal occurence data are given in Table I. It is seen that the night-time occurrence was significantly more frequent than day-time. Furthermore, almost all daytime observations of the hiss band were recorded either before 8 a.m. or after 4 p.m.

In Figure 3, also recorded during a north-south pass over Stanford, weak triggering of the LHR band by whistlers may be seen between 40 and 80 seconds. Also apparent at the beginning of the upper record of Figure 3 is a whistler echo train. Whistlers with echoes showing the same echo delay may be seen throughout most of the period illustrated. In addition, from 225 to 260 seconds, a periodic emission is observed with the period being the same as the echo delay of the previous whistlers. It is apparent that the whistlers with echoes and the periodic emissions propagated over the same outer magnetospheric path. From this we conclude that, during this pass, signals propagating along the same path in the outer magnetosphere were observed by the satellite for more than four minutes. It may be remembered that a similar conclusion was drawn from examination of the rising bands of emissions shown in Figure 1. From the satellite speed of approximately seven kilometers per second, it is found

that the satellite travels over 1700 kilometers or more than 15 degrees of latitude during a four minute interval. During this time the LHR emission frequency changes markedly and in fact measureable changes in the low frequency cutoff may occur in a very few seconds.

Another feature of the LHR emissions is illustrated by Figure 4, which shows a section of the Alouette spectra of Figure 3 together with simultaneous ground based recordings from Stanford. On the Stanford record a very weak whistler appears just before 3 seconds and other whistlers at 4, 6, $8\frac{1}{2}$, and 11 seconds. For all these whistlers, the corresponding whistlers are seen in the satellite. None of these whistlers triggers LHR emission. Other whistlers recorded by the satellite during this interval trigger LHR emissions but no whistlers corresponding to them were observed on the ground at Stanford. Furthermore, a careful examination of the whistlers in Figure 3 shows that none of the whistlers with echoes trigger LHR emissions. The observations that the whistlers which do not trigger tend to have echoes and that these are observed on simultaneous ground recordings both indicate that these whistlers are ducted [Helliwell, 1963a] whereas the whistlers which trigger LHR emissions are non-ducted. It should be pointed out that on one or two occasions, the data indicate that whistlers which triggered LHR emissions were also observed on the ground. Of course, on these occasions only the triggering whistlers were observed on the ground, not the triggered emissions. A number of the unusual features of the LHR hiss band described above

were brought to the attention of the authors by John Katsufrakis [private communication].

INTERPRETATION

It is apparent from the above observations that the LHR hiss band has a number of features which distinguish it from other VLF emissions. For these other emissions, and for whistlers, the frequency-time spectra observed simultaneously in the satellite and on the ground are essentially the same, indicating that the spectral variations are temporal rather than spatial.

The LHR hiss band almost invariably shows a general increase in the lower cutoff frequency with decrease in the latitude of the satellite. Because of this latitude dependence, we deduce that the general increase in frequency must be a spatial effect. It may be suggested that the short term variations as seen in Figure 1 are also spatial, but the possibility of temporal variation cannot be ruled out. However, the long term change in frequency is certainly spatial. Given that the lower frequency cutoff is very sharp, that it is a function of the location of the satellite, and that it changes measureably in a few seconds, we may deduce that at any given instant the LHR emissions observed by the satellite are different from those observed a few seconds previously. Since at least some of the frequency variation must be spatial, the horizontal field of view of the satellite must be limited to less than a few tens of kilometers.

One possibility is that the noise is generated near the top of the magnetic field line path and propagates strictly

along the field lines from the region of generation to the satellite. However, as was observed in Figures 1 and 3, signals propagating in the whistler mode over a single path in the outer magnetosphere may be observed in the satellite for well over a thousand kilometers. It appears unlikely then that this hiss band is generated at great heights in the magnetosphere. Furthermore, the observation of triggering of the hiss by atmospherics indicates that the generation region is at or below the satellite, while triggering by whistlers indicates generation at or above the satellite [Brice, et al, 1964]. Since the region in which the observed hiss is generated is also limited in horizontal extent, it is apparent that the observed Alouette hiss band is generated in the immediate vicinity of the satellite.

