An Investigation of Mechanisms Other Than Lightning to Explain Certain Wideband Plasma Wave Bursts Detected in the Venusian Nightside Ionosphere

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1. INTRODUCTION

This is a final report on NASA grant NAG 2-520, covering the period April 1, 1988 to February 29, 1992. During the period April 1, 1988 to September 30, 1990, the project was entitled "An Investigation of Plasma Wave Phenomena Associated with the Question of Lightning on Venus," while from October 1, 1990 to February 29, 1992, it was entitled "An Investigation of Mechanisms Other Than Lightning to Explain Certain Wideband Plasma Wave Bursts Detected in the Venusian NIghtside Ionosphere." The Principal Investigator under the grant was D. L. Carpenter of Stanford University. T. F. Bell of Stanford participated in the first year of work. Beginning in 1989, a leading role in the research was played by V. S. Sonwalkar, who deserves substantial credit for many of the recently published findings.

This report will provide a brief overview of work during the first period of the grant, until October 1, 1990, and will then summarize the more recent activity. Our work under the second project listed above had been expected to last two years; its termination after one year left us with a number of only partially developed lines of investigation. Thus, in spite of this being a final report, our findings should be understood to represent work that is essentially still in progress. It is our hope that in the next few months, and without additional funding, we will be able to prepare for publication a paper that presents a more rounded treatment of our material.

A review of the literature on related topics is beyond the scope of this report; however, a list of publications that were consulted during the course of this work is given in the reference section.

2. REVIEW OF WORK ON " AN INVESTIGATION OF PLASMA WAVE PHENOMENA ASSOCIATED WITH THE QUESTION OF LIGHTNING ON VENUS"

In our initial work as guest investigators of the OEFD data, we looked at results from a limited number of individual orbits, imposing new interpretive criteria involving wave-normal angle, dispersion, and wave polarization. With this more physically rigorous approach to individual cases, we found that the data (11 cases) tended to separate into two distinct classes, one whose properties, insofar as they could be estimated, were consistent with whistler-mode propagation from lightning, and a second whose properties were not consistent with whistler-mode propagation from such a source. Most of the former were 100 Hz only and most of the latter multifrequency, but there were sufficient exceptions to indicate the need in further statistical work for sorting the data according to additional physical criteria such as wave normal angle. This work led to a publication entitled "Testing radio bursts observed on the nightside of Venus for evidence of whistler-mode propagation from lightning", by *Sonwalkar et al.* [1991]. See attachment A for a copy of the abstract of this paper.

Our first two years of work added support to the contention that lightning is at least a candidate explanation for many of the 100 Hz-only OEFD signals, but it also indicated a need to look harder at the multifrequency bursts, which had not really been widely investigated or discussed except in the context of the debate noted above. In our most recent project, then, we proposed to investigate a number of properties of the multifrequency events and to compare them with what appear to be similar events detected in other planetary environments.

3. REVIEW OF WORK ON THE PROJECT "AN INVESTIGATION OF MECHANISMS OTHER THAN LIGHTNING TO EXPLAIN CERTAIN WIDEBAND PLASMA WAVE BURSTS DETECTED IN THE VENUSIAN NIGHTSIDE IONOSPHERE"

3.1 INTRODUCTION

This project was devoted to work on the multifrequency events, as well as to several additional issues concerning lightning as a source of some of the OEFD radio bursts. We begin with a summary of our analysis of data from 23 OEFD observing periods, of which only 11 were reported in our initial paper. This is followed by a discussion of properties of specifically multifrequency events. Our opportunity to work on this topic has not been sufficient for us to draw firm conclusions about the origins of the multifrequency bursts, but we call attention to what we consider to be several candidate sources.

3.2 CONTINUATION OF CASE STUDIES TO TEST FOR EVIDENCE OF WHISTLER MODE PROPAGATION FROM SUBIONOSPHERIC SOURCES

In order to shed further light on the lightning source issue, and to gain more information about the multifrequency burst events, the early data set, which included 11 cases of wave burst activity, was expanded to 23 cases, as indicated in Table 1.

There were 15 cases of 100 Hz only, 12 of which were consistent with whistler-mode propagation from subionospheric sources according to the wave normal test. For the 12 cases, the B field ranged between 20 and 35 nT, and the electron density was in the thousands. The altitudes of observation varied from near 150 km to 1300 km.

The 3 cases of 100 Hz only in which the inferred wave normal angles were outside the whistler-mode propagation cone were observed in a relatively low altitude range, about 150 to 400 km, and under conditions of relatively high electron density, 2000 el/cc to 10,000 el/cc.

Of the ten multifrequency burst cases, each included activity in the lower three frequency bands, while four exhibited bursts at 30 kHz as well. In nine of the cases the inferred wave normal was outside the resonance cone for whistler mode propagation. The altitudes for these cases ranged from 150 to 1700 km. All were from orbits with periapsis near 150-160 km. The magnetic field B ranged from 10 to 30 nT, somewhat lower on average than in the 100 Hz-only cases. In all ten cases the frequency of the third channel, 5.4 kHz, was above the local electron gyrofrequency. The electron density tended to be more variable than in the 100 Hz-only cases, being in the 10's and 20's at times, but in the 1000's in other cases.

In one multifrequency case, the wave normal test was passed in the 100 Hz channel. This event occurred at relatively high altitude.

A comparison of data from orbits 501 and 529 is of interest. On 501, multichannel bursts, all inferred to be outside the propagation cone, were detected at low altitude, and a 100 Hz-only burst, also outside the cone, was observed at high altitude. On 529, opposite properties were observed; a 100 Hz-only burst occurred at low altitude and a multichannel burst at high altitude, and in both cases the 100 Hz bursts were inferred to pass the whistler-mode wave normal test.

Largely because of the inherently bursty nature of the data and temporal fluctuations in the background magnetic field, it was possible to apply the polarization analysis described by Sonwalkar et al. [1991] to data from orbits 501 and 526 only. As previously reported, these added support to the findings (from the inferred wave normal) that on 526 the measured sections of 100 Hz-only data were consistent with whistler mode propagation, while on 501 they were not

3.3 RESULTS OF A SEARCH FOR DISPERSIVE EFFECTS IN THE OEFD DATA

Because of the relatively large refractive index (~ 1000) for the waves propagating in the whistler mode in the Venusian ionosphere, substantial dispersive effects are to be expected.

In particular, based on theoretical calculations for Venusian ionospheric parameters, it was estimated that dispersive effects would manifest themselves in three different ways in the OEFD data:

(1) When the ionospheric conditions permit propagation of both 100 Hz and 730 Hz signals in the whistler mode, the leading edge of the 730 Hz signal should show a detectable delay compared to that of the 100 Hz signal.

(2) The finite bandwidths of the OEFD frequency channels should lead to pulse broadening that increases with increasing propagation path length.

(3) Th finite bandwidths of the OEFD frequency channels should lead to a decrease in the peak amplitude of individual pulses with increasing propagation path length.

Effect (1) can only be tested at low altitudes where 730 Hz signals have not suffered large decreases in amplitude due to pulse broadening. A search for this effect is describe in subsection 3.3.1. 250 ms sampling rate does not allow testing of pulse broadening (effect 2) for 100 Hz signal (which remain $\sim$ 500 ms even after propagating 2000 km), and excessive attenuation due to pulse broadening does not allow detection of this effect for 730 Hz signal. However, the reduction in the peak amplitude due to pulse broadening as a function of altitude should be a measurable effect for 100 Hz signals. Since individual lightning can vary in intensity, this effect can only be tested on the average. A search for this effect is described in subsection 5.2

3.3.1 RESULTS OF A SEARCH FOR SIMULTANEOUS 100 HZ AND 730 HZ OBSERVATIONS AT ALTITUDES BELOW 150 KM

A possible further test of the hypothesis that 100 Hz bursts observed from OEFD originate beneath the ionosphere is the extent to which bursts occur simultaneously on both 100 Hz and 730 Hz when PVO is at altitudes below 150 km, close to the lower boundary or limits of the nightside Venusian ionosphere. Under such circumstances, waves at 730 Hz from lightning sources would not necessarily be subject to the excessive dispersive broadening and hence attenuation expected for observations at higher altitudes, and might therefore be detected as apparently whistler-mode signals. Or, in the cases in which the inferred wave normal is outside the resonance cone for propagation at 730 Hz, there might nevertheless be favorable opportunities for detecting leakage signals.

