1999 CEDAR Workshop
Boulder, Colorado
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Tutorial Lecture

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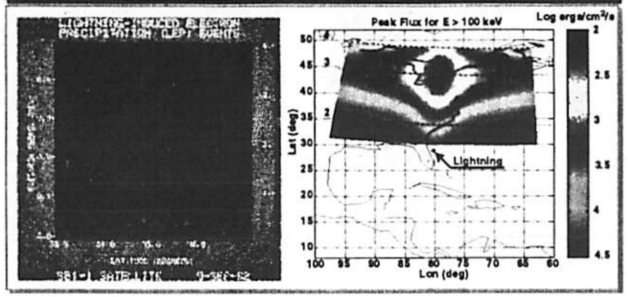
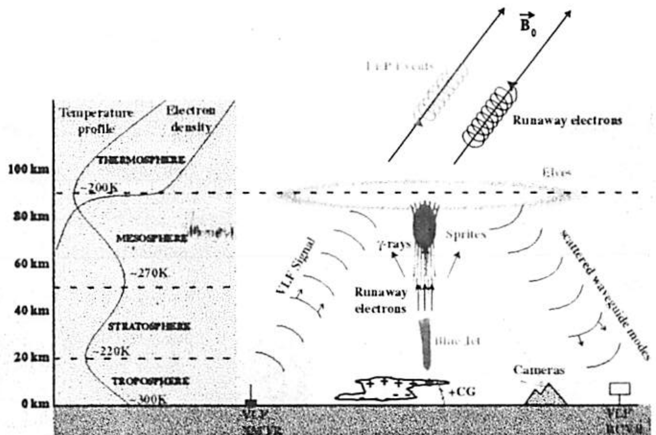
Transient Disturbances in the Nighttime Lower Ionosphere

Recently Discovered Phenomena in the Earth's Upper Atmosphere

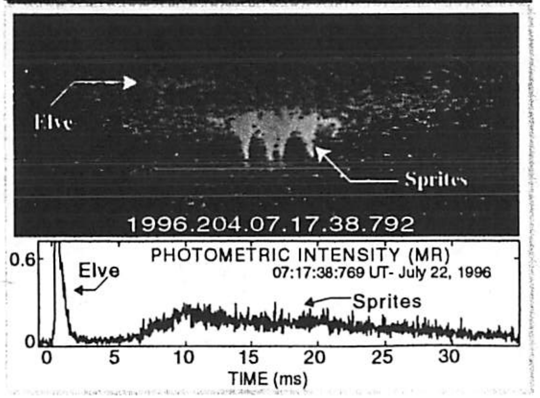
(a) LIGHTNING-INDUCED ELECTRON PRECIPITATION
Left: Energetic electron bunches precipitated by lightning-induced whistler waves.
Right: Calculated footprint of energy deposited by electrons precipitated by a whistler from a single lightning flash.

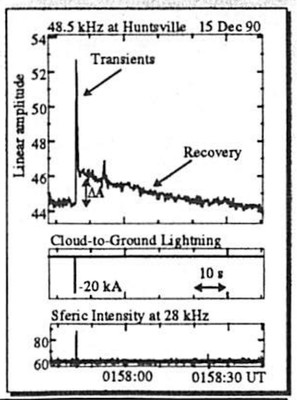


(b) SPRITES
Luminous glows occuring at altitudes ranging from ~50 to 90 km, and exhibiting red color at their top which gradually changes to blue at lower altitudes.

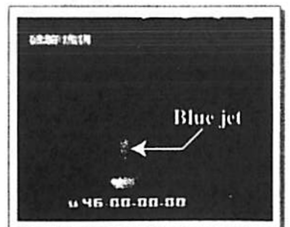


(c) ELVES
Lighting-induced ionospheric flashes, lasting ~1 ms and having a lateral extent of >300 km.





(d) EARLY/FAST VLF EVENTS
Sudden (i.e. 'fast' < 20 ms) subionospheric VLF signal changes, occuring simultaneously (i.e. 'early', < 20 ms) with lightning discharges, and produced by the scattering of the VLF signal from the disturbed region.



(e) BLUE JETS
Upward moving (~100 km/s) highly collimated beams of luminosity, emanating from tops of thunderclouds, extending up to ~50 km altitude and exhibiting primarily blue color.

(f) TERRESTRIAL GAMMA-RAY FLASHES
High-energy photons of atmospheric origin, detected by the BATSE detectors on the Compton Gamma-Ray Obsevatory (CGRO).

