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ABSTRACT

Spectrograms of very low frequency radio noise recorded by University of Iowa satellite Injun 3 at invariant latitudes greater than 50°N are used to determine the behavior of VLF emissions during magnetic storms. Variations in the wide-band intensity of VLF emissions from L = 3 to L = 8 are studied for the period from 28 April to 28 August 1963 by means of the automatic gain control levels of the satellite VLF receiver.

During a sudden-commencement magnetic storm the VLF emission called polar chorus characteristically appears at the onset of the storm, may increase in upper frequency extent to ∿ 5 kHz, may change from spike to burst structure (normal chorus), and occurs over the greatest area on the fourth day of the storm, subsequently fades into low frequency, spike-structure polar chorus again and eventually disappears into the ELF hiss band generally present. Chorus occurrence shows symmetry about the 9:00 - 21:00 magnetic local time meridian with a large maximum in magnetic morning and a smaller maximum in magnetic evening. Daily regions of occurrence are shown for the duration of a prototypical storm.

Contour maps of wide-band VLF field strength as a function of shell parameter L and universal time are presented for May through August, 1963. A correlation with D_{st} is observed. The wide-band VLF noise intensity rises from the background noise level at the onset of a magnetic storm and peaks during the early recovery phase.

The Kennel-Petschek limiting flux hypothesis is investigated by looking for VLF noise on the appropriate L-shells when equatorial $\geq$ 40 keV electron fluxes reach predicted limiting values. The VLF noise levels predicted in the equatorial plane by Kennel and Petschek are not observed at the altitude of the Injun 3 satellite (less than 2785 km).

I. INTRODUCTION

Two principal classes of magnetospheric radio noise phenomena occur in the very low frequency (VLF) range (1 to 30 kHz) [Gallet and Helliwell, 1959], whistlers and VLF emissions. Whistlers are VLF electromagnetic waves whose energy originates from lightning discharges and which have propagated through the magnetosphere [Storey, 1953]. VLF emissions are electromagnetic waves generated by charged particles in the earth's magnetosphere. Various generation mechanisms involving wave-particle interactions have been suggested to explain VLF emissions. See, for example, Ellis [1959], Gallet and Helliwell [1959], Ondoh [1961], Maeda and Kimura [1962], Brice [1963], Kennel and Petschek [1966a and b], and Helliwell [1967]. Observational evidence has not yet made it possible to identify the correct generation mechanisms.

The purpose of this study is to present satellite observations of VLF emissions during magnetic storms using data from the Injun 3 satellite. By comparing variations in the intensity and spectra of VLF emissions with

variations in the energetic electron fluxes in the magnetosphere during the storm periods, we can investigate generation mechanisms, particularly the Kennel-Petschek [1966a and b] model.

Early investigations of VLF emissions by Storey [1953] and Allcock [1957] disclosed an association between magnetic disturbances and VLF emissions. This association has been examined from ground stations by Aarons, et al. [1960], Ellis [1960], Yoshida and Hatanaka [1962a and b], Laaspere, et al. [1964], and others. Ground-based studies have shown that the occurrence of VLF emissions during magnetic storms is partly controlled by ionospheric propagation conditions, particularly absorption and reflection at the base of the ionosphere. Advantages of satellite studies of VLF emissions include the following: (1) Absorption and internal reflection at the base of the ionosphere are no longer factors in interpreting VLF intensities because the waves are detected before they reach the base of the ionosphere. (2) Uncertainty in assigning and L-shell of origin to a source is reduced because waves are detected before they enter the earth-ionosphere waveguide. (3) Rapid surveys of the spatial extent of VLF noises are possible over geographical areas far greater than those surveyed by ground stations.

II. DESCRIPTION OF THE INJUN 3 EXPERIMENT

The University of Iowa/Office of Naval Research satellite Injun 3 was launched on 13 December 1962 into a low altitude, elliptical polar orbit having an apogee of 2785 km, a perigee of 237 km, and an inclination of 70.4° to the earth's equatorial plane.

The magnetic component of VLF electromagnetic waves propagating in the magnetosphere is detected by a 12" diameter loop antenna oriented with its axis perpendicular to the direction of the geomagnetic field line. The satellite wide-band receiver has a frequency range of approximately 0.2 to 7.0 kHz. An automatic gain control (AGC) circuit in the receiver compresses the signal from the loop antenna to a constant amplitude. The signals are then telemetered to tracking stations on the ground, where they are tape-recorded for later analysis with spectrum analyzing equipment such as the Rayspan spectrum analyzer. The AGC feedback voltage is telemetered to the ground as a measure of wide-band VLF magnetic field intensity. The noise threshold for the wide-band field strength measurement is $\sim 10^{-3}\ \gamma$ ($1\ \gamma = 10^{-5}$ gauss). Gurnett and

O'Brien [1964] describe the VLF experiment on Injun 3 in more detail.

III. CHARACTERISTICS OF VLF EMISSIONS DURING MAGNETIC STORMS

Gallet [1959] divided VLF noises into three broad classes: whistlers, emissions, and interactions between whistlers and emissions. Helliwell [1965] gives a classification scheme for VLF emissions involving the following principal categories: hiss, chorus, discrete emissions, triggered emissions, periodic emissions, and quasi-periodic emissions. In this study, as in a previous study by Taylor and Gurnett [1968], three types of emissions are commonly observed: ELF hiss, VLF hiss, and chorus. Incoherent, band limited white noise with a duration of minutes and with little temporal structure on a time scale less than one second is called hiss. If there are frequency components from a few hundred Hz to about 2 kHz it is called extremely low frequency (ELF) hiss; otherwise it is called VLF hiss. ELF hiss generally occurs in bands about 1 kHz wide during local daytime at middle and high latitudes. Chorus is a sequence of discrete emissions occurring randomly in time and generally rising in frequency on a time scale of a few tenths of a second. Ungstrup and Jackerott [1963] distinguish between normal chorus, previously called dawn chorus

[Storey, 1953], which occurs mostly at middle latitudes and at frequencies above 2 kHz, and polar chorus, which occurs mostly at high latitudes and below 2 kHz. Polar chorus commonly occurs with one or more ELF hiss bands. The spectrogram in Figure 1 shows examples of VLF hiss, polar chorus with an ELF hiss band, and normal chorus.

The three coordinates used in analyzing the data are universal time (UT), invariant latitude (INV), and magnetic local time (MLT). Since VLF waves in the magnetosphere tend to be guided along magnetic field lines, we have not considered altitude variations in this study. Invariant latitude is defined by the relation: $INV = \text{Arccos } L^{-1/2}$, where L is the shell parameter of McIlwain [1961]. Magnetic local time is defined as the hour angle between the magnetic meridian through the satellite and the magnetic meridian through the sun, using the centered dipole approximation [Chamberlain, 1961]. The data available are classified by MLT-INV "sector." Sector 3-60, for example, includes data between 3 and 4 hours MLT and between 60° and 70° INV. The same sector size, 1 hour MLT by 10° INV, is used throughout the paper.

Five sudden-commencement magnetic storms and one "quiet time" were chosen for study from the Injun 3 data

on the basis of the quantity and quality of data available. Table 1 lists these periods, gives the sudden commencement times of storms [Lincoln, 1964a and b], and indicates the number of MLT-INV sectors of each period for which data were assembled and analyzed.

The method of data analysis is straightforward. Satellite orbit plots such as that shown in Figure 1 were used to select sectors for which data were available during each day of the storm. Using a Rayspan spectrum analyzer, frequency-time spectrograms such as that shown in Figure 1 were produced for all passes through these sectors. A visual analysis was made of the types of VLF emissions observed each day in the spectrograms of each sector. Figure 2 illustrates selected parts of the data from one such sector, sector 5-60 of the 6 June magnetic storm. Visual examination of 69 sector charts such as that shown in Figure 2 reveals the following:

(1) ELF hiss is present in most sectors most of the time, including pre-storm times.

(2) VLF hiss is present occasionally with no apparent tempor pattern.

(3) Chorus appears after the storm's sudden commencement. Its upper limit may increase to frequencies of $\sim$ 5 kHz, its nature may change from a spike to a burst structure,

and it frequently becomes a periodic emission [Cf. Helliwell, 1965] having recurrent spectral forms on intervals of the order of 10 seconds. Figure 1 shows examples of both burst-type chorus and spike-type chorus. High-frequency, burst-type, possibly periodic chorus is generally observed from the second through the fourth days of a storm, after which the chorus returns to lower frequencies, reverts to spike structure, and eventually fades into the ELF hiss background normally present.