Among the first 5000 PVO orbits, 36 were identified as reaching the nightside altitude range of interest. In these cases, most of which were examined by means of 12-sec averaged data, no examples were found in which both 100 Hz and 730 Hz were in the allowed cone of angles for whistler-mode propagation. Furthermore, there was no case in which burst activity occurred on both channels, and was in the allowed wave normal range on 100 Hz only.

3.3.2 INVESTIGATION OF CHANGES WITH ALTITUDE IN DISPERSIVE BROADENING EFFECTS IN THE TIME SIGNATURES OF 100 HZ BURSTS

Because of the high refractive index for whistler-mode propagation in the Venusian ionosphere, a series of 100 Hz bursts observed by the narrow band receiver on OEFD would be expected to vary with altitude in a distinctive way, provided that the bursts originated in impulsive sources beneath the ionosphere. As altitude increases, the duration of a typical burst should increase (other conditions on the source being the same), leading to a decrease in the peak amplitude. This decrease is roughly proportional to $D^{-1/2}$, where D is the distance travelled by the signal in the ionosphere. We have looked at 100 Hz from two orbits, 529 and 531, both of which contain burst activity over a wide range of altitudes. In neither case did the 100 Hz impulses registered at the higher altitudes exhibit the decrease in peak amplitude that would be expected for whistler-mode propagation from a subionospheric source. Figures 1a and 1b show 100 Hz signals observed during orbit 529 in two altitude ranges, 159 to 250 km and 1533 to 1709 km. In both cases the 100 Hz signal had passed the initial wave normal test. On the average, we expect the peak amplitudes of these signals in the higher altitude range to be about five times lower than those in the lower altitude range. No such difference in the amplitudes is evident in the data shown in Figure 1. Figures 2a, 2b, and 2c show similar data for orbit 531 in three different altitude ranges: 301 - 188 km, 514 - 301 km, and 743 - 1206 km. We expect the peak amplitudes in the second and third altitude ranges relative to the first to be about 1.5 and 3 times lower, respectively. Again, no such difference in the amplitudes is evident in the data. Thus, even in these cases in which the signals had previously been found to pass the wave normal test, their failure to meet the dispersion requirement removes them from consideration as having propagated in the whistler mode to PVO.

3.4 A SURVEY OF BURST ACTIVITY AT ALTITUDES ABOVE 1000 KM

A survey was made of those orbits among the first 2000 with solar zenith angles larger than about 135 degrees, thus affording nightside observing conditions. A significant number of the data sets were found to contain burst activity. For example, in the thirteen cases from orbits 1868 through 1880, with periapsis near 1900 km, at least eight contained identifiable burst activity, and in all of those cases activity appeared on the 100 Hz channel and on at least one other channel. Figure 3 shows two examples from this series, from orbits 1871 and 1880. The four channels of OEFD data are shown above, and the reported magnetic field (OMAG) and electron density values (OTEP) are shown in the middle and lower panels, respectively.

The burst activity in the altitude range 1000-2000 km showed a number of features, including a tendency to appear in regions of relatively low electron density. Figure 4 shows two particularly clear examples of this, from orbits 1192 and 1188, both with periapsis near 1160 km. On orbit 1192, at the left, the visually identifiable activity was confined to the 100 Hz channel, while on 1188, both 100 Hz and 730 Hz show burst activity during observation of a pronounced dip in electron density.

In the visual survey of cases with periapsis in the 1000-2000 km range, examples devoid of identifiable burst activity were infrequent, and in such cases the electron density tended to be relatively high and smoothly distributed along the orbit. Figure 5 shows two such cases, from orbits 1210 and 1202, with periapsis near 1200 km. In these examples the electron density remained near 1000 el/cc during the period of nightside observing conditions, while the magnetic field magnitude was less than a few nT most of the time.

The complexities of the data are illustrated by Figures 3 and 6, which show orbits 1871 and 1880 (Figure 3) and orbits 1872 and 1873 (Figure 6). On orbit 1871, the burst activity is mostly prior to periapsis, but is not simply related to electron density. Simultaneous bursts appear on 730 Hz and 5.4 kHz when the magnetic field reverses direction at periapsis. On the next two orbits (Figure 6), the magnetic field configuration differs from that observed during 1871, and the burst activity differs as well. The similarities in burst activity on 1872 and 1873 appear to be mirrored by similarities in the associated magnetic field configurations. Is this similarity on two successive days important? On orbit 1880, (Figure 3b), the magnetic field profile is again roughly similar to that of orbits 1872 and 1873, but now the burst activity is again concentrated prior to periapsis, and to a region of reduced electron density. Low density also appears to be associated with burst activity on orbits 1872 and 1873, so one must continue to regard the density as a factor of perhaps overriding importance.

The multifrequency signals, and very possibly the 100 Hz component in many of the cases, cannot be understood as waves propagating upward from lower altitudes, in view of their frequent observation at altitudes well above those at which such cases have been reported by other investigators to drop off steeply in occurrence. Furthermore, they occur at frequencies at which propagation can not, in theory, be locally supported.

3.5 POSSIBLE CONNECTION OF THE MULTIFREQUENCY BURSTS TO OBSERVATIONS NEAR OTHER PLANETS

In observations near other planets, wave bursts have been found to originate both in lightning and in other mechanisms. Wideband dispersionless wave bursts have been found to be a common feature of satellite observations near Earth [*Ondoh et al.*, 1989; *Sonwalkar et al.*, 1990], and bursts of this general type have also been reported near the Earth's magnetopause [*Reinleitner et al.*, 1982, 1983] and in the environments of Jupiter and Saturn [*Reinleitner et al.*, 1984]. These burst emissions have several characteristics common to the multichannel bursts observed on PVO [*Sonwalkar et al.*, 1990]. They are impulsive and show very little or no dispersion, their frequencies range from well below to well above the local gyrofrequency, but remain below the local electron plasma frequency, and there is an indication that their wave normal direction may be perpendicular to the local geomagnetic field. If these signals were sampled by a receiver similar to the one on PVO, their temporal and spectral characteristics would be similar to those observed on PVO orbits such as 501 (Figure 7). Near Earth these signals have been observed on both electric and magnetic field antennas and have been detected in the low-density region outside the plasmapause at all local times [*Sonwalkar et al.*, 1990]. They show no association with terrestrial lightning (the spectral signature of lightning in these regions of the Earth's magnetosphere is reasonably well understood). The signals were initially interpreted as electrostatic noise generated by a resistive medium instability [*Reinleitner et al.*, 1983]. This instability is triggered by a beam of electrons of the order of several hundred eV, which could be generated by electrons trapped by the wave fields of natural chorus or hiss emissions. However, the observation of a magnetic component for these bursts has called this mechanism into question [*Sonwalkar et al.*, 1990].

New data has been found (under other sponsorship) indicating the local nature of dispersionless bursts registered near Earth on the DE-1 satellite. During observations in auroral regions, such burst activity was found to occur preferentially in regions of low density, < 1 el/cc. While propagating waves such as hiss and Omega transmitter signals were found to be excluded from frequencies above the local plasma frequency, the dispersionless bursts extended upward from the high frequency limits of the propagating waves, suggesting that the former were not propagating, but of local origin [*Sonwalkar and Helliwell*, 1991].

4. CONCLUDING REMARKS

The multifrequency bursts observed in the 1000-2000 km altitude range do not appear to represent propagating waves and thus may originate near PVO. Locally low electron density appears to be a factor in their occurrence. Their origin may involve the as yet unknown mechanism associated with observations of dispersionless radio bursts near Earth and other planets. The bursts near Earth are regularly observed under locally low density conditions, such as prevail beyond the plasmapause or in auroral cavity regions. Furthermore, recent data provide evidence of an origin of such bursts near an observing satellite.

In the low altitude OEFD data, we have studied burst sequences that are consistent with whister-mode propagation from subionospheric sources, insofar as the wave-normal test is concerned. However, there clearly is a body of 100-Hz only signals that fails the wave normal test, and this has been taken into account in recent work by the Principal Investigator for the OEFD and his associates.

The results of our search for two-frequency events below 150 km appear to be inconsistent with a model of whistler-mode propagation from lightning. Furthermore, our search for dispersive effects in the form of amplitude variations with altitude caused several of the cases previously considered to be whistler-mode candidates to be disqualified as such. However, these lines of enquiry were not pursued long enough to justify judgments about the amount of burst activity that must continue to be regarded as of possible lightning origin.

There are clearly ways in which the lightning hypothesis could be further explored, for example through additional studies of altitude-dependent dispersive effects on the 100 Hz burst profiles.