The observation that whistlers with echoes (which are also observed on the ground) do not trigger the hiss, while whistlers without echoes (which are not observed on the ground) do trigger the hiss may be interpreted as follows. It is suggested that the whistlers with echoes are ducted whistlers, while those without echoes are not ducted [Helliwell, 1963a]. For this interpretation, the non-ducted would be expected to have larger wave normal angles than the ducted whistlers [Yabroff, 1961], suggesting that triggering is more likely for signals propagating with large wave-normal angles.

From considerations of amplitude alone, it would be expected that triggering of this hiss band by atmospherics would be observed far more frequently than triggering by whistlers.

Since it is expected that whistlers generally have larger wave normal angles than atmospherics, the observation that triggering by whistlers and atmospherics occur with almost equal frequency may also be indicative that triggering is more favorable at larger wave normal angles. Further support for this suggestion is also found in Figure 2, where very weak whistlers produced longer enhancements of the LHR hiss band than atmospherics.

POSSIBLE ORIGIN

In considering possible origins for the LHR hiss band, it should be borne in mind that the observed noise is generated in the immediate vicinity of the satellite, that the noise may be triggered, and that triggering appears to be enhanced for waves propagating with large wave-normal angles. Also all of the mechanisms suggested for the generation of VLF emissions observed on the ground invoke resonances between particles and whistler mode waves propagating quasi-longitudinally [Brice, 1964a]. Further, it has been suggested by Calvert and Goe [1963] that the high frequency "spikes" observed in the Alouette top-side sounder records are related to the resonances in the plasma surrounding the satellite. Since the LHR emissions are a function of the location of the satellite (as are the high frequency spikes), it appears likely that these emissions also arise from a resonance between electromagnetic waves and the ambient plasma in the vicinity of the satellite. The frequency of LHR emissions lies above the proton gyrofrequency and below the electron gyrofrequency. The

only resonance in this frequency range is the lower hybrid resonance.

The lower hybrid resonance defines a cutoff frequency for propagation transverse to the ambient magnetic field. For a plasma consisting of electrons and one ion species, and for which the ion plasma frequency (F_o) is much larger than the ion gyrofrequency (F_H), the resonance frequency (f_r) is given by [Stix, 1962]:

$$\frac{1}{f_r^{\,2}} = \frac{1}{F_o^{\,2}} + \frac{1}{f_H\, F_H} \tag{1}$$

where f_H is the electron gyrofrequency.

It is apparent that the resonance frequency will be of the order of the ion plasma frequency or the geometric mean of the electron and ion gyrofrequencies, whichever is the less. The geometric mean gyrofrequency for protons in the ionosphere is always less than 40 kc.

THEORY OF THE LOWER HYBRID RESONANCE

Equation (1) may be rewritten in terms of the electron plasma frequency, f_o, as

$$\frac{1}{M\, f_r^{\,2}} = \frac{1}{f_o^{\,2}} + \frac{1}{f_H^{\,2}} \tag{2}$$

where M is the mass to charge ratio of the ions relative to electrons. As is seen in Table I, the LHR emissions are observed

in Alouette predominately at night. At this time and at the height of the satellite (1000 km) the electron plasma frequency is usually less than the electron gyrofrequency for latitudes of interest here (roughly, $L = 2.5$ to 5). In this situation the lower hybrid resonance is approximately the ion plasma frequency. For this case, a simple physical picture of the resonance may be given. The resonance frequency is much less than the electron gyrofrequency, so that the electrons are tightly bound by the earth's magnetic field. The ion gyrofrequency is much less than the resonance frequency so that the ions are considerably more mobile. Thus if the ions are displaced across the static magnetic field, the tightly bound electrons form a fixed negatively charged background and the ions oscillate at their plasma frequency in a manner similar to electrons in the absence of a magnetic field.