Tables were compiled to indicate whether VLF hiss, ELF hiss, or chorus was observed to occur in each sector during each day of each period. Rates of occurrence found for phenomena are always minimum rates because dubious phenomena were ignored. It was found that variations in the number of passes per sector does not systematically distort the occurrence rates. In the analysis which follows, data for corresponding sectors and days of different storms is summed. Since each storm contributes sectors on a different section of the polar magnetic map due to precession of the satellite orbit about the magnetic pole, this procedure allows the construction of a picture of what occurs on all sides of the north magnetic pole during magnetic storms.

Figure 3 shows the time development of the occurrence rates of chorus, VLF hiss, and ELF hiss averaged for the five storms. The rate of occurrence of ELF hiss is high throughout the storms, and constant to within our confidence limits. The error bar on the rate of occurrence is $\sqrt{N}/N$ where N is the average number of sectors for which data was added in order to assign an occurrence rate to one day. The error bars are similar for all points in the figure. The rate of occurrence of VLF hiss is low, and while it appears to increase with the onset of the storm, the statistics of this study preclude a definite statement. The frequency of occurrence of chorus shows a significant increase after the onset of the storm, with a maximum on the fourth day of the storm.

Figure 4 shows the time development of the occurrence of chorus, averaged over sectors, for the 30 April, 6 June, and 18 August magnetic storms, for which the most data were available. In two of these storms (30 April and 6 June) the behavior of chorus is very similar, occurring in over 80% of the sectors on the fourth day of the storms. Chorus never occurs in more than 40% of the sectors during the 18 August storm, probably because the data for this period were from evening MLT sectors only, where VLF emissions are least often observed [Taylor and Gurnett, 1968].

In Figure 5 the patterns of occurrence of chorus (summed over five storms) are shown for each day from two days before, to the sixth day after, the sudden commencements of the storms. Approximate symmetry about the 9:00 - 21:00 MLT meridian is maintained throughout the storm and the greatest geographical coverage of chorus occurs on the fourth day. Chorus extends to higher invariant latitudes in the morning side than in the evening. Chorus does not occur at any time near 1 or 17 hours MLT. These "null" regions define an evening peak centered on 21 hours MLT. The main (morning) lobe of chorus does not appear until the second day of the storm and has broken up on the sixth day. A temporary breakup occurs on the third day. The evening lobe, which we first observe on the second day, remains through at least the sixth day of the storm. Its disappearance on the fifth day is probably due to lack of data in the evening region.

The sector chart shown in Figure 2 provides an example of these results. The data were taken in MLT-INV sector 5-60 during the 6 June magnetic storm. No emissions are observed on the two days before the storm or on the day of the storm's sudden commencement. However, chorus is observed on the second through the sixth days of the storm, reaching frequencies of 4 kHz on the fourth day (9 June).

The pass during which the data in Figure 1 were taken occurred on 7 June, the second day of a large magnetic storm. Below about 70° INV intense chorus is observed, on both magnetic morning and noon ends of the pass. This example of chorus occurrence is consistent with the generalizations made on the basis of Figure 5.

A definitive statement about the differences between types of chorus generally observed in magnetic morning and in magnetic evening is not possible because no single storm considered involved data from both local time regions. Burst-type, normal chorus can occur in magnetic evening during a storm as well as in magnetic morning.

We shall now discuss further the results just presented and compare them with the findings of other investigators. The observation of normal chorus during the first four days of magnetic storms is consistent with the results of Storey [1953] and Allcock [1957], who find that middle latitude (normal) chorus correlates positively with magnetic activity. Crouchley and Brice [1960] and Ungstrup and Jackerott [1963] report a negative correlation of polar chorus, as seen from the ground, with magnetic activity. We infer a positive correlation. This apparent discrepancy is explained by the hypothesis of Pope [1959, 1963] that the

negative correlation is due to ionospheric absorption, which is not an important factor in the satellite observations. Helliwell [1965] also offers evidence in support of this interpretation.

It has been found that chorus occurrence peaks near dawn at middle latitudes and that the peak spirals towards noon at high latitudes [Ondoh, 1961; Pope, 1963]. The broad peak we observe centered on 9 hours MLT at high latitudes does not seriously disagree with this, and a slight discrepancy may be expected due to the effect reported by Laaspere, et al. [1964], who find that disturbed day chorus peaks earlier than quiet day chorus. The 9 hours MLT result for the position of the diurnal maximum is consistent with the results of a 1963 ground station study by Jørgensen [1965] and with a statistical study using Injun 3 data by Oliven and Gurnett [1968]. Brice [1964b] offers a theoretical explanation for this diurnal variation. An evening peak in chorus occurrence was discovered in Australia by Crouchley and Brice [1960] using ground station data.

Most evidence implies that chorus is generated by energetic electrons. The shape of the high latitude limit of chorus occurrence resembles the shape of the trapping boundary for $\geq$ 40 keV electrons of Frank et al. [1964].

Oliven and Gurnett [1968] found a connection between electron microbursts (time scale $\sim$ 0.25 sec.) and chorus. It was found that electron microbursts were <u>always</u> accompanied by VLF chorus emissions; the converse was not true, however. It was not possible to establish a one-to-one correspondence between individual bursts of electrons and chorus. Brice's [1964b] explanation of the diurnal variation of chorus assumes that the generating mechanism for the emissions is the transverse resonance plasma instability for electrons.

IV. SPATIAL AND TEMPORAL VARIATIONS OF VLF EMISSION INTENSITY

Spatial and temporal variations of VLF radio noise intensity in the frequency range 0.2 to 7.0 kHz can be studied by means of the AGC feedback voltage of the Injun 3 VLF receiver. The objective of this portion of the study is to produce contour maps of constant wide-band VLF field strength (AGC) as a function of L value and universal time (UT). A description of the procedure follows. AGC readings are available every four seconds during a satellite pass over a receiving station. Only northern hemisphere data with $3 \leq L \leq 8$ and 28 April $\leq$ UT $\leq$ 28 August (1963) were used, since the density of data was too low outside these limits. That 4 second AGC reading which was nearest to, but at higher latitude than, each 0.2 L increment was selected for each revolution. The highest AGC value for each 0.2 L increment during each day was selected as the grid point for that 0.2 L by 1 day block. Contours of constant AGC were drawn on the grid thus created. These final AGC maps are reproduced in Figures 6 and 7. Maps were also made as a function of invariant latitude and universal time.

The analysis was performed separately for northbound and southbound passes because these passes occurred at substantially different magnetic local times, as can be seen from Figure 1, which shows a typical orbit in magnetic coordinates. Even on a northbound or a southbound portion of a pass, the satellite may traverse about a 6-hour MLT range. The approximate magnetic local time of the northbound and southbound passes at 60° INV are shown as darkened hours on the "clock dial" diagrams in Figures 6 and 7. The largest error in the production of the maps is the error introduced in drawing the contours. A reasonable standard deviation for the positions of the lines drawn is 0.2 L by 1 day (one grid point). Uncertain contours are indicated by dotted lines.

The utility of contour maps in presenting VLF emission intensities may be emphasized by pointing out that the contours presented in Figures 6 and 7 summarize about 10^5 4-second experimental measurements.

Given below is a summary of observations of wideband field strength made from AGC contour maps.

(1) Contour peaks center on about 63° INV ($L \simeq 5$).

(2) Most regions of activity extend northward to about 75° INV, and few regions exceed this limit. We call

this 75° INV limit an average maximum northern extent of activity.

(3) Activity sometimes extends below 50° INV, which was the lowest latitude for which data were analyzed.

(4) Rough MLT dependence can be investigated by comparison of data taken during northbound passes with data taken during southbound passes. Regions of high AGC appear largest during forenoon MLT (6 to 12 hours) and smallest during evening MLT (18 to 24 hours).

(5) Continuity was observed in latitude readings; that is, peaks fade gradually on both sides.

(6) Very little continuity is observed in the data between revolutions. The time scale of the details of the phenomena is often less than two hours.