As Guest Investigators in a situation in which an acrimonious debate had arisen, we might have attempted to comment in detail on how our work relates to all that has been said by the parties to the debate in the literature. However, the resources and time at our disposal have been limited, and we have chosen to focus on results and the development of methods of gaining results rather than extensive commentary about what others have claimed. As in many arguments in space physics in which phenomena are attributed to a single predominant cause, the truth seems to lie somewhere between the positions that have been taken. Our work provides a basis, albeit shrinking, for the lightning hypothesis, while strongly suggesting the existence of other source mechanisms for the OEFD bursts.

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FIGURE CAPTIONS

Figure 1. Data illustrating an absence of an amplitude decrease (due to pulse broadening) as a function of altitude in the 100 Hz signal during orbit 529. (a) Altitude range: 159 - 250 km; (b) altitude range: 1533 - 1709 km.

Figure 2. Data illustrating an absence of an amplitude decrease (due to pulse broadening) as a function of altitude in the 100 Hz signal during orbit 531. (a) Altitude range: 514 - 301 km; (b) altitude range: 301 - 188 km; (c) altitude range: 743 - 1206 km.

Figure 3. PVO 12-second average data from OEFD, OMAG, and OTEP, showing examples of radio burst activity when periapsis was at ~1900 km.

Figure 4. Examples from near 1200 km altitude illustrating association of burst activity with low values (10-100 el/cc) of local electron density.

Figure 5. Examples from near 1200 km altitude illustrating absence of burst activity in the high electron density (~ 1000 el/cc) regions.

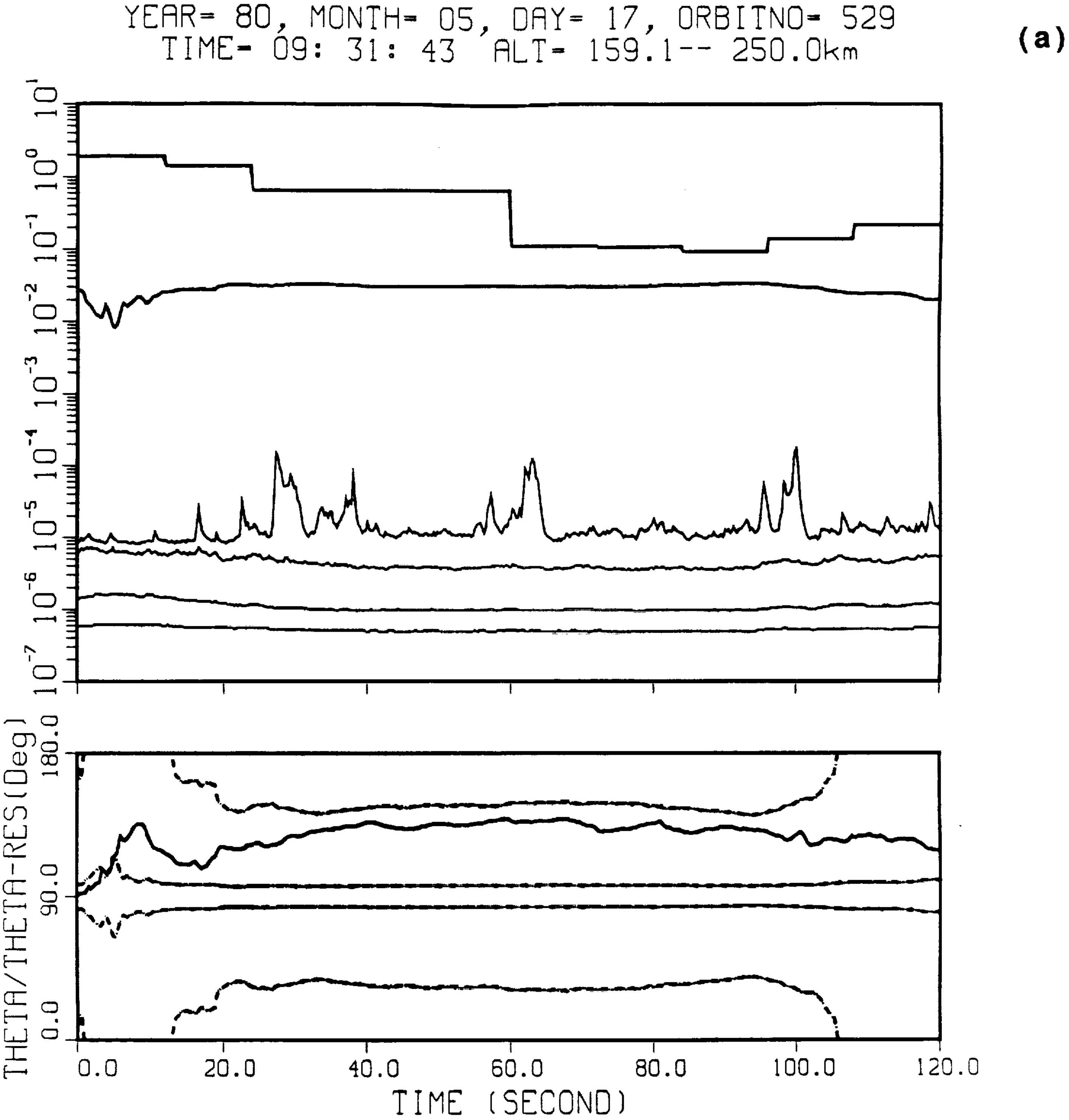
Figure 6. Further examples from near 1900 km altitude showing the importance of the relation between electron density and the observed burst activity. Figure 6 should be compared with Figure 3.

Figure 7. High resolution data showing dispersionless multifrequency bursts observed near 150 km altitude on orbit 501. Wideband impulsive signals observed near earth and other planets would show similar signatures if they were observed using a detector similar to OEFD.

TABLE 1

ORBIT NUMBER	ALTITUDE (km)	FREQUENCY (Hz)	B (nT)	N_e (el/cc)	WHISTLER MODE?
66	263-161	100	25	5000	Yes
66	199-435	100	25	5000	Yes
68	287-176	100	20	2000	Yes
68	191-209	100	35	3000	Yes
86	411-507	100	20	N.A.	Yes
502	380-716	100	30	2000-400	Yes
506	190-210	100	20	10000	Yes
515	319-540	100	25	1000	Yes
526	150-228	100	30	30000-8000	Yes
529	159-484	100	25	1000-2000	Yes
531	566-197	100	20	2000	Yes
531	620-1326	100	25	1000-4000	Yes
65	194-156	100	10-15	5000	No
499	166-234	100	20	10000	No
501	356-419	100	20-30	2000	No
85	204-143-184	100, 730, 5400	20-10	10-20000	No
86	197-147	100, 730, 5400	10-20	40-N.A.	No
219-169-194	100, 730,	30 5400	30-300	No	
499	156-166	100, 730 5400	20-30	20000	No
501	198-155-218	100, 730, 5400, 30000	20-30	4000-10000	No
503	206-167	100, 730, 5400	20	5000-6000	No
506	147-198	100, 730, 5400, 30000	20-30	30000-10000	No
515	181-188	100, 730, 5400, 30000	10-30	4000-20000	No
531	167-155-163	100, 730, 5400, 30000	30	20000	No
529	1125-1709	100, 730, 5400	20	2000	Yes

FIGURE 1


(a)
YEAR= 80, MONTH= 05, DAY= 17, ORBITNO= 529
TIME= 09: 31: 43 ALT= 159.1-- 250.0km
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
THETA/THETA-RES(Deg)
180.0
90.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
TIME (SECOND)

(b)