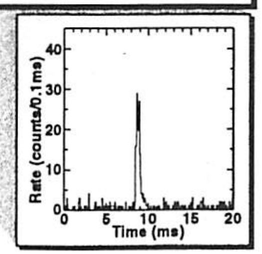
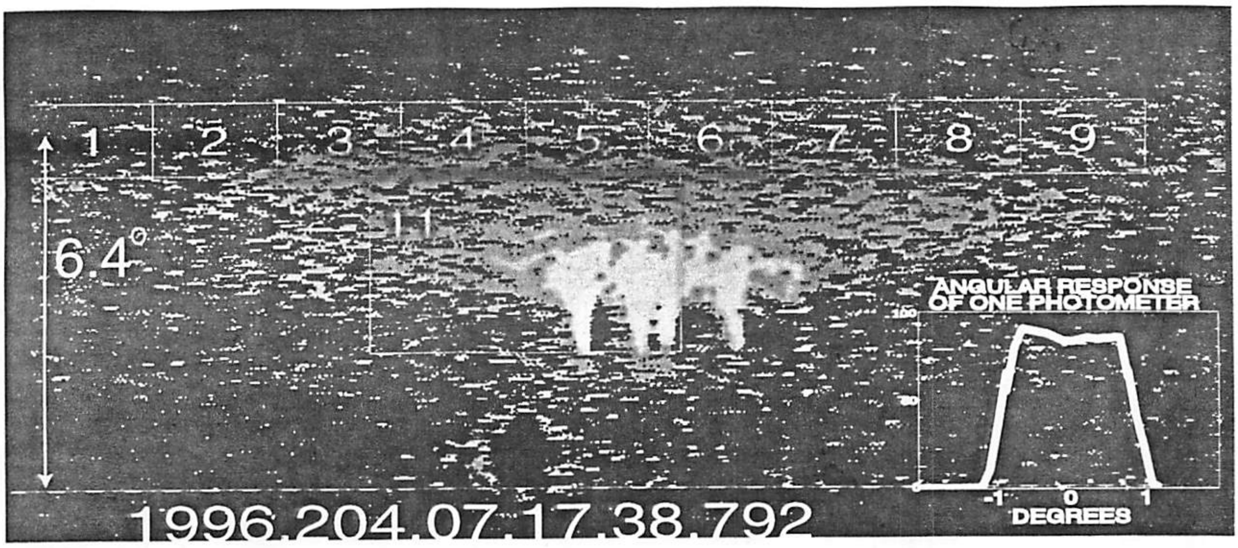
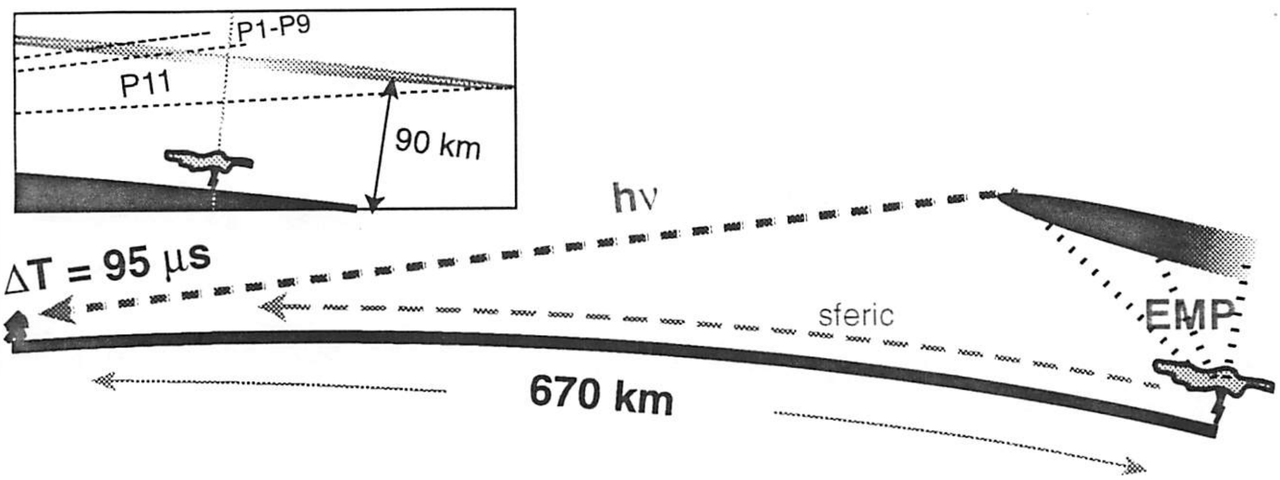