(7) Correspondence with magnetic index K_p is fair. Each peak with $K_p \geq 4$ can be associated with a major peak or region of enhancement on the AGC maps, although the converse is not true. Also, periods indicated to be quiet by K_p are generally quiet in radio noise intensity. In comparing the AGC maps with K_p and D_{st} it must be kept in mind that the maps will reflect local substorms which may not be reflected in the planetary averages K_p and D_{st}.

(8) Correspondence with the horizontal component D_{st} is good. Major fluctuations in D_{st} can nearly always be

associated with increases in wide-band field strength, and, unlike the correspondence with K_p, the details of small fluctuations in D_{st} often appear to be reflected in the AGC readings.

(9) Three sudden commencement magnetic storms occurred during the period for which AGC maps have been made. These occurred on 30 April, 6 June, and 18 August (Cf. Table 1) and were discussed in Section III. We suggest that generally, the wide-band VLF field strength rises above background noise at the onset of the storm, grows during the initial and main phases, and peaks during the early recovery phase. The first two storms are clear examples of this behavior, while the 18 August storm is not. However, the latter is not a standard type of storm [Akasofu, 1966], as it has no clearly defined main phase.

The results just presented will now be discussed further and compared with the findings of other investigators. The observation made from the AGC maps of a magnetic morning maximum of VLF emission intensity at about 63° INV agrees well with the frequency of occurrence distribution of VLF emissions found in a statistical study by Taylor and Gurnett [1968]. An average maximum northern extent of activity at 75° INV is also consistent with Taylor and Gurnett's results.

ELF hiss is the strongest and most common emission observed by Injun 3 [Gurnett, 1968], and little error is made if the maps of wide-band field strength are assumed to reflect the intensity of ELF hiss. Comparison of the wide-band field strength contour maps with the equatorial omni-directional $\geq$ 40 keV electron flux contours of Owens and Frank [1968] (Cf. Figure 8) discloses no more agreement than would be expected due to the general correlation of the two phenomena with K_p.

Tokuda [1962] and others have previously reported that VLF emission activity correlates with the horizontal component of the geomagnetic field.

V. INVESTIGATION OF THE KENNEL-PETSCHEK HYPOTHESIS

Kennel and Petschek [1966a and b] have proposed a model for wave-particle interactions which predicts a limiting flux for given energy trapped particles due to pitch angle scattering by whistler mode noise. The limiting equatorial flux J^* for $\geq$40 keV electrons is predicted to be

$$J^* \approx \frac{7 \times 10^{10}}{L^4} \text{ (cm}^2 \text{ sec)}^{-1}$$

The Kennel-Petschek model predicts that when the equatorial electron flux J is greater than J^* on a given L shell, VLF noise will be generated. This noise will in general propagate along the magnetic lines of force of that L shell to the earth. The strength of the noise at 1000 km should be about 10^{-1} γ for L = 5 if field-aligned propagation is assumed.

Values of equatorial $\geq$ 40 keV omnidirectional electron fluxes obtained with the Explorer 14 satellite are given by Owens and Frank [1968]. Omnidirectional electron flux is approximately equal to trapped electron flux. Electron fluxes and VLF noise intensity data are both available for May,

June, and July of 1963. During the latter two months electron fluxes exceeded the limiting flux by small margins five times. Figure 8 shows electron intensity contours, regions of $J \geq J^*$, and wide-band field strength contours.

The correspondence of $J \geq J^*$ regions, indicated by cross-hatching, to peaks in the wide-band field strength, is poor. Nowhere inside the $J \geq J^*$ regions is VLF magnetic field intensity observed to exceed 2 mγ. However, it should be noted that if the $J \geq J^*$ regions are displaced inward by about 1 1/2 L shells, four of them will approximately overlap VLF radio noise intensification regions with intensities as high as 4 mγ. One noise region has an 8 mγ spike. The fifth $J \geq J^*$ region occurred during a period when VLF data was not continuously available. In all cases the wide-band field strengths are considerably less than the $10^{-1}\gamma$ predicted by the Kennel-Petschek theory. In the following paragraphs we comment upon explanations which may be relevant, particularly with reference to the intensity discrepancy.

(A) Absorption in the Magnetosphere

Absorption of waves as they propagate from the generation region in the equatorial plane to low altitudes near the poles may be largely discounted. Collisional

damping is negligible because of the extremely small electron collision frequency in the outer magnetosphere. Cyclotron damping would be important only near the equator, where this resonance leads to wave growth, not damping. Landau damping is significant only for components of the waves propagating nearly perpendicular to the static magnetic field. Thus, for whistler mode waves propagating nearly parallel to the geomagnetic field, it seems probable that absorption is not an important factor in the wave propagation.

(B) Reflection of Waves in the Magnetosphere

Reflection of the waves before they descend to Injun altitudes is a possibility. Thorne and Kennel [1967] have suggested that waves which do reach low altitudes will have wave-normal angles almost perpendicular to the geomagnetic field. A consequence of this is that the waves can be reflected when the wave frequency is below the lower hybrid resonance frequency. Thus, a large fraction of the waves may be reflected or Landau-damped before reaching the satellite. Ducting of whistler mode waves along field aligned irregularities, such as occurs for whistlers [Helliwell, 1965], can prevent this reflection mechanism from occurring. The ratio of ducted to unducted VLF noise has not been determined. However, the fact that chorus, ELF

hiss and other satellite-observed VLF noises are commonly observed by ground-based stations is evidence that the wave normal angle actually remains nearly parallel to the geomagnetic field for many, not few, waves. Also, the OGO-I VLF/LF experiment by Stanford [Dunckel and Helliwell, 1966] reports magnetic intensities in the equatorial plane very similar to those reported by us at high latitudes. This suggests that the attenuation of waves between the equatorial plane and Injun altitudes is small and that most of the wave energy is not reflected before reaching Injun altitudes.

(D) Frequency Range of the Injun 3 Receiver

In Figure 9 we show that the frequency range of the Injun 3 wide-band VLF receiver (∿0.2 to 7.0 kHz) does include the frequencies of noise generated by 40 keV electrons in the $3 \leq L \leq 8$ region according to the Kennel-Petschek theory. Figure 9 is a plot of the result of solving their resonance condition:

$$E_R = E_M \frac{f_g}{f} \left(1 - \frac{f}{f_g}\right)^3$$

for f, where:

f = resonant wave frequency,

f_g = electron gyrofrequency (centered dipole approximation),

E_R = resonant particle energy (40 keV considered),

$E_M = \frac{B^2}{8\pi N}$ = magnetic energy per particle, and

N = number density of electrons, from Angerami and Carpenter [1966].

The result plotted in Figure 9 is only a general guide to the frequencies expected. Uncertainty in the number density N is large, and the motion of the plasmapause [Carpenter, 1966; Angerami and Carpenter, 1966] inward during magnetic storms has been ignored.

It should be noted that the intensity of noise below 1 kHz will not be correctly determined from the Injun 3 AGC readings. The wide-band field strength measurement was calibrated using a white noise source which caused all frequency components to be weighted equally [Cf. Gurnett and O'Brien, 1964]. Because the receiver frequency response is not flat, the AGC reading will give an incorrect field strength measurement if the magnetic field noise spectrum is not flat. At the lowest frequency expected from Figure 9 (about 300 Hz) the magnetic field strength is approximately 15 db greater than that computed from the AGC reading. The data in Figure 9 suggest that the effect of reduced receiver response at low frequencies is important only at high lati-

tudes ($L \geq 6$). This may partially explain why the VLF noise regions in Figure 8 appear to be shifted to lower L values than the corresponding $J \geq J^*$ particle flux regions.

While resonant particles of other energies may contribute different frequencies of VLF noise, Figure 9 does suggest that there might be an observable latitude dependence of the frequency of maximum noise, with lower frequencies at higher latitudes. Such an effect can be seen in Figure 1, and has been reported before [Gurnett, 1968]. Chorus is the phenomenon most affected.

We have found no conclusive explanation for the large factor by which the VLF noise levels observed are below those predicted by Kennel and Petschek, or for the lack of correlation between VLF intensities and limiting fluxes as functions of L and UT. It is likely that the wave intensities predicted and the correlation of limiting fluxes with VLF emissions postulated by Kennel and Petschek are wrong. The complexity of the phenomena being described is impressive; the simplifications made by the theory are severely limiting. Inclusion of large-wave-normal-angle effects in the theory might yield a considerable improvement. Inclusion of a more realistic electron number density profile in the theory may also aid in reducing the large uncertainty in predictions concerning VLF phenomena.