Since the ionosphere contains in general more than one ion constituent, it is of interest to derive the resonance frequency for plasmas with multiple ion species. For propagation transverse to the earth's magnetic field, it has been shown by Smith and Brice [1964] that a resonance occurs when

$$1 + \sum_r \frac{X_r}{Y_r^2 - 1} = 0 \qquad (3)$$

where the X_r are the ratios of plasma frequency squared to wave frequency squared and the Y_r are the ratios of gyrofrequency to wave frequency for the various constituents (electrons and ions) present.

In the ionosphere, ion plasma frequencies are much greater than ion gyrofrequencies and the lower hybrid resonance is much less than the electron gyrofrequency so that we may assume

$$Y_e^2 \gg 1 \; ; \qquad Y_i^2 \ll 1$$

where subscript e refers to electrons and i to ions. Using these approximations, equation (3) becomes

$$1 + \frac{X_e}{Y_e^2} - X_e \sum_i \frac{\alpha_i}{M_i} = 0 \tag{4}$$

where the fraction of the positive charge density which is due to the i th ion is α_i and M_i is the mass to charge ratio of the i th ion with respect to that of the electron.

We define the effective mass, M_{eff}, as

$$\frac{1}{M_{eff}} = \sum_i \frac{\alpha_i}{M_i} \tag{5}$$

and find

$$\left(\frac{1}{M_{eff}}\right)\left(\frac{1}{f_r^2}\right) = \frac{1}{f_o^2} + \frac{1}{f_H^2} \tag{6}$$

Note that for a single ion species, the resonance frequency from equation (6) is the same as that given by equation (1) taken from Stix [1962].

The term "lower hybrid resonance frequency" is used here

to denote the frequency of resonance for propagation strictly perpendicular to the earth's magnetic field. From the theory presented by Smith and Brice [1964] it may be shown that for wave normal angles less than 90°, the frequency of resonance is higher than the lower hybrid resonance frequency. Thus the frequencies at which a resonance may occur have a natural lower frequency cutoff.

In view of the observation that LHR emissions are observed more frequently in Alouette than in Injun, it is of interest to consider the polarization at the lower hybrid resonance since the Alouette receiver is fed from an electric dipole antenna while Injun uses a magnetic loop antenna. It may be shown (see for example, Smith and Brice, 1964) that for frequencies near the lower hybrid resonance the polarization for transverse propagation is approximately linear and that the dominant wave field component is the wave electric field in the wave normal direction. Given this information and that a resonance is found for higher frequencies for other angles, we may anticipate that the impedance of an electric dipole in the medium would show zero reactance and very large resistance at the lower hybrid resonance frequency and that the resistance would decrease very rapidly for lower frequencies and much more slowly for higher frequencies. These factors do indeed appear in calculations of impedance for a dipole antenna in a plasma [W. Blair, private communication]. The antenna used for the Alouette VLF receiver is a 150 foot dipole. For a typical frequency of 6 kc, the free

space wavelength is 50 km. However, near resonance the refractive becomes extremely large and the wavelength in the medium relatively small so that the antenna may not be small compared with a wavelength.

DISCUSSION

It has been shown that the LHR hiss band is a highly localized phenomenon, suggesting a resonance in the ambient plasma. It has been noted that the frequencies observed in the hiss band are between the electron and proton gyrofrequencies, and that the only resonance in this frequency range is the lower hybrid resonance.

In addition, several of the properties of this resonance may be related to characteristics of the hiss band.

The frequencies at which a resonance may occur have a sharp lower frequency limit; the LHR hiss band has a sharp lower frequency cutoff. The resonance is characterized by large electric fields; the hiss band is found more often on a receiver fed from an electric or dipole antenna (Alouette I) than a receiver fed from a magnetic or loop antenna (Injun III). The lower hybrid resonance occurs for a wave normal angle of ninety degrees; triggering of the hiss band appears to be enhanced for signals propagating with large wave-normal angles.