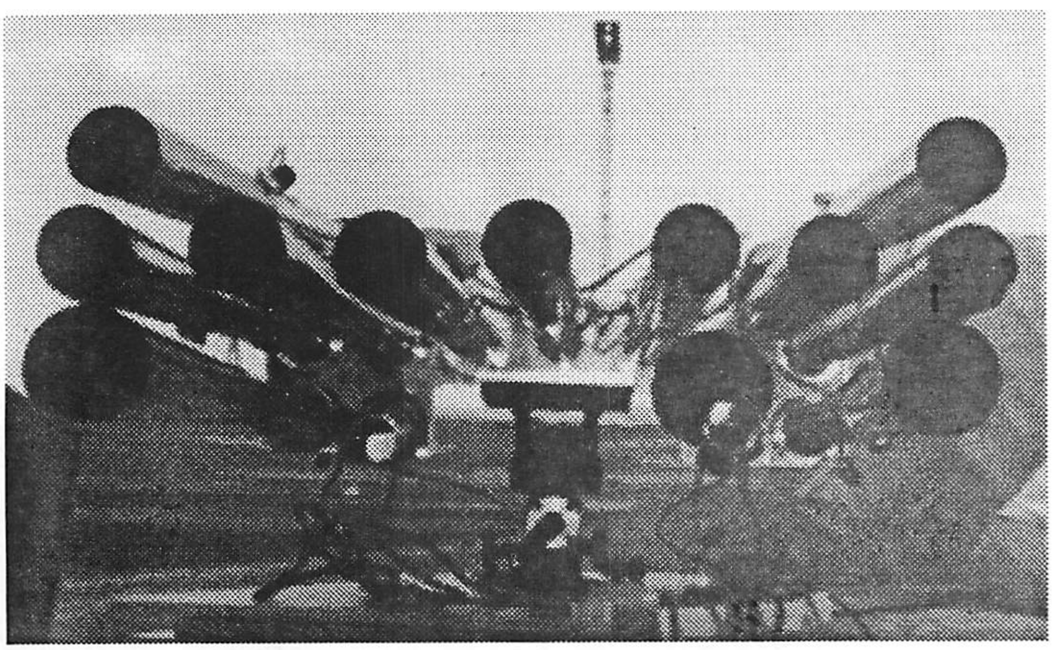
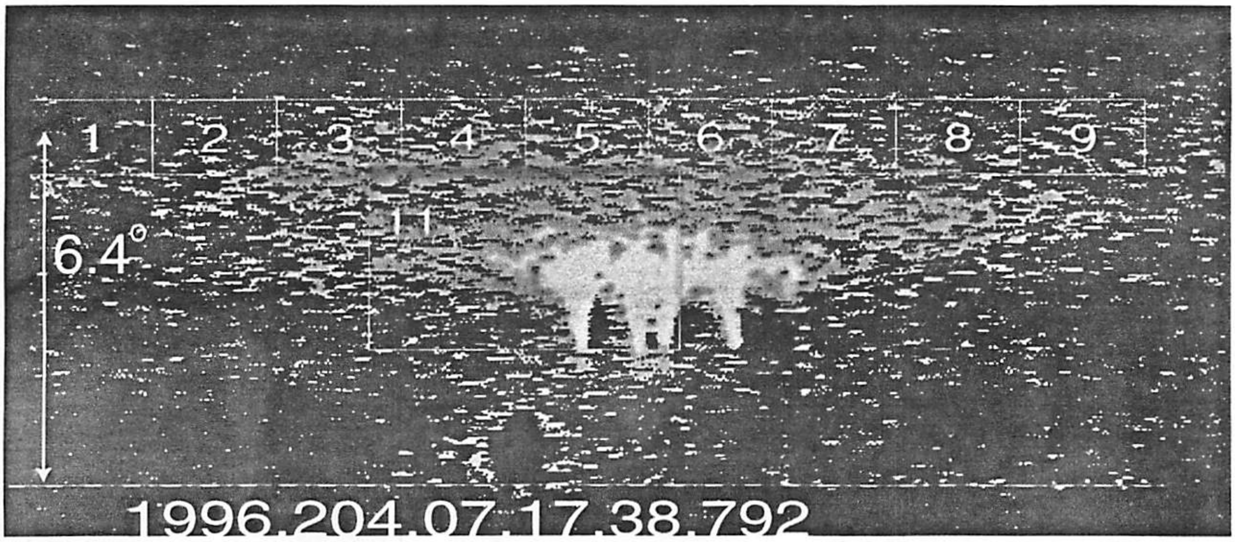