Also, as noted by Kennel and Scarf [1968], when the magnetic energy $B^2/(8\pi N)$ is comparable to the resonant particle energy the generation of whistler mode waves may be inhibited. Magnetic energies will exceed 40 keV in a region just outside the plasmapause ($4 \lesssim L \lesssim 5$, using the assumptions made in producing Figure 9).

The experimental requirements for further testing the Kennel-Petschek hypothesis include VLF measurements in the equatorial plane at high L values and measurements over wider frequency ranges.

TABLE 1

Periods Studied

Period Type	Sudden Commencement Times		Data Analyzed	
	Date (1963)	Day-Hour-Minute	Dates	Number of Sectors per Day Analyzed
Magnetic Storms	April 4	04-05-46	April 3 - 9	3
	April 30	30-15-22	April 29 - May 7	8
	June 6	06-15-11	June 5 - 11	18
	August 18	18-08-16	August 15 - 24	13
	September 13	13-19-25	September 12 - 30	2
Quiet Time	August 11		August 11 - 13	12

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FIGURE CAPTIONS

Figure 1 Wide-band VLF field strength and emission spectrum observed by Injun 3 during a polar pass on 7 June 1963. A large magnetic storm began on 6 June. The orbit of the satellite while the data was being received is shown in magnetic polar coordinates at the top of the figure.

Figure 2 Sample of VLF emissions observed by Injun 3 between 5 and 6 hours MLT and between 60° and 70° INV during the 6 June 1963 magnetic storm. (SC) indicates the sudden commencement of the storm.

Figure 3 Time development of ELF hiss, VLF hiss, and chorus during five magnetic storms.

Figure 4 Time development of chorus during three magnetic storms.

Figure 5 Daily occurrence of chorus in invariant latitude and magnetic local time during five magnetic storms. Suggested boundaries of chorus regions are indicated.

Figure 6 Injun 3 wide-band VLF field strength contours for May and June, 1963, shown with D_{st} and K_p indices.

Figure 7 Continuation of Figure 6 for July and August, 1963.

Figure 8 Top: Explorer 14 equatorial > 40 keV electron flux contours for June and July, 1963 from Owens and Frank [1968] with regions exceeding the Kennel-Petschek limiting flux indicated.

Bottom: Injun 3 wide-band VLF field strength contours.

Figure 9 Frequencies of electromagnetic radiation resonant with 40 keV electrons in the equatorial plane.

G68-692-2

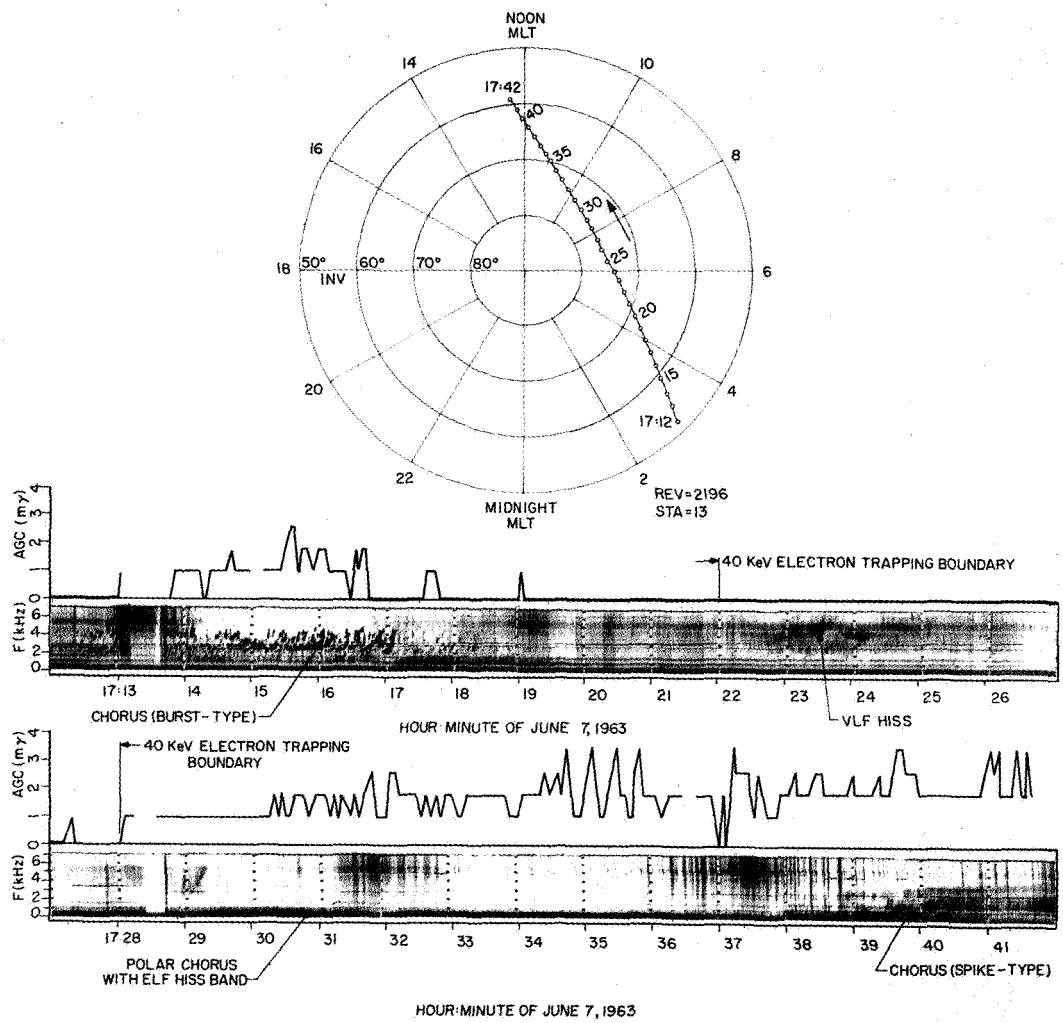
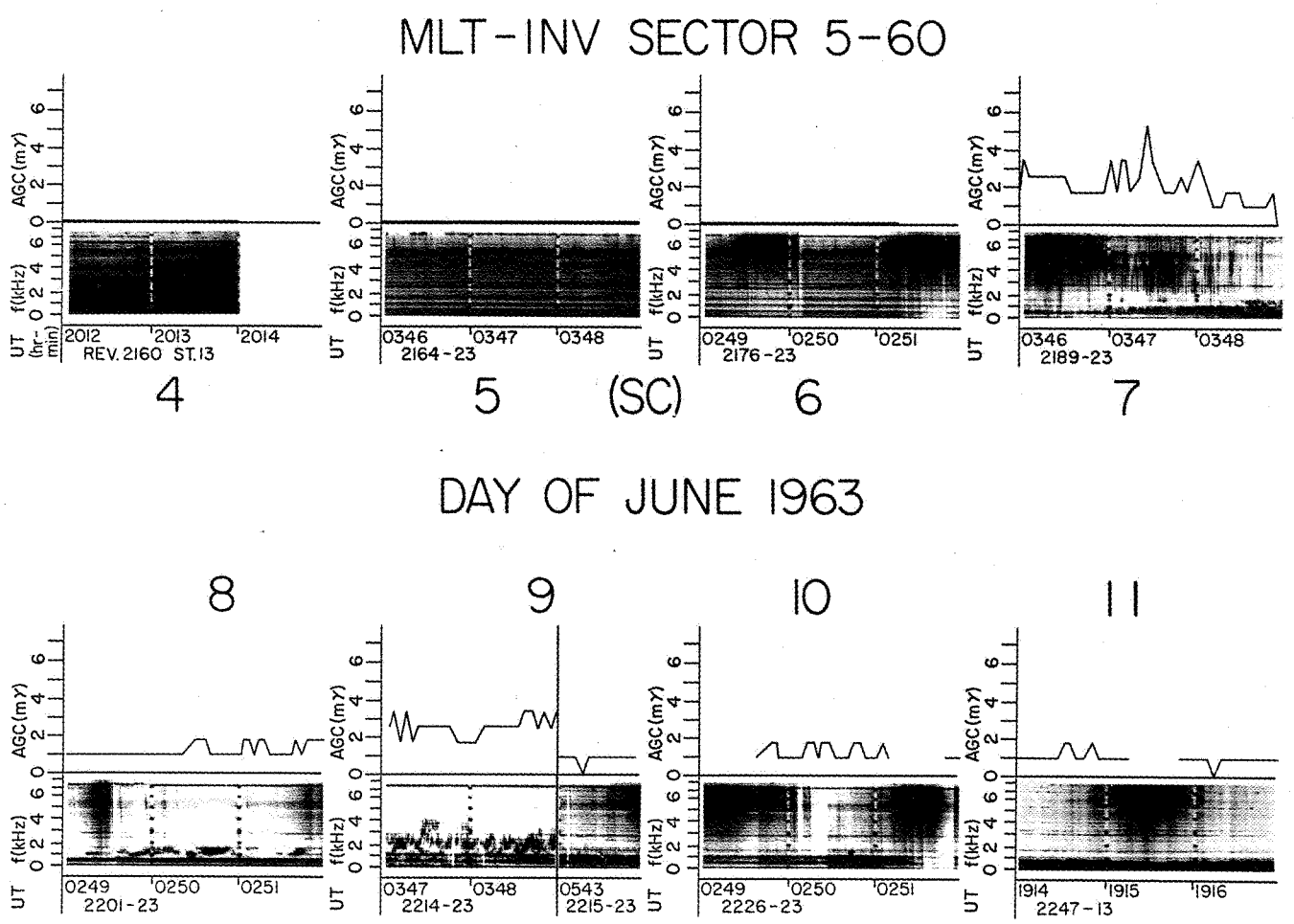