While the hiss band and the lower hybrid resonance are both at frequencies intermediate between the electron and ion gyrofrequencies, it is necessary to determine whether the

postulated association between them requires unreasonable values of effective mass. By taking typical values of electron plasma frequency of 600 kc and electron gyrofrequency of 1 Mc, we find that the range 5 to 10 kc of hiss frequencies would require effective masses in the range 2.1 to 8.3 times the proton mass. These are by no means unreasonable values, so it may be said that the lower cutoff frequencies of the LHR hiss band are of the order of those expected for the lower hybrid resonance.

From the LHR postulate, it is seen that the resonance frequency increases with the electron plasma frequency. It may be suggested then that the high electron densities (and hence plasma frequencies) found near local noon usually give lower hybrid resonance frequencies above 10 kc (the upper frequency cutoff of the Alouette VLF receiver). This suggestion provides a plausible explanation of the infrequent observation of the hiss band in the hours near local noon.

With regard to the variation in low frequency cutoff of the hiss band with latitude, it has been suggested by Brice [1964b] that this is typically somewhat greater than the typical variation in electron plasma frequency at 1000 km. Thus from the LHR postulate, it would be deduced that the effective mass at 1000 km height increases with increasing latitude. This deduction agrees with that made from predictions of Angerami and Thomas [1964], and satellite measurements [Bowen, et al, 1964].

SUMMARY

The local generation of the LHR hiss band and the range of frequencies observed suggest that the hiss is directly related to the lower hybrid resonance. Further support for this hypothesis is found in the sharp low frequency cutoff of the band, the more frequent occurrence in the receiver fed from an electric antenna, and the enhanced triggering at large wave normal angles. This postulate provides an explanation of the absence of the hiss band in the hours around local noon; it requires a variation of effective mass with latitude which agrees qualitatively with that found by other workers.

Thus the properties of the band found to date are all consistent with the lower hybrid resonance hypothesis.

In view of this evidence, it is of interest to assume that knowledge of the lower hybrid resonance frequency may be otained (from hiss, or from antenna impedance measurements) and to consider the applications of this knowledge in ionospheric research. As was shown above, the lower hybrid resonance frequency is directly related to the effective mass of the ionic constituents and thus provides a useful diagnostic tool. Since the weighting factor is the inverse ionic mass, the effective mass will be largely determined by the lighter ions. In the protonosphere, where the ionic mass is known, a measurement of the lower hybrid resonance frequency and the earth's magnetic field strength will in principle yield the electron density.

This method of measuring electron density would be useful in the height range above Alouette (1000 km) and below that at which whistler measurements are available.

If the short term fluctuations in the hiss band noted earlier are in fact spatial rather than temporal, then it may be suggested that they are the result of small fluctuations in the ambient electron density. These fluctuations could be related to the field-aligned ducts of ionization postulated for whistlers by Smith [1961].

SUGGESTED EXPERIMENTS

The work above suggests a number of interesting experiments for rockets and satellites. In addition the search for noise at the lower hybrid resonance in a laboratory plasma might prove instructive (this resonance has apparently been recently found in a laboratory plasma by Von H. Schlüter [private communication]).

Following the suggestion above that noise is observed near a resonance at very low frequencies, it would be of interest to examine the output of a very high sensitivity swept frequency h-f receiver to determine whether ambient noise is enhanced at the resonant frequencies already found by the top-side ionosonde.

Simultaneous or alternate top-side ionosonde and VLF recordings would be extremely useful. From the high frequency spikes the electron plasma and gyrofrequency may be found. This information in conjunction with the VLF spectra would then yield the effective ion mass. Since the Alouette hiss band is not

always observed, antenna impedance measurements at very low frequencies would be preferred. The frequency range of the VLF receiver or impedance measurement should cover from the highest possible hybrid resonance frequency of 40 kc to at least the lowest ion gyrofrequency expected for the height range covered.