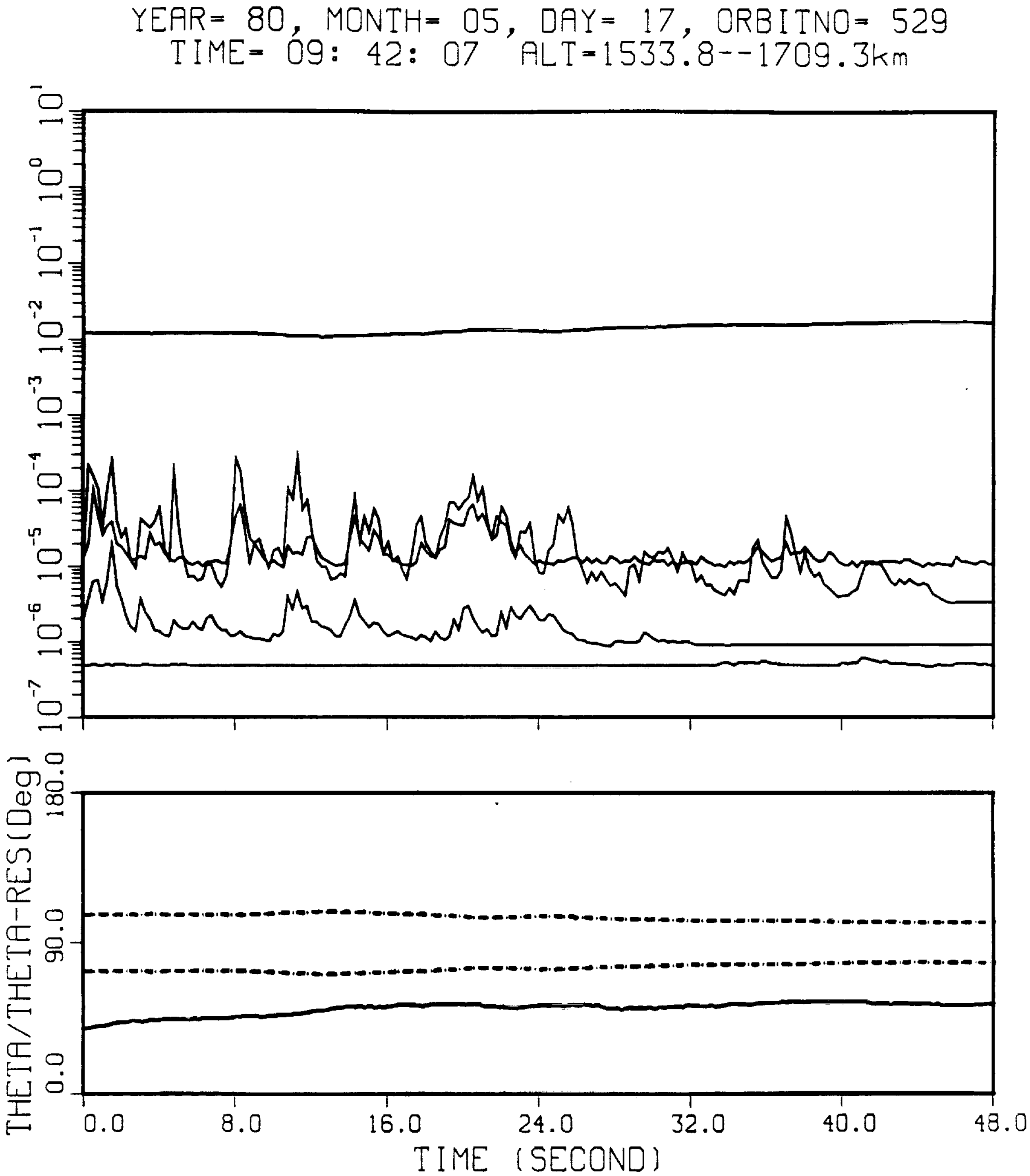
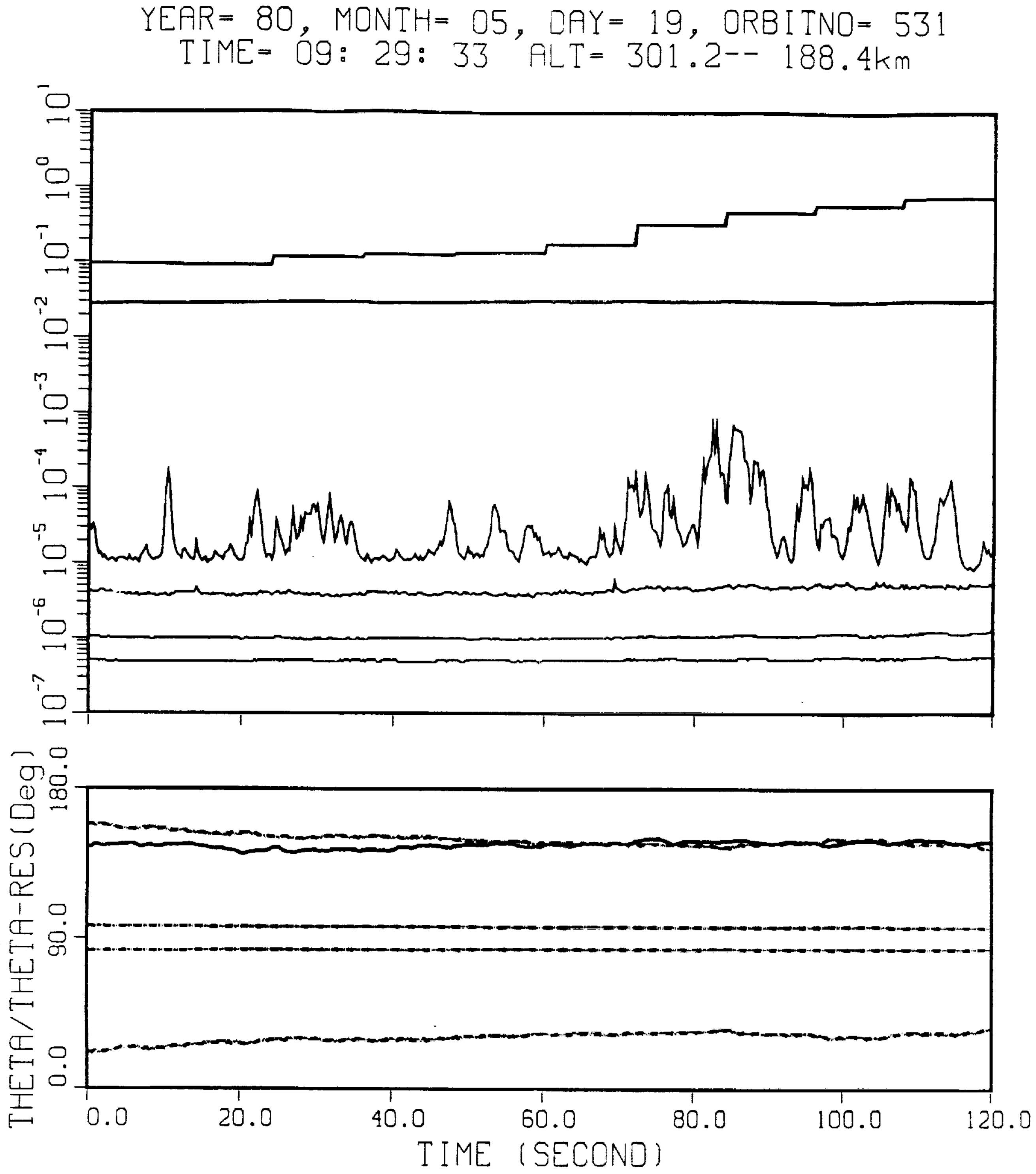
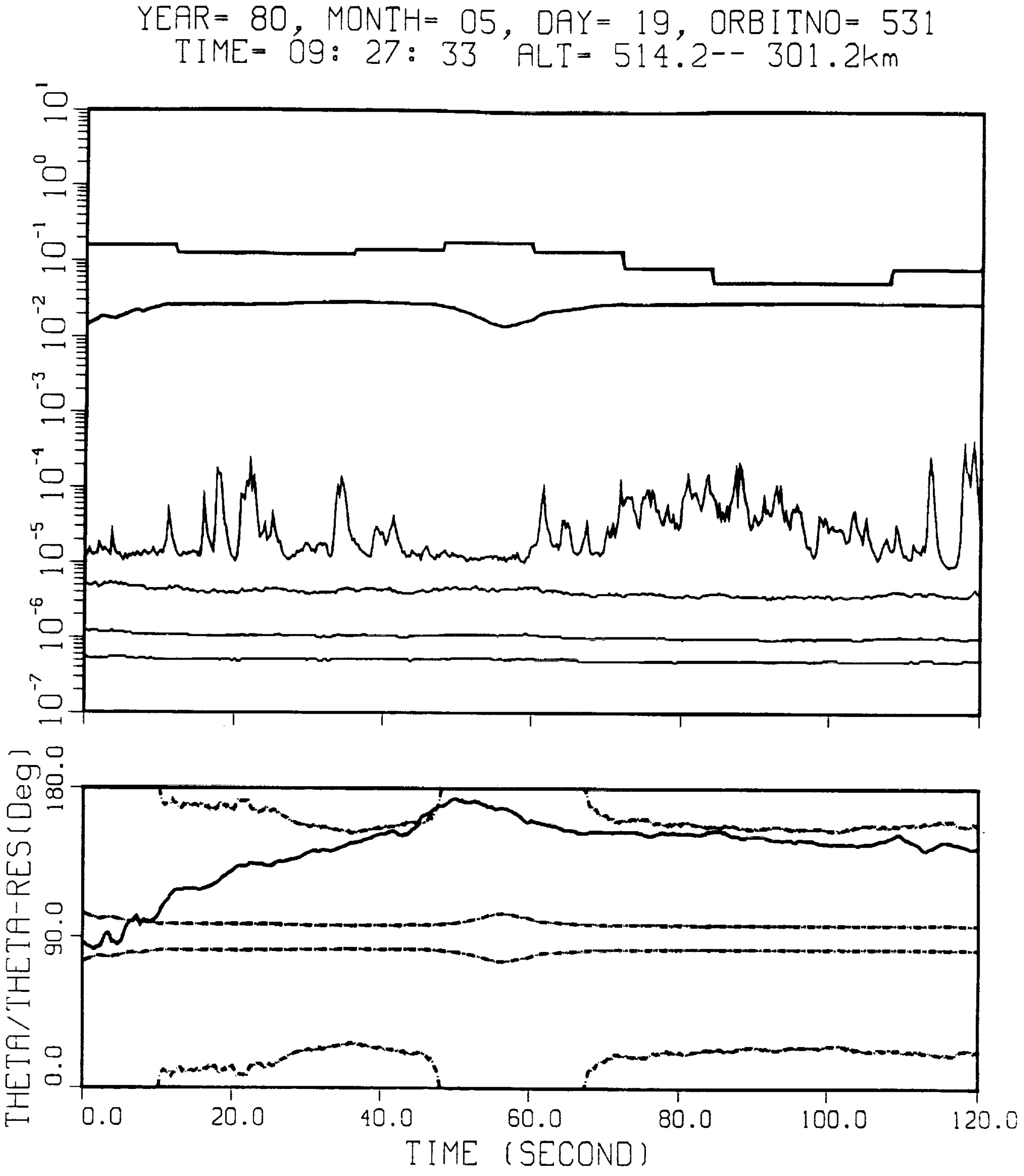