Figure 1

G68-461



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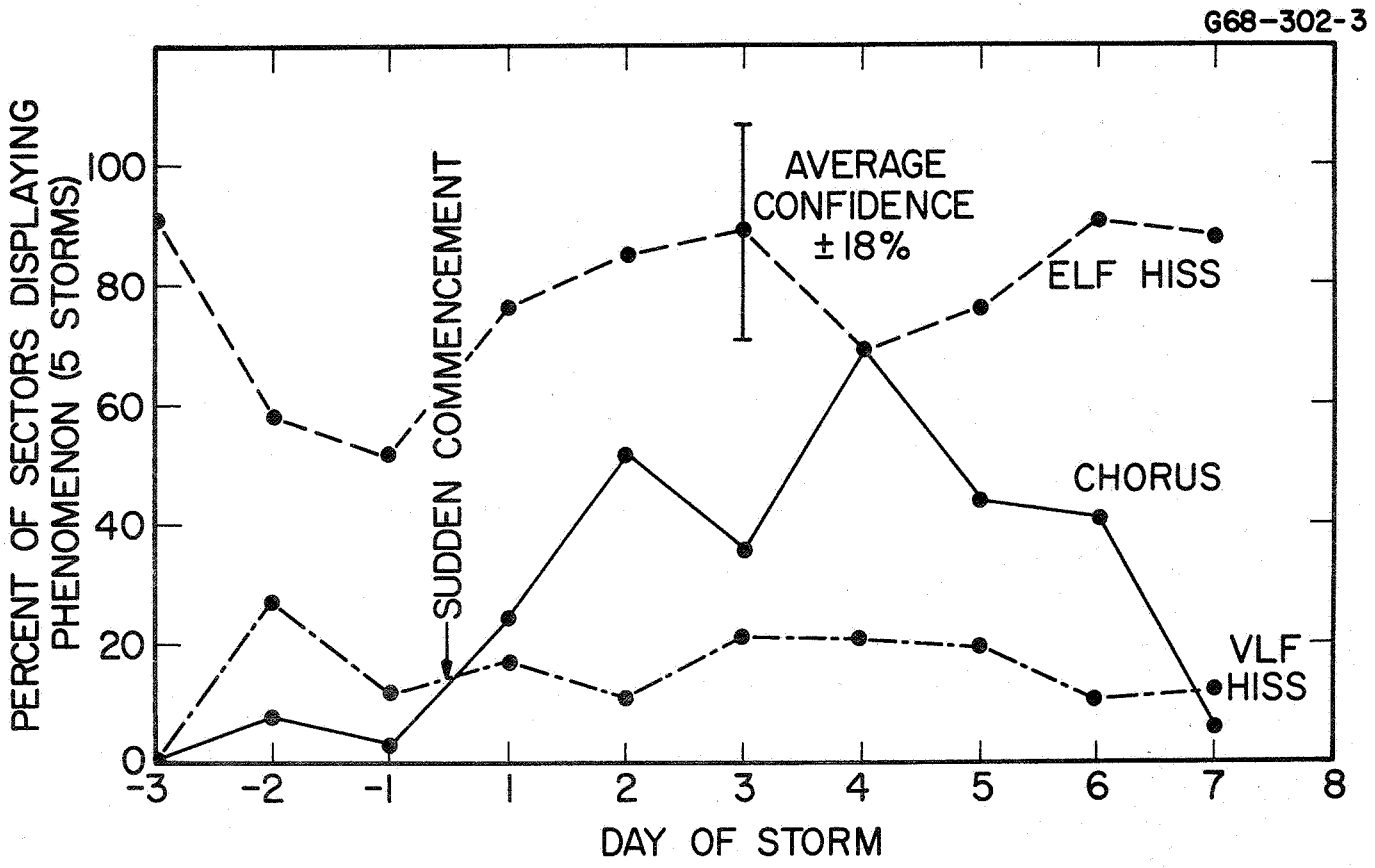
G68-302-3
PERCENT OF SECTORS DISPLAYING PHENOMENON (5 STORMS)
100
80
60
40
20
0
-3
-2
-1
1
2
3
4
5
6
7
8
DAY OF STORM
SUDDEN COMMENCEMENT
AVERAGE CONFIDENCE ±18%
ELF HISS
CHORUS
VLF HISS

Figure 3

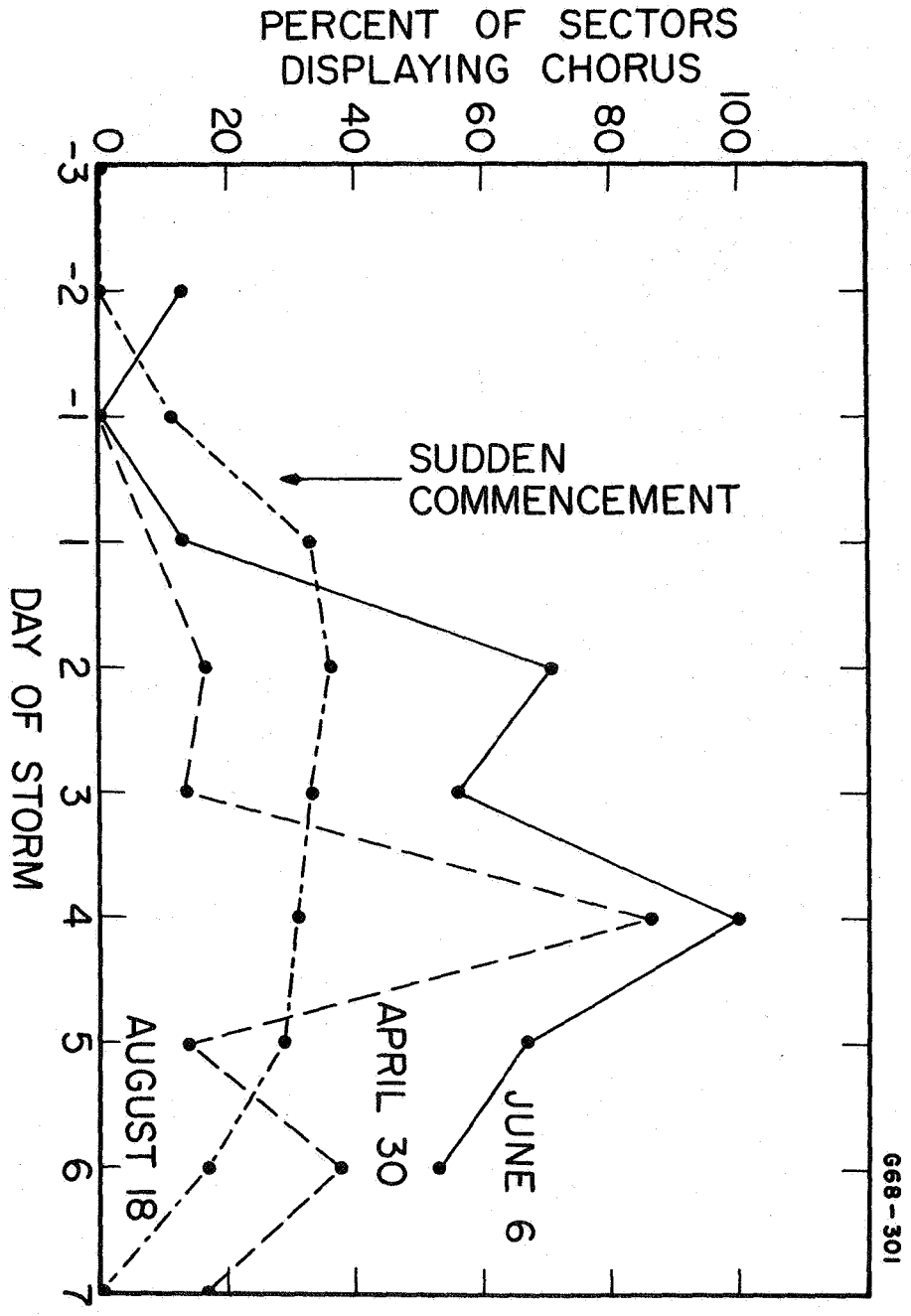
PERCENT OF SECTORS
DISPLAYING CHORUS
100
80
60
40
20
0
SUDDEN
COMMENCEMENT
JUNE 6
APRIL 30
AUGUST 18
-3
-2
-1
1
2
3
4
5
6
7
DAY OF STORM
G68-301