A VLF ionosonde or separated transmitter-receiver pair could be used to study resonance frequencies, and, in addition, artificial stimulation of VLF emissions [Helliwell, et al, 1964].

Observation of the LHR hiss together with independent measurements of ionic constituents and antenna impedance would provide a test of the hypothesis suggested above.

ACKNOWLEDGMENT

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TABLE CAPTION

Table I. Occurances of LHR emissions on Alouette I from February 2, 1963 to April 20, 1964.

TABLE I

	1963				1964	
	Spring Night	Summer Day	Fall Night	Winter Day	Spring Night	Total
Present	15	11	13	2	11	52
Absent	7	6	4	19	6	42

Day	34%
Night	67%
Total	55%

Note Summer Day occurances were morning and evening; absent near noon; "present" is observation of steady <u>or</u> spheric triggered <u>or</u> whistler triggered LHR emissions

FIGURE CAPTIONS

Figure 1. Simultaneous VLF recordings from Alouette satellite and Eights Station, Antarctica showing LHR emission in satellite.

Figure 2. Alouette VLF recording showing LHR emissions and whistlers.

Figure 3. Alouette VLF recording showing LHR emissions triggered by atmospherics and whistlers.

Figure 4. Simultaneous VLF records from the Alouette satellite and ground station (Stanford) showing LHR emissions triggered by whistlers seen only in satellite.