YEAR= 80, MONTH= 05, DAY= 17, ORBITNO= 529
TIME= 09: 42: 07 ALT=1533.8--1709.3km
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
THETA/THETA-RES(Deg)
180.0
90.0
0.0
0.0
8.0
16.0
24.0
32.0
40.0
48.0
TIME (SECOND)

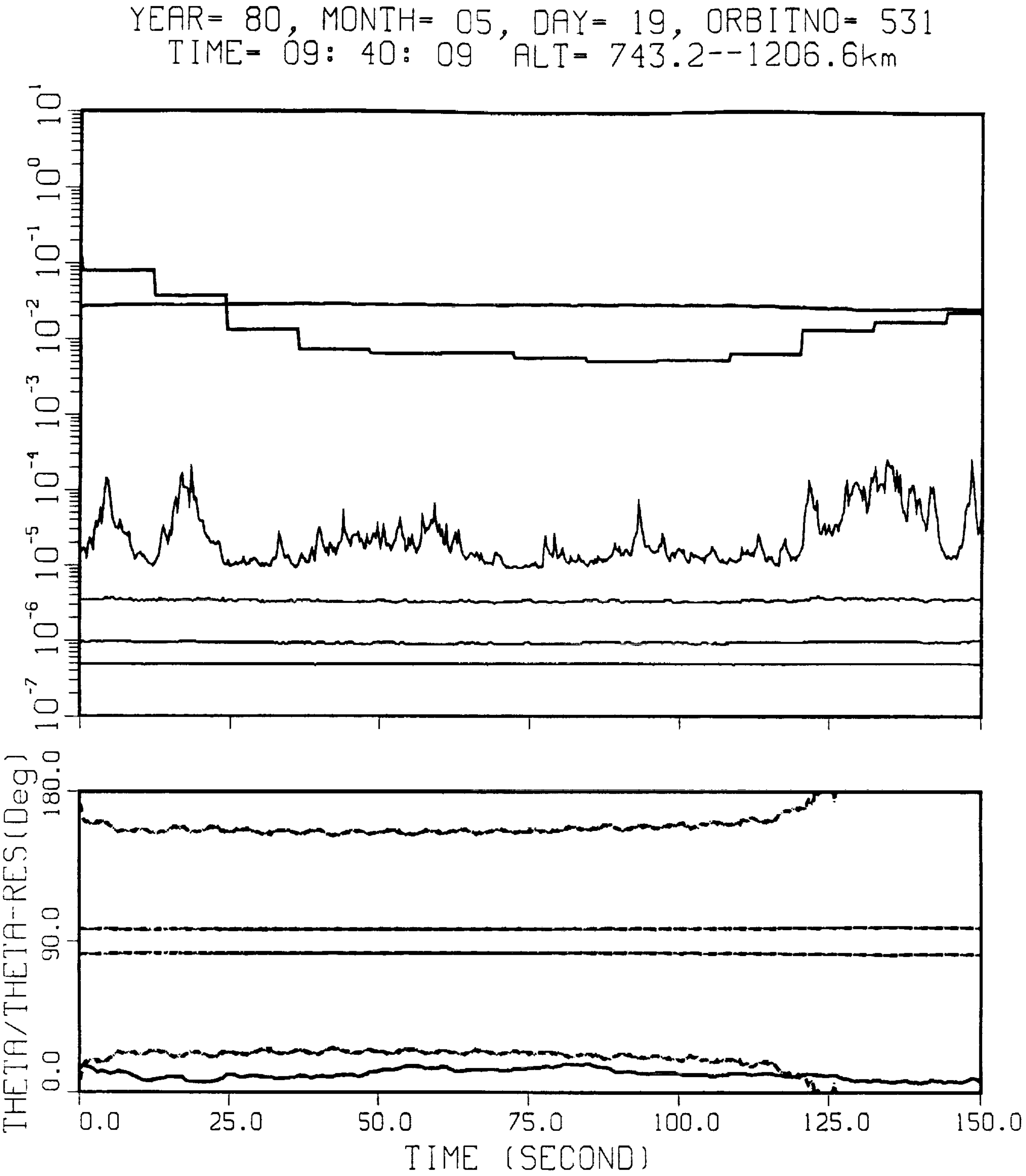
FIGURE 2

(a)


YEAR= 80, MONTH= 05, DAY= 19, ORBITNO= 531
TIME= 09: 29: 33 ALT= 301.2-- 188.4km
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
THETA/THETA-RES(Deg)
180.0
90.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
TIME (SECOND)


YEAR= 80, MONTH= 05, DAY= 19, ORBITNO= 531
TIME= 09: 27: 33 ALT= 514.2-- 301.2km
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
THETA/THETA-RES(Deg)
180.0
90.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
TIME (SECOND)

(b)


YEAR= 80, MONTH= 05, DAY= 19, ORBITNO= 531
TIME= 09: 40: 09 ALT= 743.2--1206.6km
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
THETA/THETA-RES(Deg)
180.0
90.0
0.0
0.0
25.0
50.0
75.0
100.0
125.0
150.0
TIME (SECOND)

(c)