Figure 2

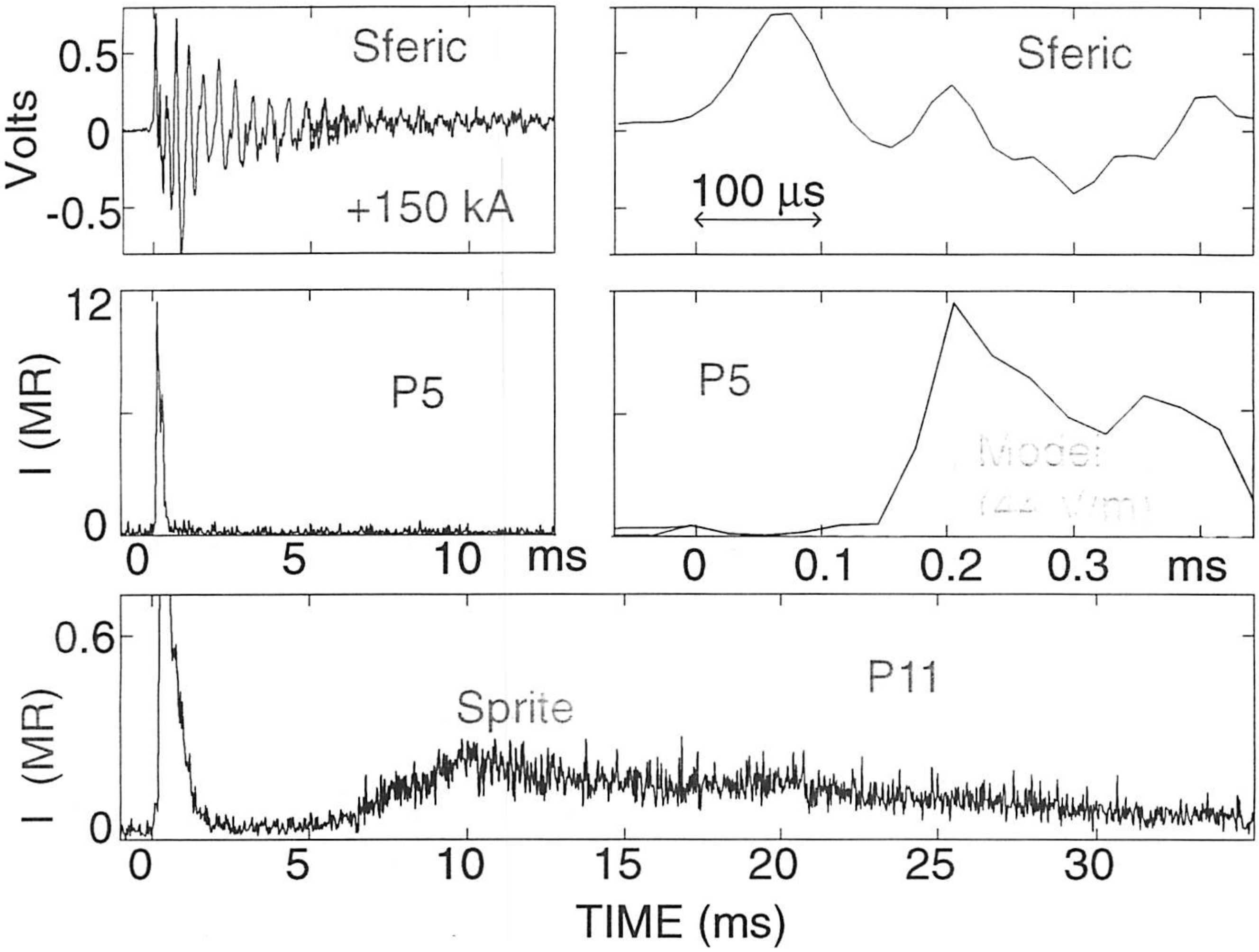

1 2 3 4 5 6 7 8 9
6.4°
11
ANGULAR RESPONSE OF ONE PHOTOMETER
-1 0 1
DEGREES
1996.204.07.17.38.792

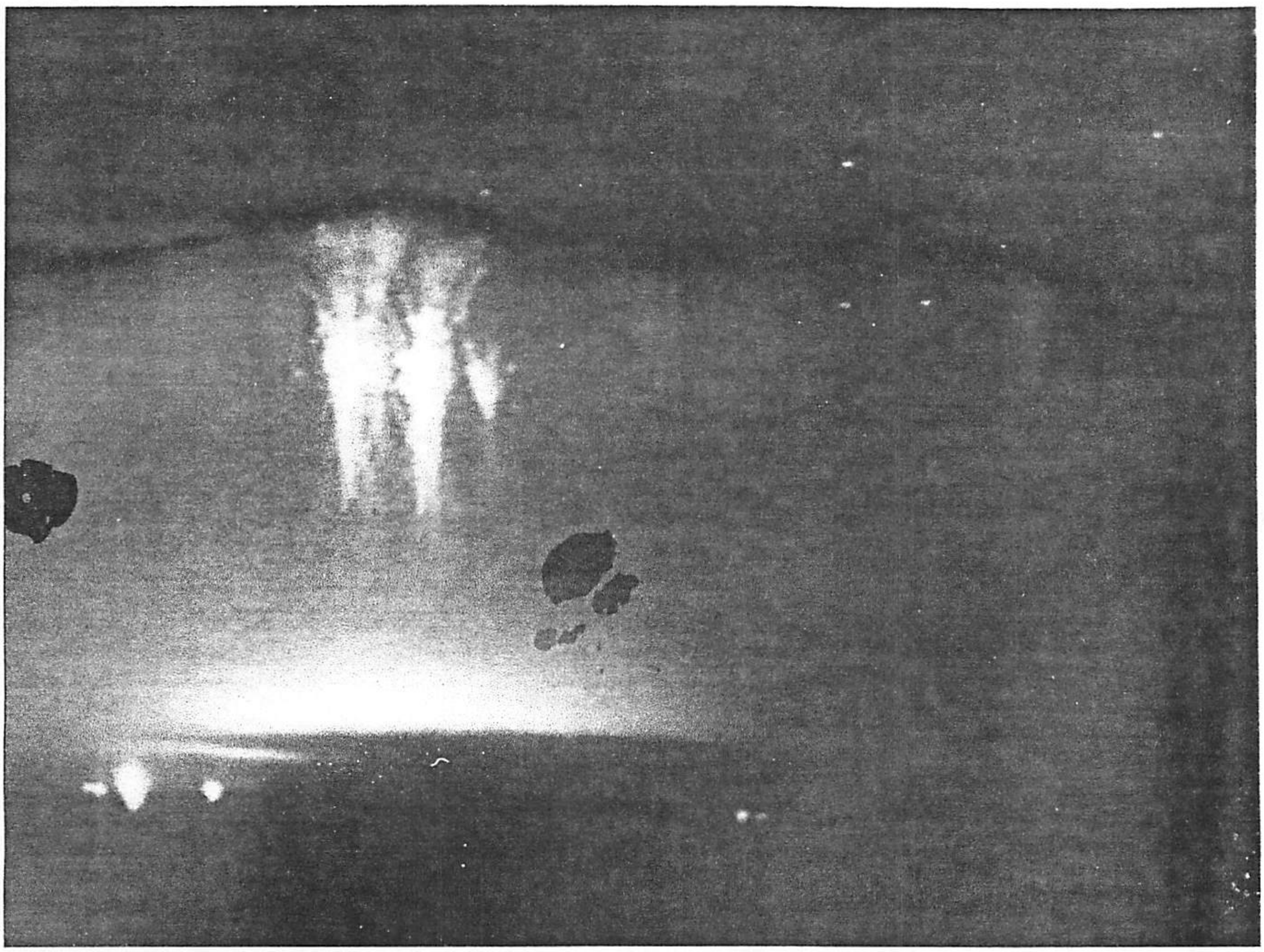

P1-P9
P11
90 km
hν
ΔT = 95 μs
sferic
EMP
670 km



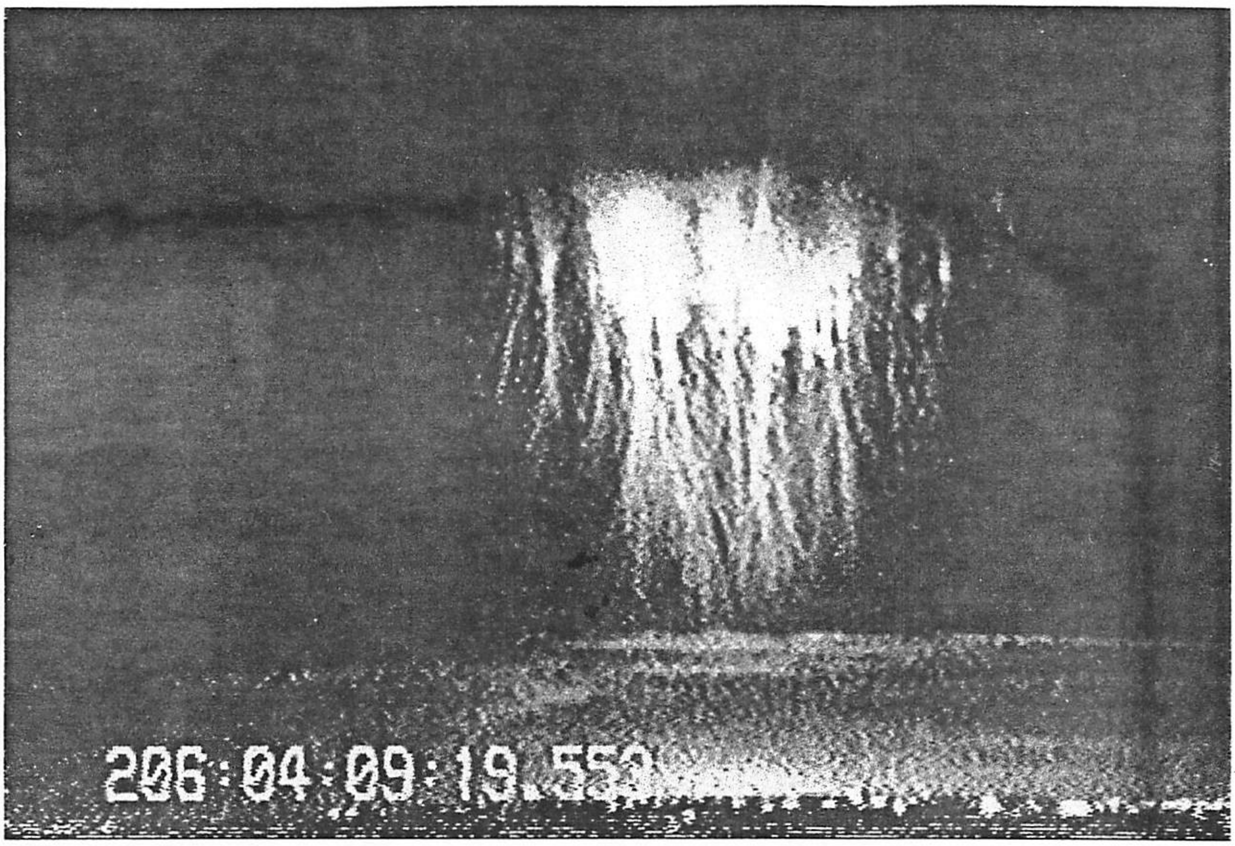


EVENT 07:17:38:769 - July 22, 1996





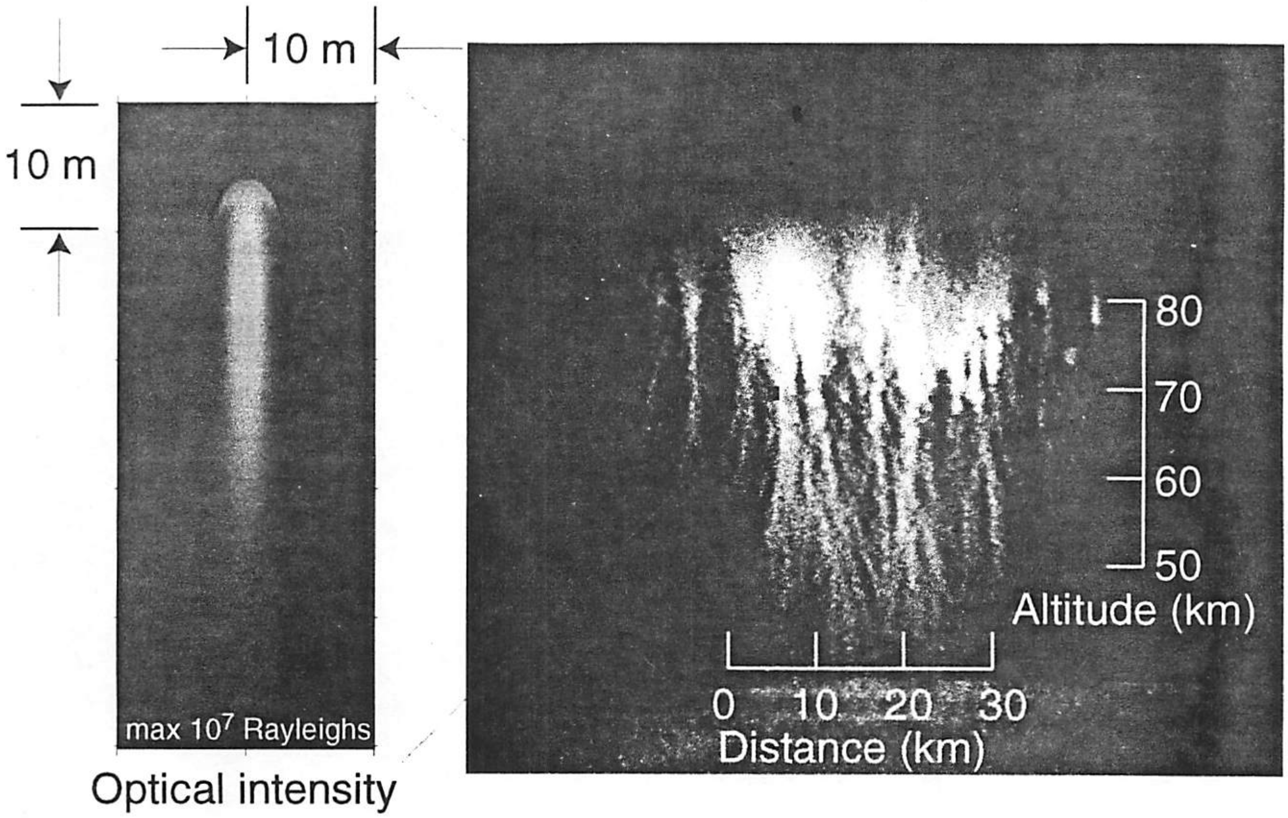
Visual accounts of glows in clear air above thunderstorms have appeared in the literature since the 19th century, the most vivid accounts being those by air transport pilots [*Vaughan and Vonnegut*, 1989]. The possibility of 'upward' lightning or 'lightning to the ionosphere' was seriously considered [*Wilson*, 1925; *Vonnegut*, 1980; *Vaughan and Vonnegut*, 1982] long before what is now known as sprites were first documented in video [*Franz et al.*, 1990]. The discovery of these elusive lights high in the sky have captured the imagination of the scientific community and the public, with over 1000 articles appearing in newspapers and popular magazines worldwide (see Section 2.1). These new findings have brought to fore fundamental questions concerning the nature of the electrodynamic coupling between thunderclouds and the upper atmosphere.