Figure 4

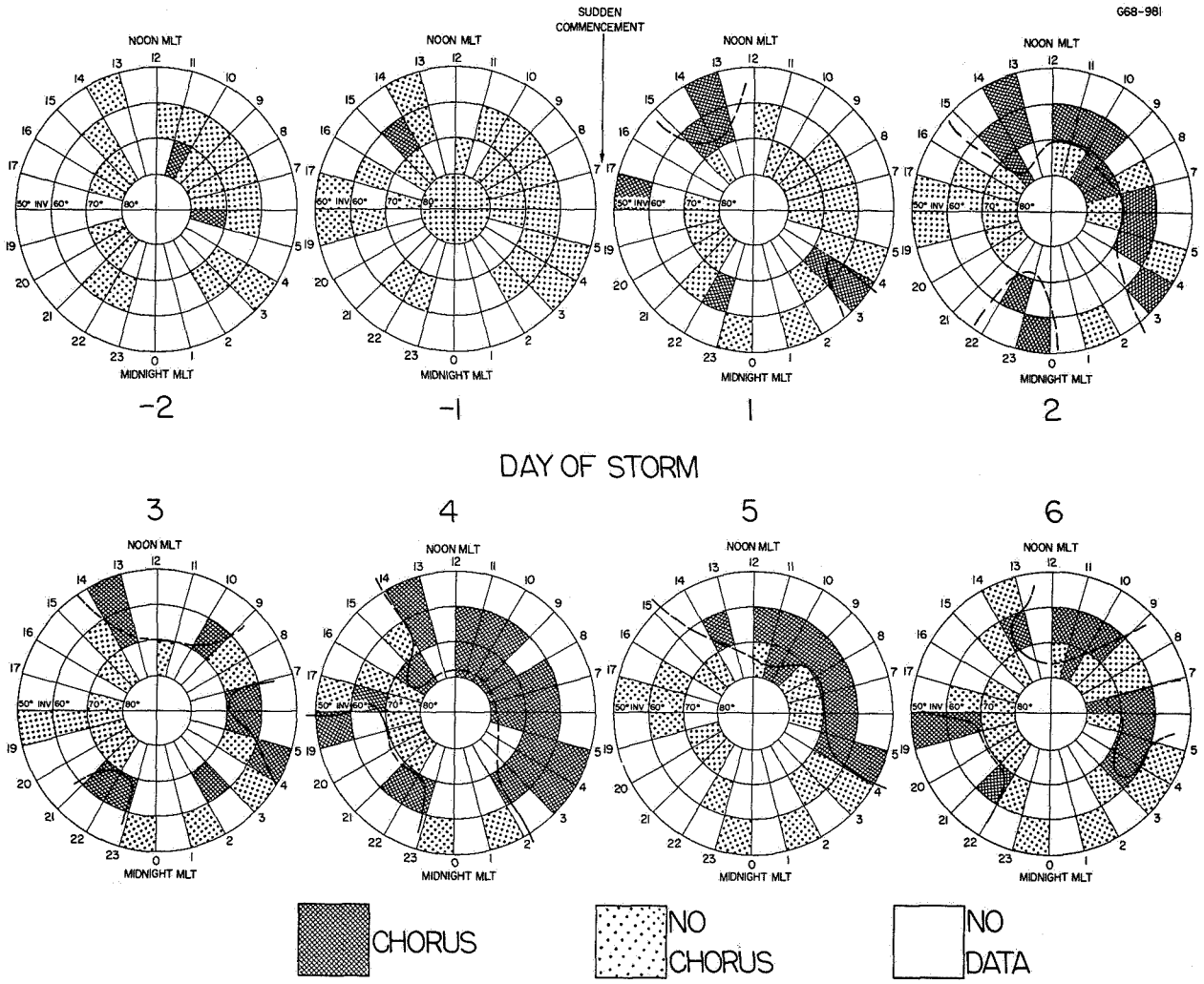
G68-981
SUDDEN COMMENCEMENT
NOON MLT
MIDNIGHT MLT
50° INV
60°
70°
80°
-2
-1
1
2
DAY OF STORM
3
4
5
6
CHORUS
NO CHORUS
NO DATA

Figure 5

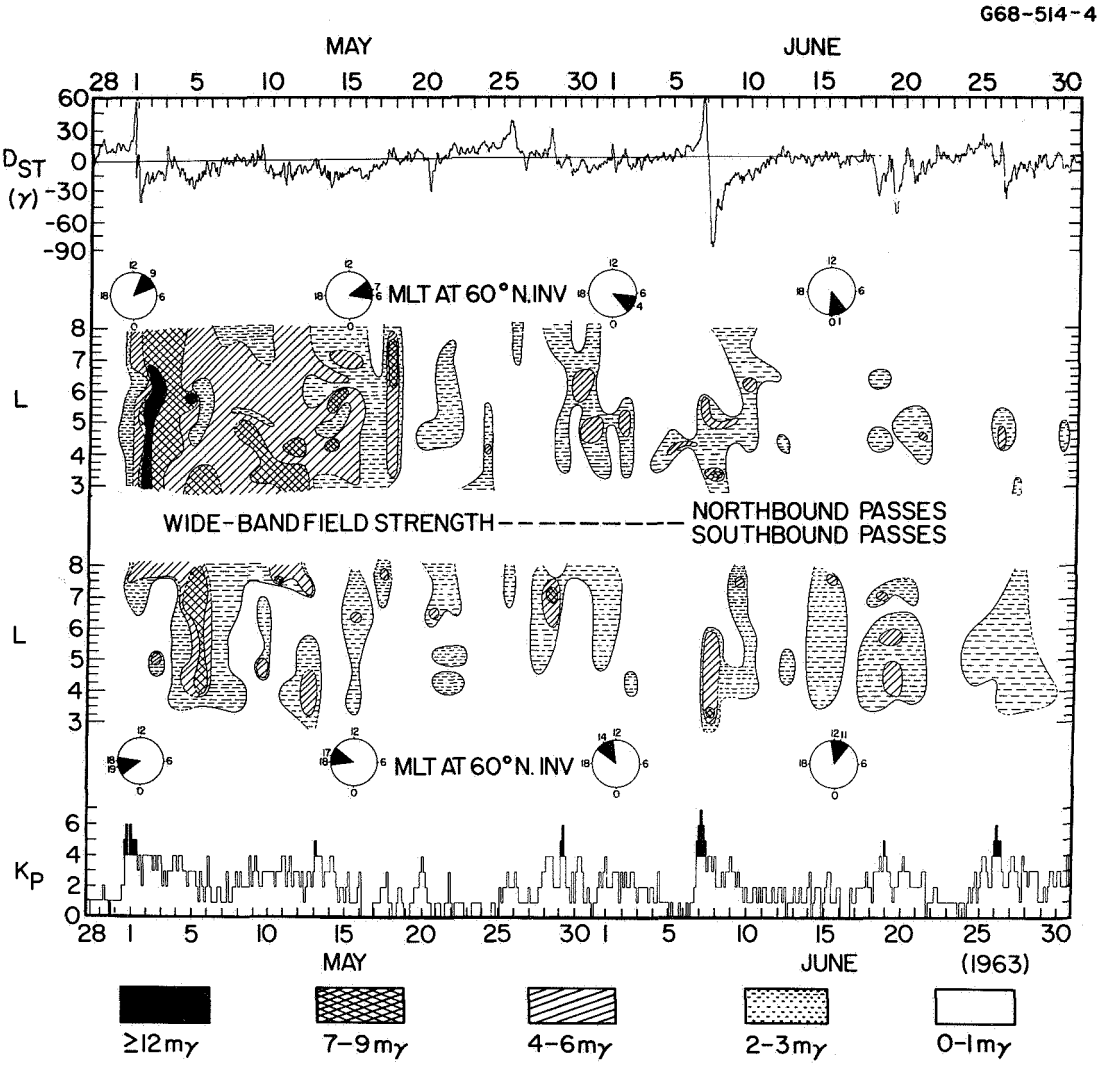
G68-514-4
MAY
JUNE
28 1 5 10 15 20 25 30 1 5 10 15 20 25 30
DST (γ)
60
30
0
-30
-60
-90
MLT AT 60° N.INV
L
8
7
6
5
4
3
WIDE-BAND FIELD STRENGTH
NORTHBOUND PASSES
SOUTHBOUND PASSES
MLT AT 60° N. INV
KP
6
4
2
0
(1963)
≥12mγ
7-9mγ
4-6mγ
2-3mγ
0-1mγ