FIGURE 3

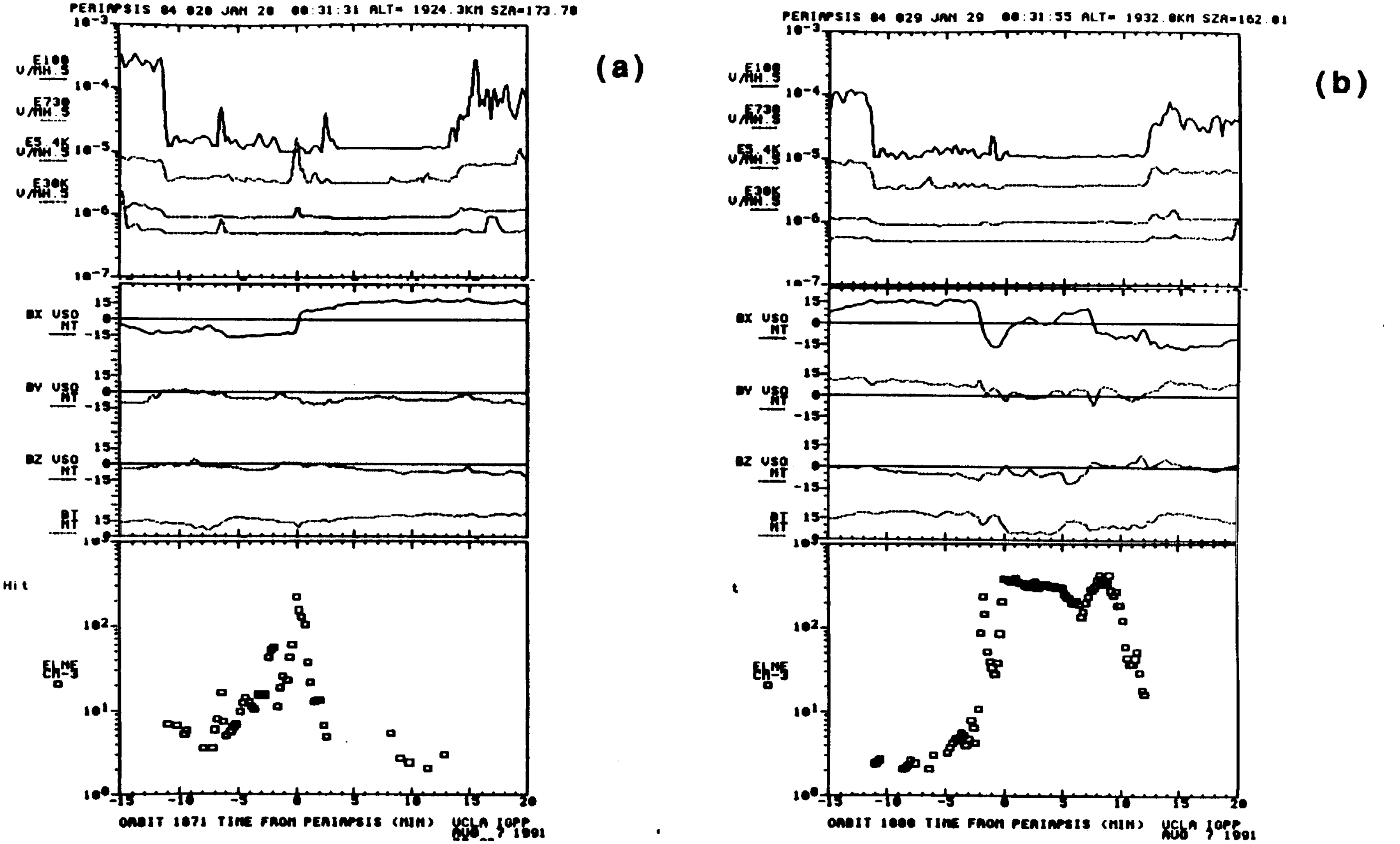

(a)
PERIAPSIS 84 020 JAN 20 00:31:31 ALT= 1924.3KM SZA=173.78
E100 V/MH.S
E730 V/MH.S
E5.4K V/MH.S
E30K V/MH.S
BX VSO NT
BY VSO NT
BZ VSO NT
BT NT
ELNE CM-3
ORBIT 1071 TIME FROM PERIAPSIS (MIN)
UCLA IGPP AUG 7 1991
(b)
PERIAPSIS 84 029 JAN 29 00:31:55 ALT= 1932.0KM SZA=162.01
E100 V/MH.S
E730 V/MH.S
E5.4K V/MH.S
E30K V/MH.S
BX VSO NT
BY VSO NT
BZ VSO NT
BT NT
ELNE CM-3
ORBIT 1080 TIME FROM PERIAPSIS (MIN)
UCLA IGPP AUG 7 1991

FIGURE 4

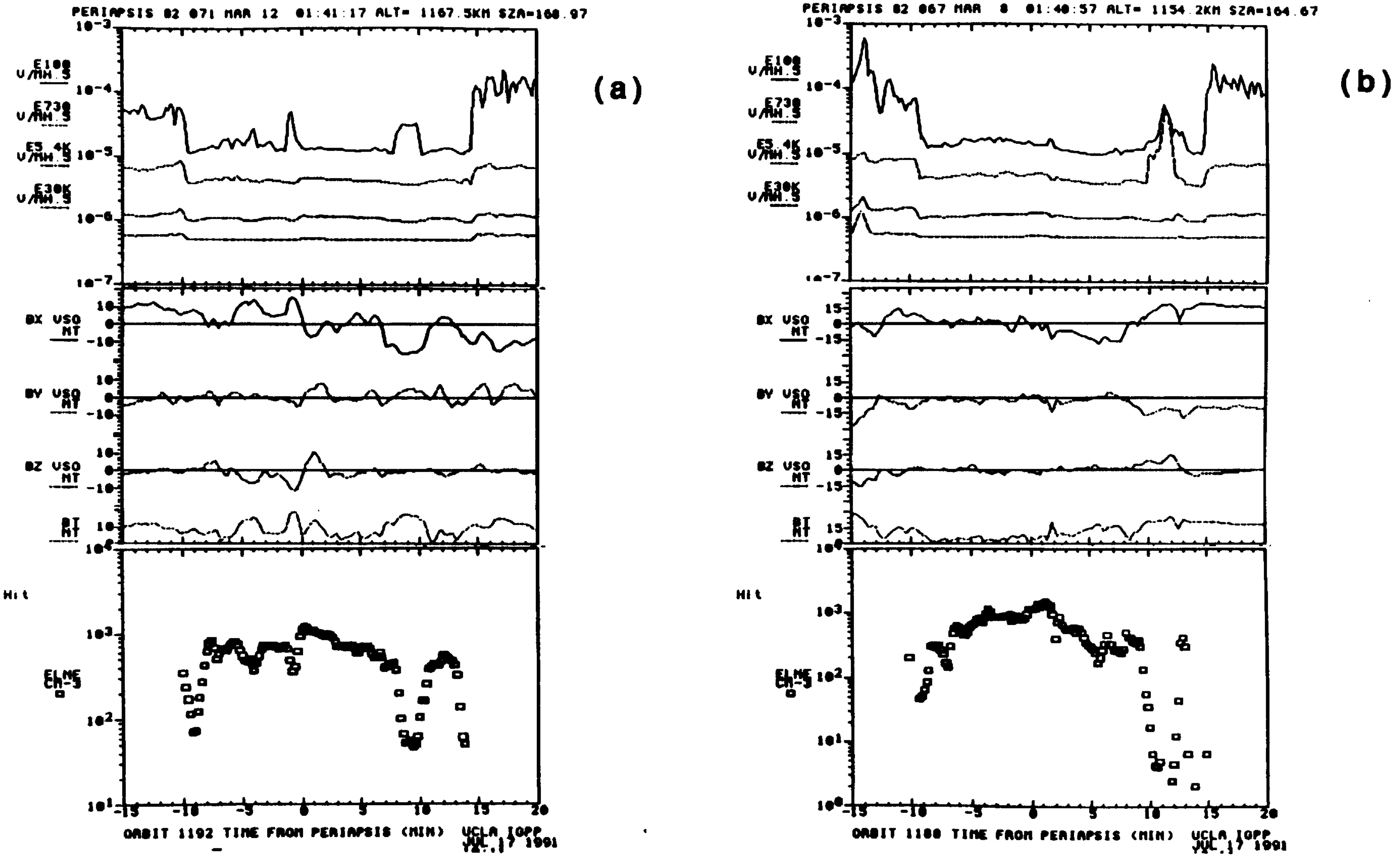

PERIAPSIS 82 071 MAR 12 01:41:17 ALT= 1167.5KM SZA=160.97
(a)
E100 V/MM.S
E730 V/MM.S
E5.4K V/MM.S
E30K V/MM.S
BX VSO NT
BY VSO NT
BZ VSO NT
BT NT
Hit
ELNE CM-3
ORBIT 1192 TIME FROM PERIAPSIS (MIN)
UCLA IGPP JUL 17 1991
PERIAPSIS 82 067 MAR 8 01:40:57 ALT= 1154.2KM SZA=164.67
(b)
ORBIT 1188 TIME FROM PERIAPSIS (MIN)