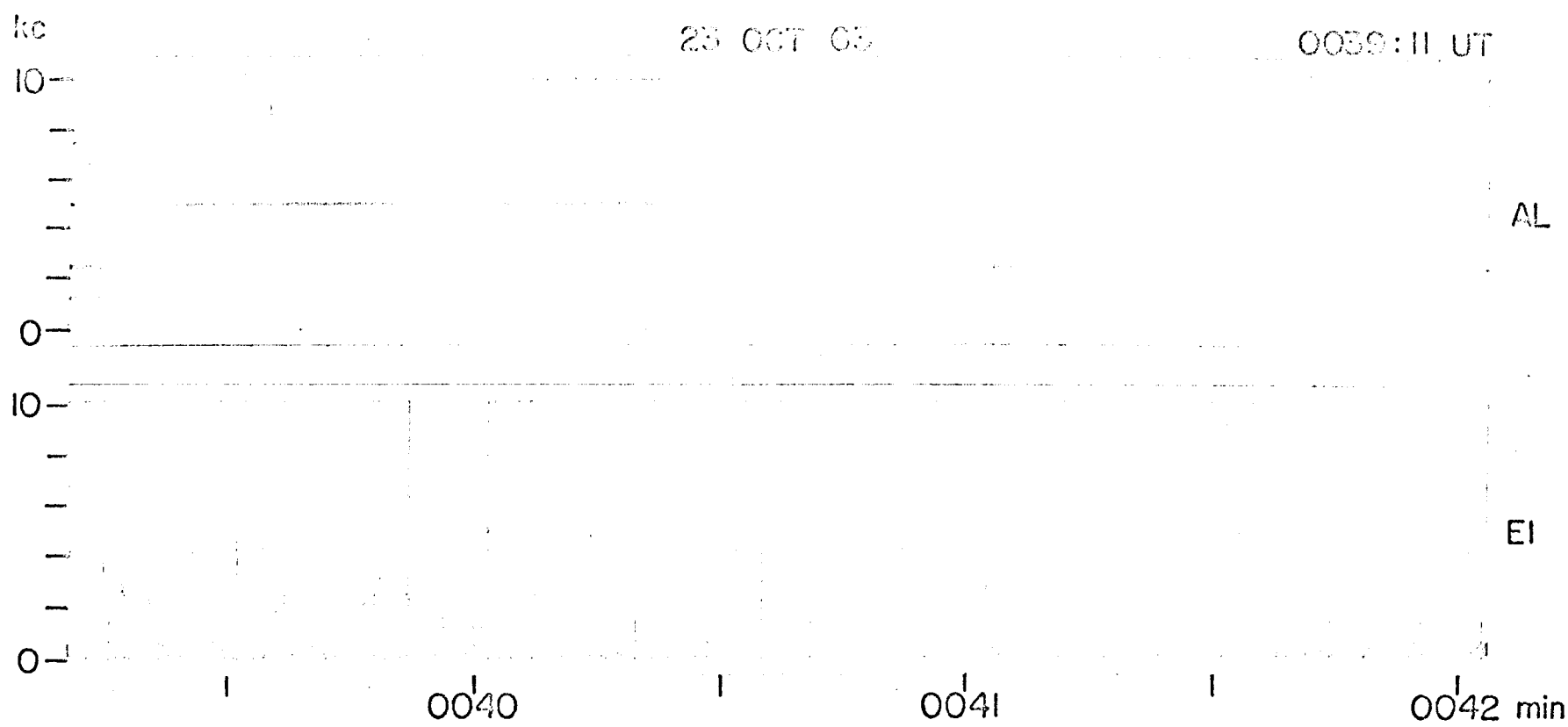

Fig. 1

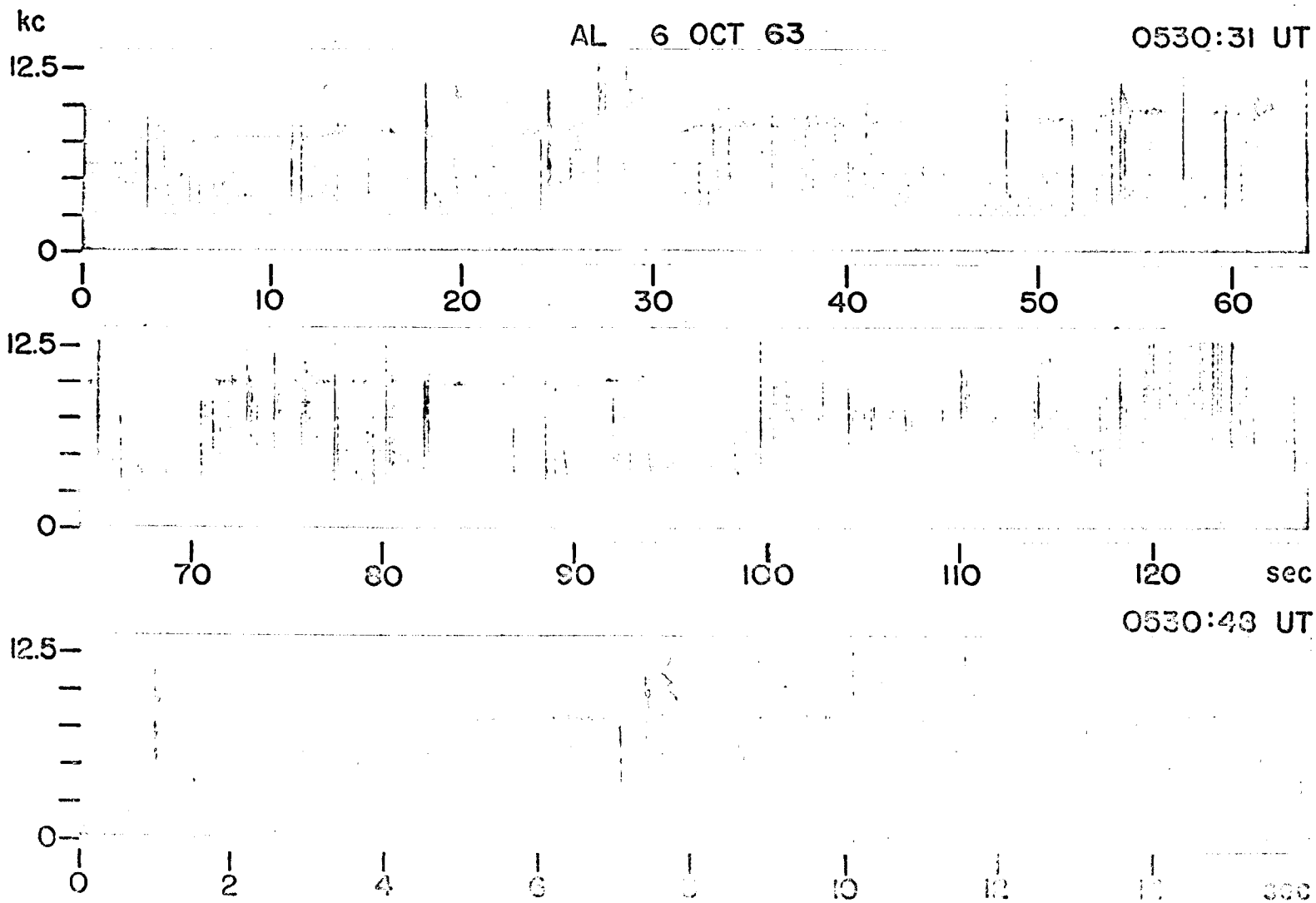
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Fig. 2