Figure 6

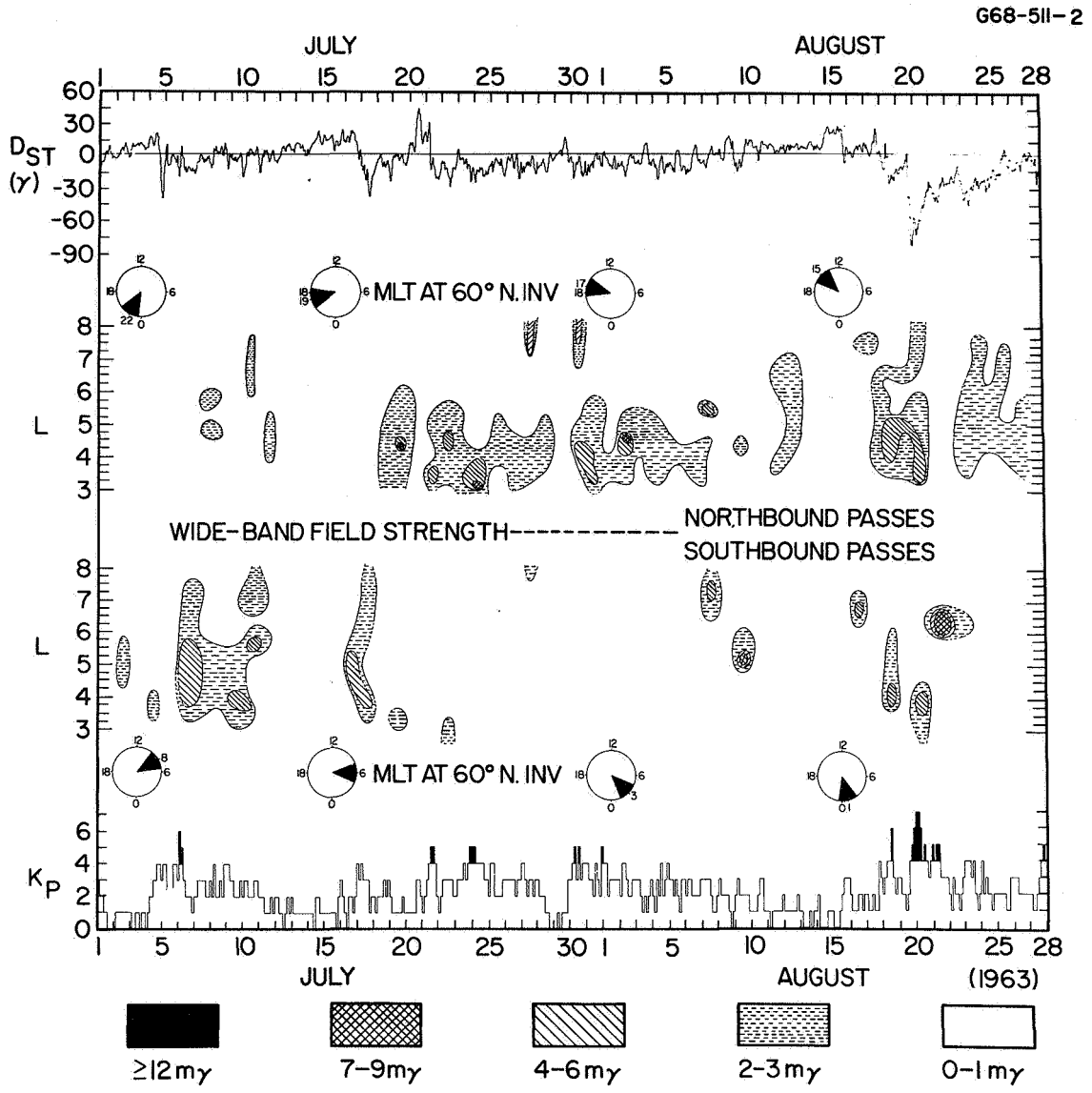
G68-511-2
JULY
AUGUST
DST (γ)
MLT AT 60° N. INV
L
WIDE-BAND FIELD STRENGTH
NORTHBOUND PASSES
SOUTHBOUND PASSES
KP
(1963)
≥12mγ
7-9mγ
4-6mγ
2-3mγ
0-1mγ