FIGURE 5

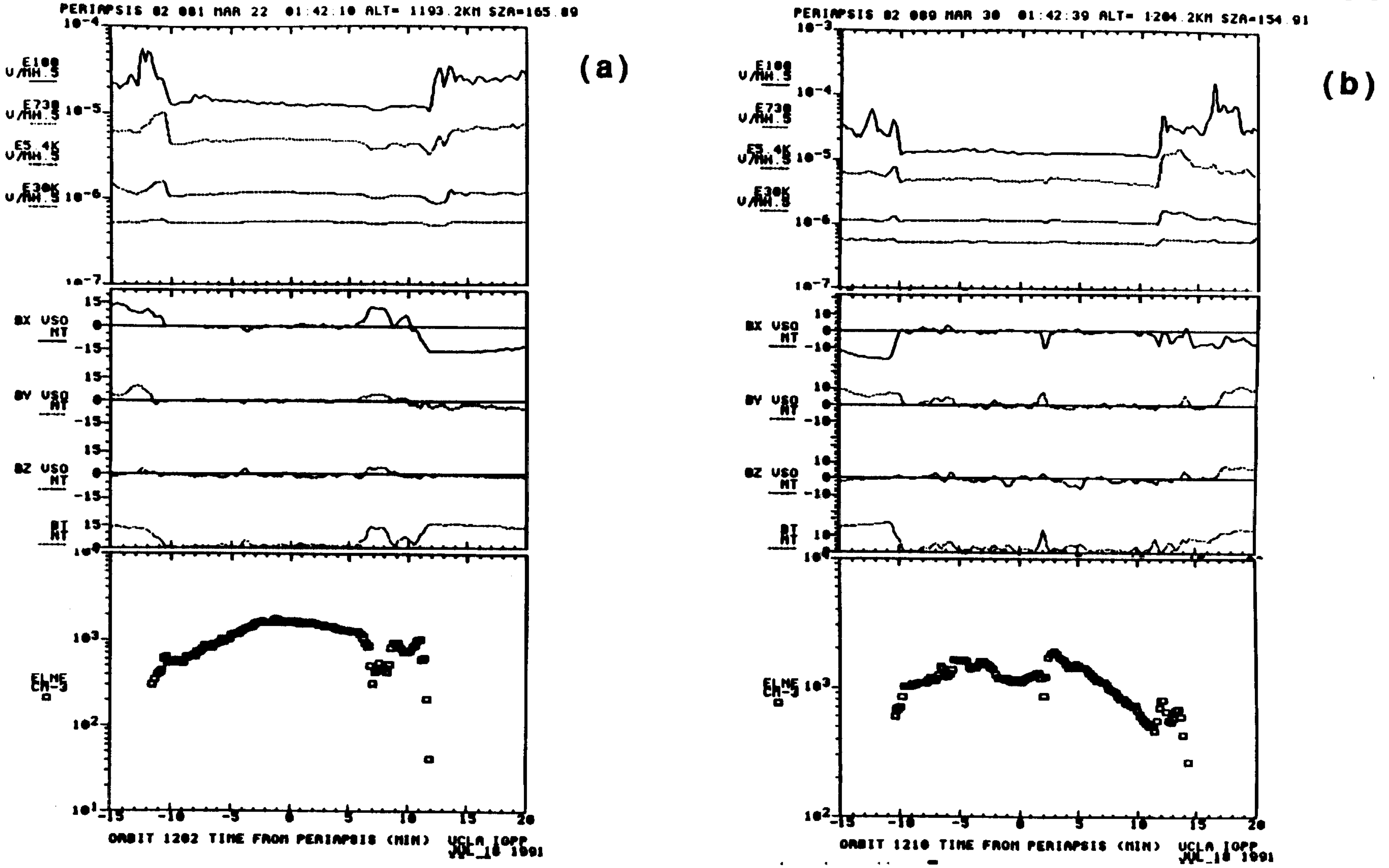

(a)
PERIAPSIS 02 081 MAR 22 01:42:10 ALT= 1193.2KM SZA=165.89
E100 V/M/H.5
E730 V/M/H.5
E5.4K V/M/H.5
E30K V/M/H.5
10-4
10-5
10-6
10-7
BX VSO NT
BY VSO NT
BZ VSO NT
BT NT
15
0
-15
ELNE CM-3
10^3
10^2
10^1
-15
-10
-5
0
5
10
15
20
ORBIT 1202 TIME FROM PERIAPSIS (MIN)
UCLA IGPP JUL 18 1991
(b)
PERIAPSIS 02 089 MAR 30 01:42:39 ALT= 1204.2KM SZA=154.91
E100 V/M/H.5
E730 V/M/H.5
E5.4K V/M/H.5
E30K V/M/H.5
10-3
10-4
10-5
10-6
10-7
BX VSO NT
BY VSO NT
BZ VSO NT
BT NT
10
0
-10
ELNE CM-3
10^3
10^2
ORBIT 1210 TIME FROM PERIAPSIS (MIN)
UCLA IGPP JUL 18 1991

FIGURE 6

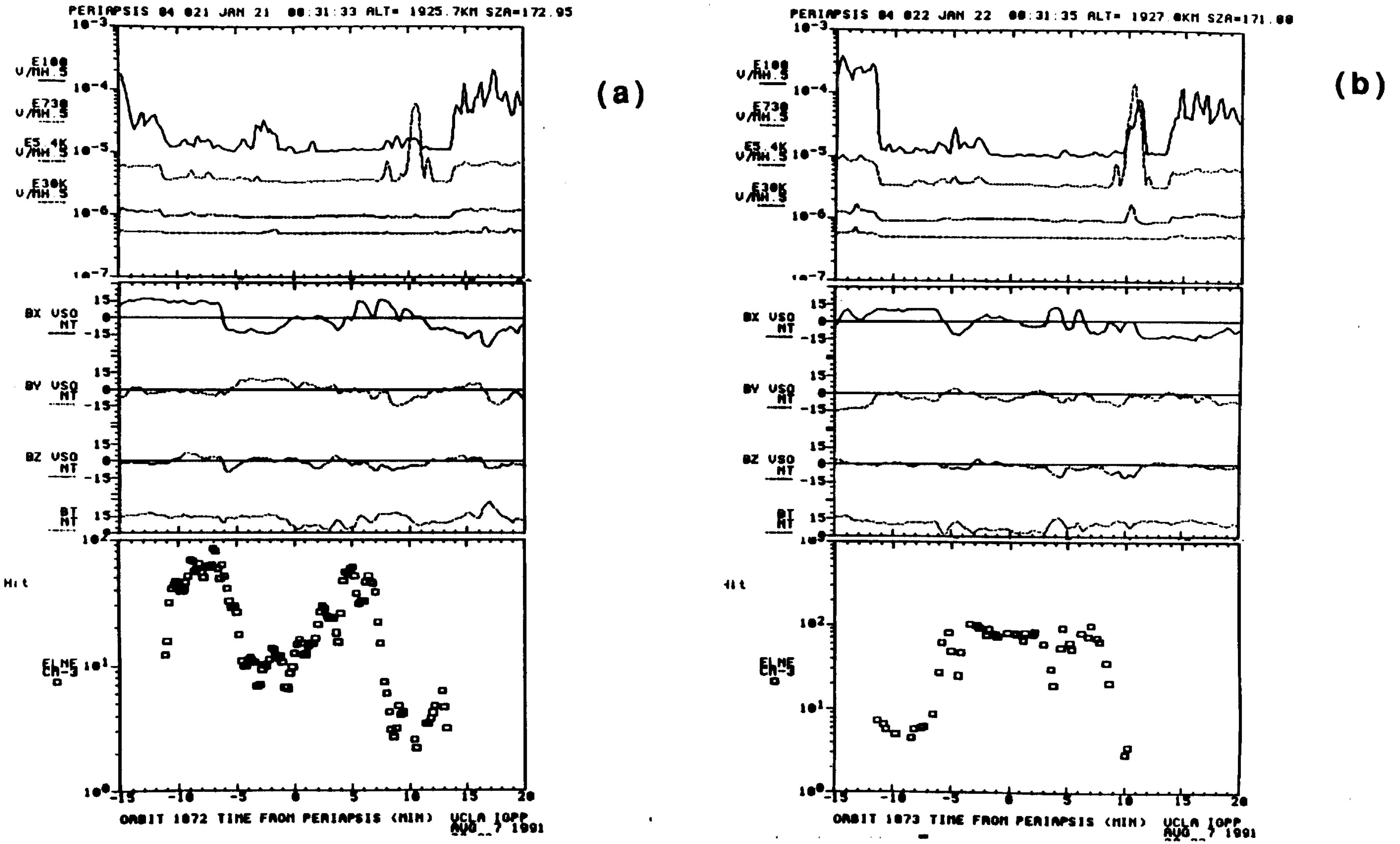
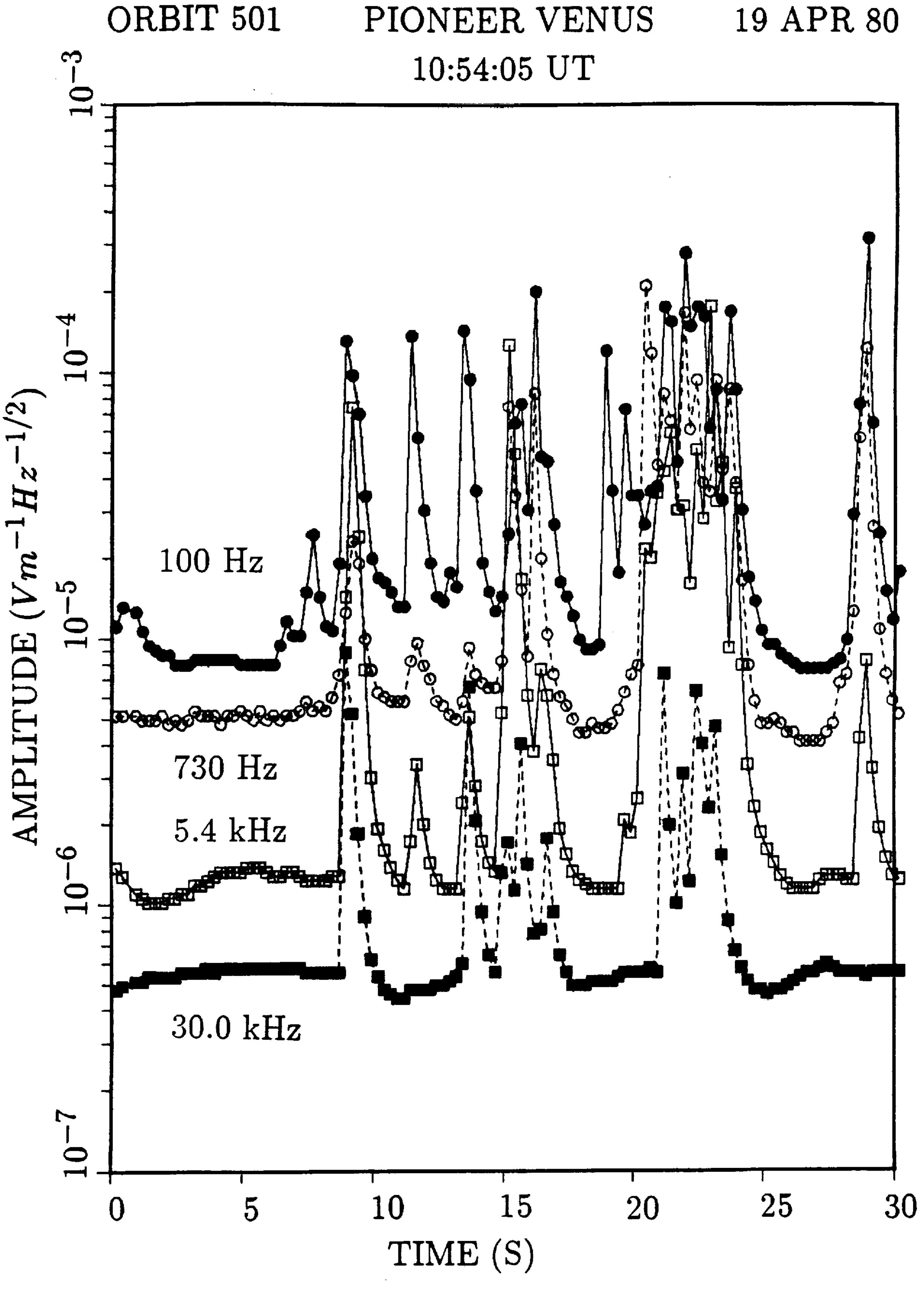