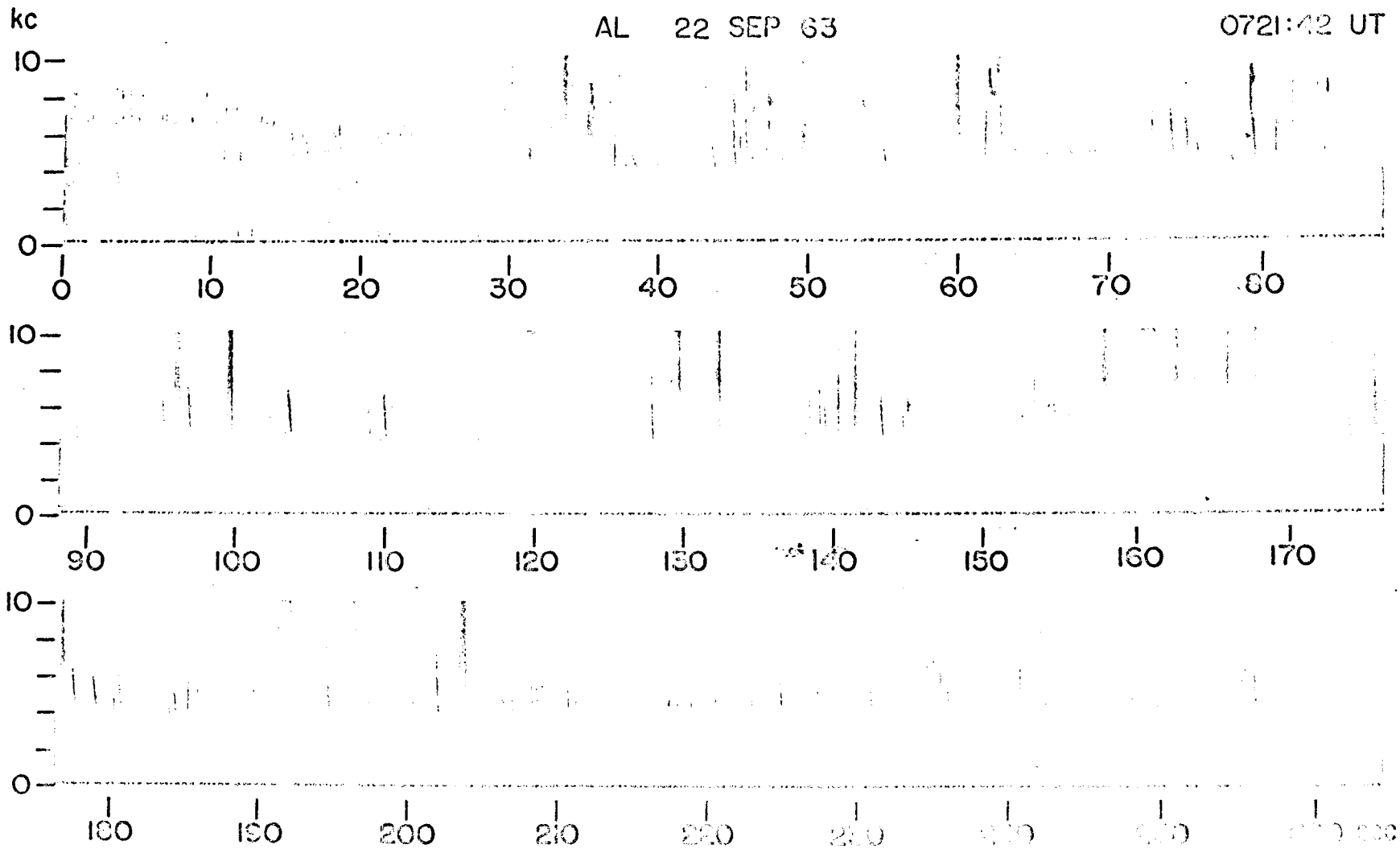
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Fig. 3