Figure 7

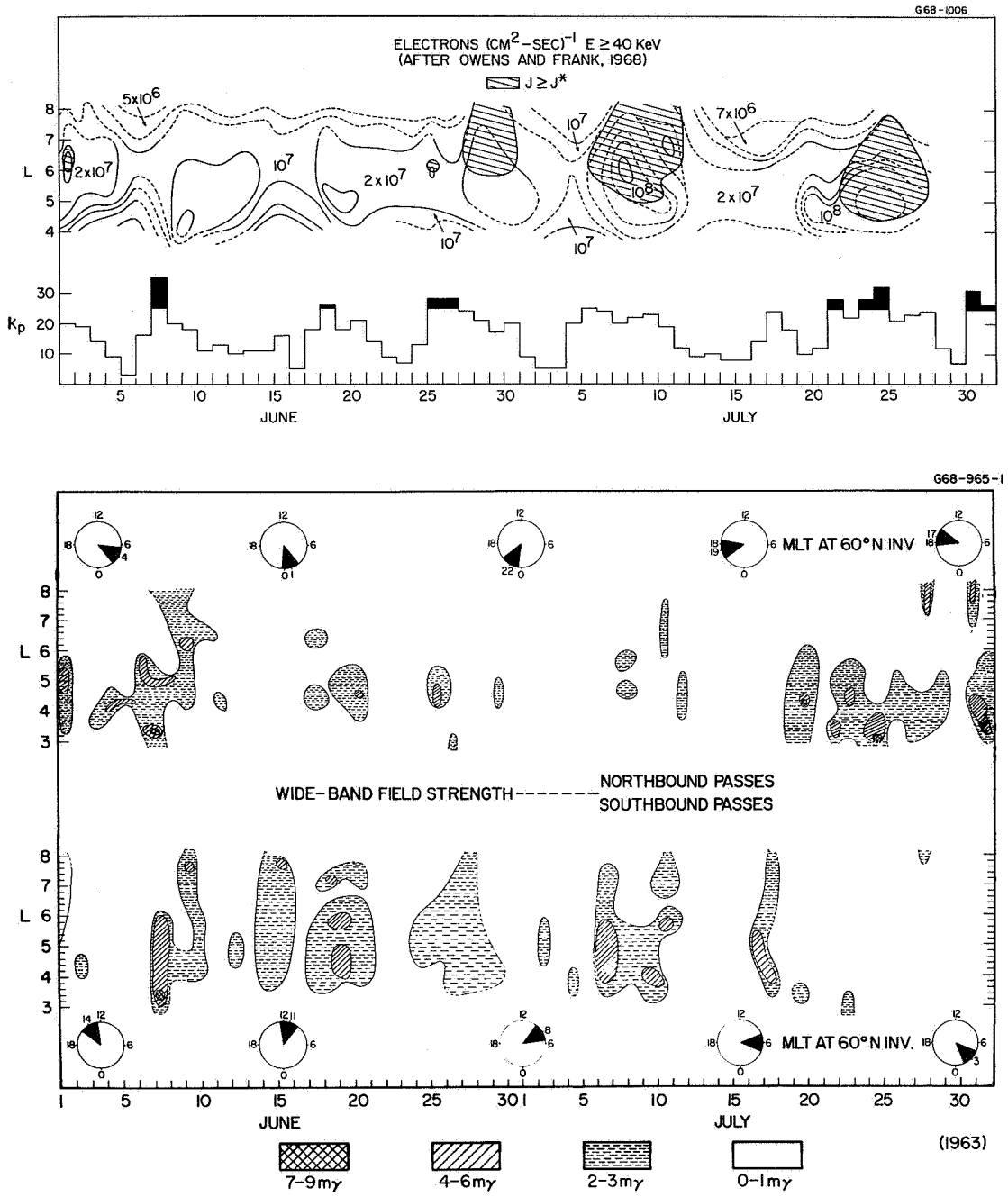
G68-1006
ELECTRONS (CM^2-SEC)$^{-1}$ E ≥ 40 KeV
(AFTER OWENS AND FRANK, 1968)
J ≥ J*
5x10^6
7x10^6
2x10^7
10^7
2x10^7
10^8
L
Kp
JUNE
JULY
G68-965-1
MLT AT 60°N INV
WIDE-BAND FIELD STRENGTH
NORTHBOUND PASSES
SOUTHBOUND PASSES
(1963)
7-9mγ
4-6mγ
2-3mγ
0-1mγ

Figure 8

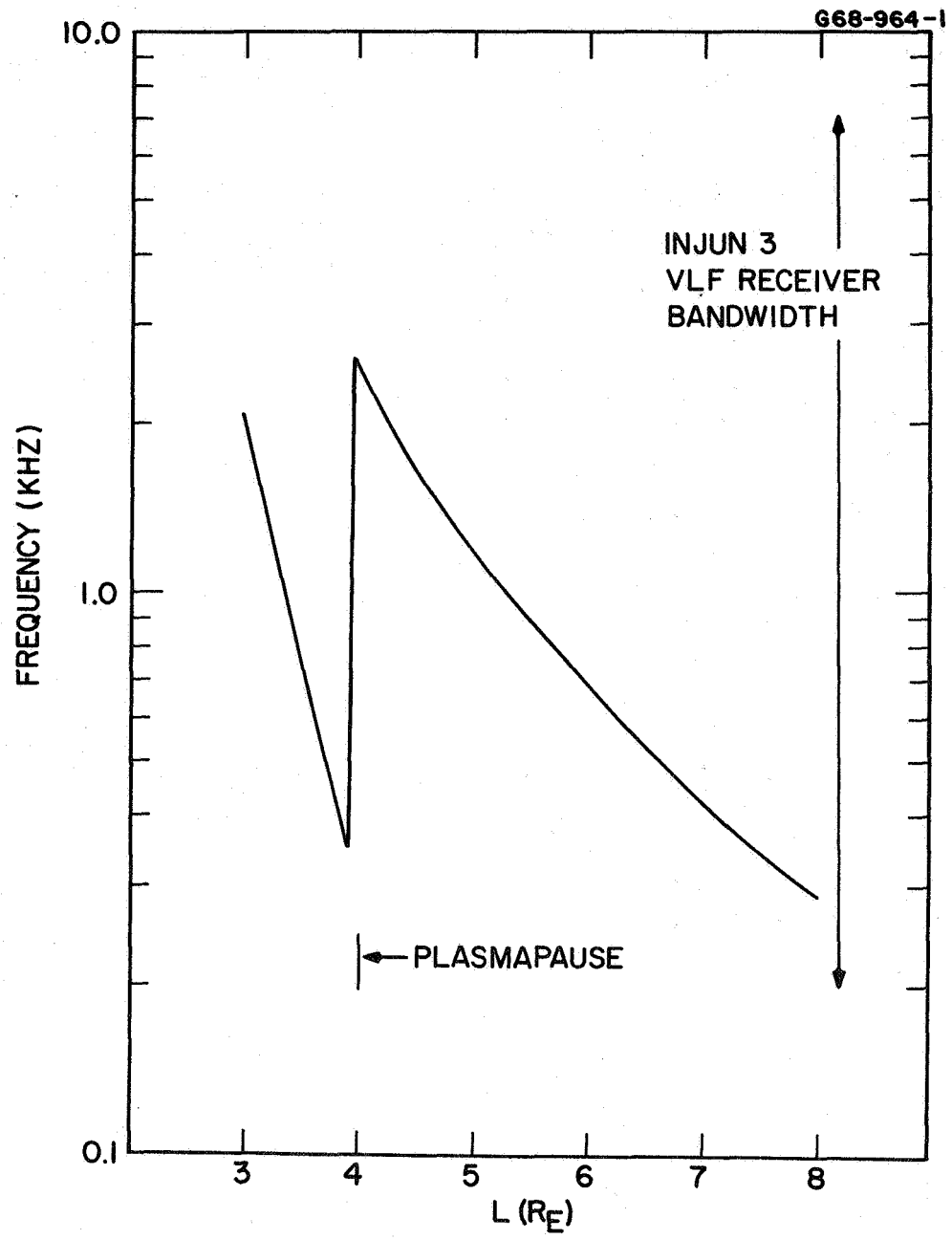
G68-964-1
10.0
1.0
0.1
FREQUENCY (KHZ)
INJUN 3
VLF RECEIVER
BANDWIDTH
PLASMAPAUSE
3
4
5
6
7
8
L (R_E)

Figure 9

unclassified
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3. REPORT TITLE

VLF Emissions During Magnetic Storms and their Association with 40 keV Electrons

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

progress report

5. AUTHOR(S) *(Last name, first name, initial)*

Cauffman, David P. and Gurnett, Donald A.

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13. ABSTRACT Spectrograms of very low frequency radio noise recorded by University of Iowa satellite Injun 3 at invariant latitudes greater than 50°N are used to determine the behavior of VLF emissions during magnetic storms. Variations in the wide-band intensity of VLF emissions from L = 3 to L = 8 are studied for the period from 28 April to 28 August 1963 by means of the automatic gain control levels of the satellite VLF receiver.

During a sudden-commencement magnetic storm the VLF emission called polar chorus characteristically appears at the onset of the storm, may increase in upper frequency extent to ~ 5 kHz, may change from spike to burst structure (normal chorus), and occurs over the greatest area on the fourth day of the storm, subsequently fades into low frequency, spike-structure polar chorus again and eventually disappears into the ELF hiss band generally present. Chorus occurrence shows symmetry about the 9:00 - 21:00 magnetic local time meridian with a large maximum in magnetic morning and a smaller maximum in magnetic evening. Daily regions of occurence are shown for the duration of a prototypical storm.

Contour maps of wide-band VLF field strength as a function of shell parameter L and universal time are presented for May through August, 1963. A correlation with D_{st} is observed. The wide-band VLF noise intensity rises from the background noise level at the onset of a magnetic storm and peaks during the early recovery phase.

The Kennel-Petschek limiting flux hypothesis is investigated by looking for VLF noise on the appropriate L-shells when equatorial > 40 keV electron fluxes reach predicted limiting values. The VLF noise levels predicted in the equatorial plane by Kennel and Petschek are not observed at the altitude of the Injun 3 satellite (less than 2785 km).

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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Association with 40 keV Electrons						

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