PERIAPSIS 84 021 JAN 21 00:31:33 ALT= 1925.7KM SZA=172.95
E100 V/MH.5
E730 V/MH.5
E5.4K V/MH.5
E30K V/MH.5
10-3
10-4
10-5
10-6
10-7
BX VSO NT
BY VSO NT
BZ VSO NT
BT NT
15
0
-15
ELNE CM-3
10^2
10^1
10^0
-15
-10
-5
0
5
10
15
20
ORBIT 1072 TIME FROM PERIAPSIS (MIN)
UCLA IOPP AUG 7 1991
(a)
PERIAPSIS 84 022 JAN 22 00:31:35 ALT= 1927.0KM SZA=171.00
ORBIT 1073 TIME FROM PERIAPSIS (MIN)
UCLA IOPP AUG 7 1991
(b)

FIGURE 7



PLOT 1 13.00.49 FRI 21 JUL, 1989 JOB-7VTA173:, STAR LAB DISSPLA 10.5

Attachment A

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Testing Radio Bursts Observed on the Nightside of Venus for Evidence of Whistler Mode Propagation From Lightning

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Radio burst events recorded on the nightside of Venus by the orbiting electric field detector (OEFD) on Pioneer Venus Orbiter (PVO) have been interpreted as originating in subionospheric lightning. This lightning source interpretation has been subject to repeated challenges. During many of the burst observations, activity occurred in the lowest, or 100 Hz, filter band channel only, while in a smaller number of cases, activity occurred at two or more of the four filter band frequencies 100 Hz, 730 Hz, 5.4 kHz, and 30 kHz. Previous work with the data has been primarily statistical in nature. In some studies, only events with activity limited to the 100-Hz channel were considered; 100 Hz had been found to be lower than typical values (~100-1000 Hz) of the ambient electron gyrofrequency, and such cases appeared to be candidates for whistler mode propagation from lightning sources to the satellite. In general it was recognized that if the higher-frequency signals were of subionospheric origin, their observation from PVO would require an ionospheric penetration mechanism other than the conventional one associated with excitation of the cold plasma whistler mode at the lower ionospheric boundary. In the present work, methods have been developed for testing the hypothesis that particular burst events were the result of whistler mode propagation of signals from subionospheric lightning sources. The tests allow prediction of the resonance cone angle, wave normal direction, refractive index, wave dispersion, and wave polarization and are believed to represent an improved way of categorizing OEFD burst data for purposes of investigating source/propagation mechanisms. The tests, which are capable of refinement, were applied to observations from 11 periods along seven orbits. Most of these cases had been illustrated in the literature in support of conflicting interpretations of the observations. The key wave normal test was applied to each of the 11 cases, and the dispersion and polarization tests were also applied to the limited extent that the properties of the particular data sets would permit. The results obtained from the limited data sample indicate that there are at least two main categories of burst events, one for which the assumed vertical wave normal angle was within the allowed cone of angles for whistler mode propagation and one for which this was not the case. Lightning is thus considered to be a candidate source for at least some of the OEFD bursts. Its further assessment as a source must await studies of additional events and, in particular, examination of cases to which the more stringent dispersion and polarization tests can be applied. Four of the five burst events that were found to be inconsistent with the hypothesis of whistler mode propagation from lightning involved receptions at multiple OEFD filter band frequencies, while one involved 100 Hz only. A search for the cause of such events should include possible mechanisms of ionospheric wave penetration at frequencies both above and below the gyrofrequency, as well as plasma instability mechanisms local to the spacecraft.

1. INTRODUCTION

A spirited and now protracted debate has arisen in the literature over the extent to which certain wave bursts observed on the nightside of Venus from the Pioneer Venus Orbiter (PVO) can be interpreted as evidence of lightning in the Venusian atmosphere [*Russell et al.*, 1988*a*, *b*, 1989*a*, *b*; *Russell*, 1989; *Scarf et al.*, 1987; *Scarf and Russell*, 1988; *Taylor and Cloutier*, 1986, 1988; *Taylor et al.*,1985, 1988, 1989]. A key element in the debate is the fact that the orbiting electric field detector (OEFD) on PVO was limited by telemetry considerations to the measurement of signals within four narrow (~30%) frequency bands centered at 100 Hz, 730 Hz, 5.4 kHz, and 30 kHz. That limitation precluded the type of wideband spectrum analysis that in the Earth's environment has permitted researchers to distinguish relatively easily between signals of lightning origin and others that appear to originate in plasma instabilities of various kinds. Lacking the desired wideband information, the OEFD investigators designed their instrument so that, under the plasma conditions that were expected to prevail at Venus, there could be at least a limited registration of signals that might propagate to the spacecraft from lightning sources [*Taylor et al.*, 1979; *Scarf et al.*, 1980]. In particular, the lowest frequency channel was set at 100 Hz, a frequency expected to be low enough to propagate through the Venusian ionosphere in the so-called whistler mode.

The debate thus far has been dominated by the results of statistical studies [*Russell et al.*, 1988*a*, *b*, *c*; *Scarf et al.*, 1987; *Taylor et al.*, 1985, 1989; *Scarf and Russell*,1983, 1988; *Taylor and Cloutier*,1987, 1988; *Singh and Russell*, 1986; *Russell*, 1989], although attention has also been given to details of the instrument response to wave bursts [*Taylor et al.*, 1979; *Scarf et al.*, 1980; *Taylor and Cloutier*, 1988], to

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