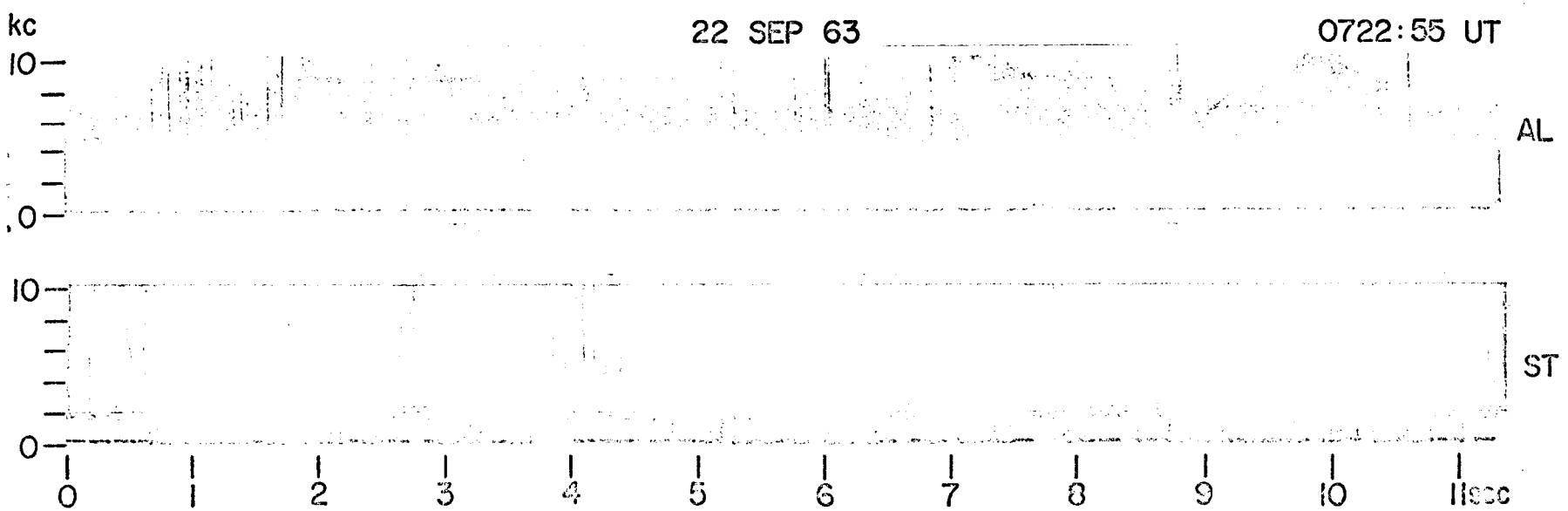

Fig. 4