206:04:09:19.55


206:05:30:31.131

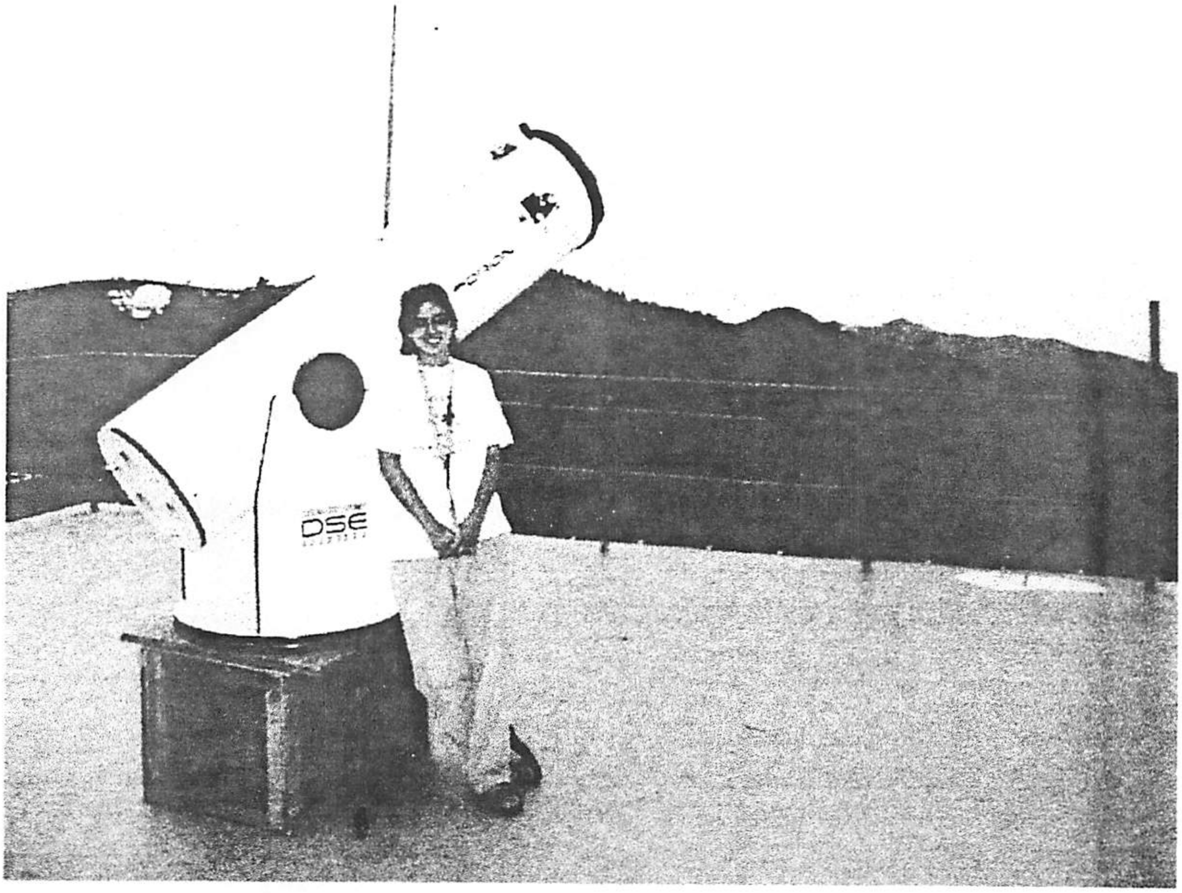
Small Scale Structure of Sprites

Proposed mechanism [*Pasko et al.*, 1998]:

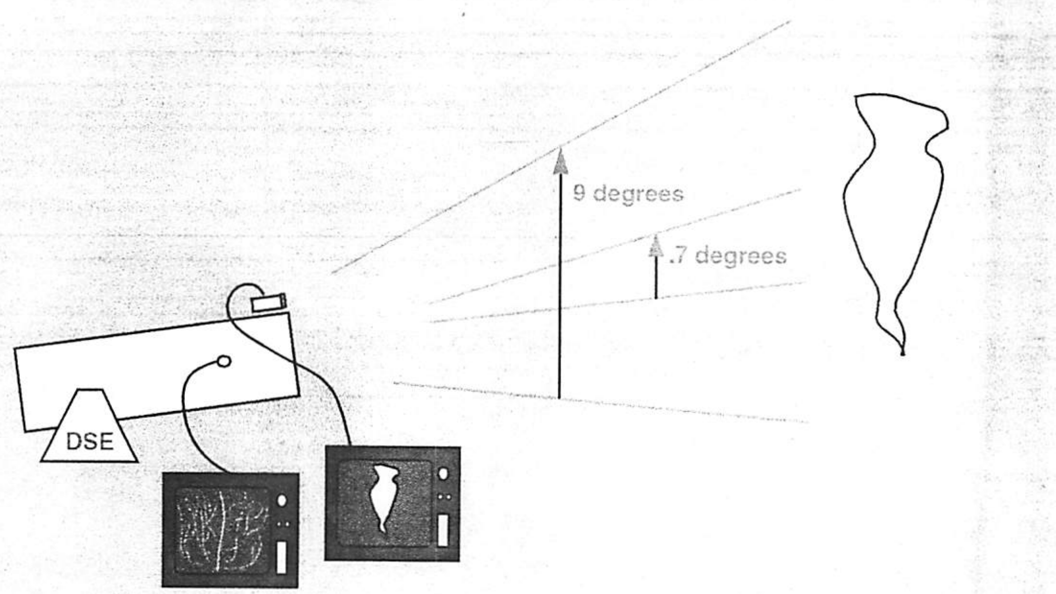


Right panel: A bright sprite event observed with Lockheed video camera on the night of July 24, 1996 during Fly's Eye observational program of Stanford University.
Left panel: Recent theoretical results of *Pasko et al.* [1998] suggest that sprites consist of thousands of ionization channels (streamers) having primarily red color and emitting strong blue emissions from their tips.

Inan



FIELDS OF VIEW OF SPOTTER CAMERA AND TELESCOPE



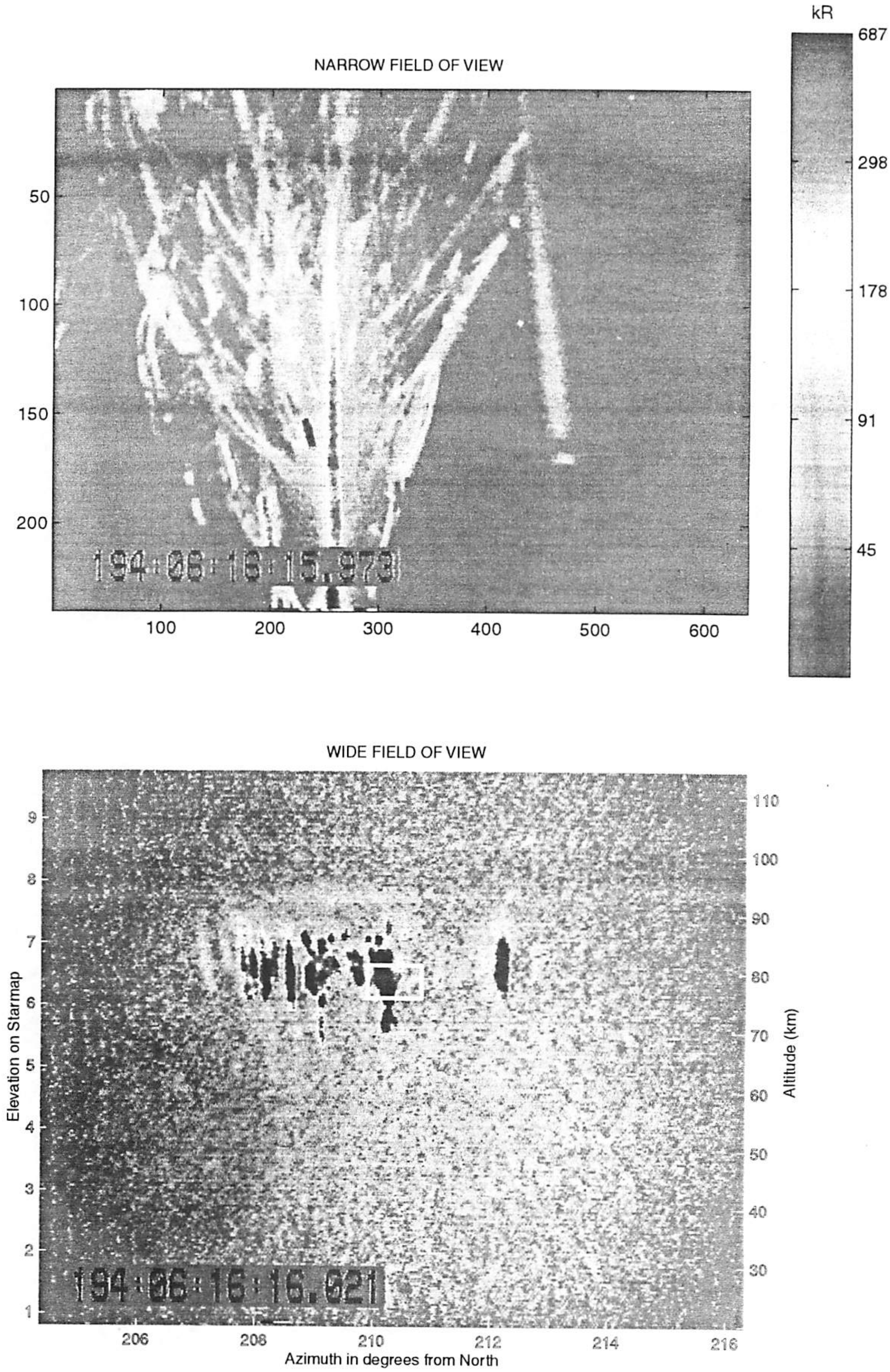


figure 2: July 13 sprite. NLDN data: 213deg, 589km, 45kA

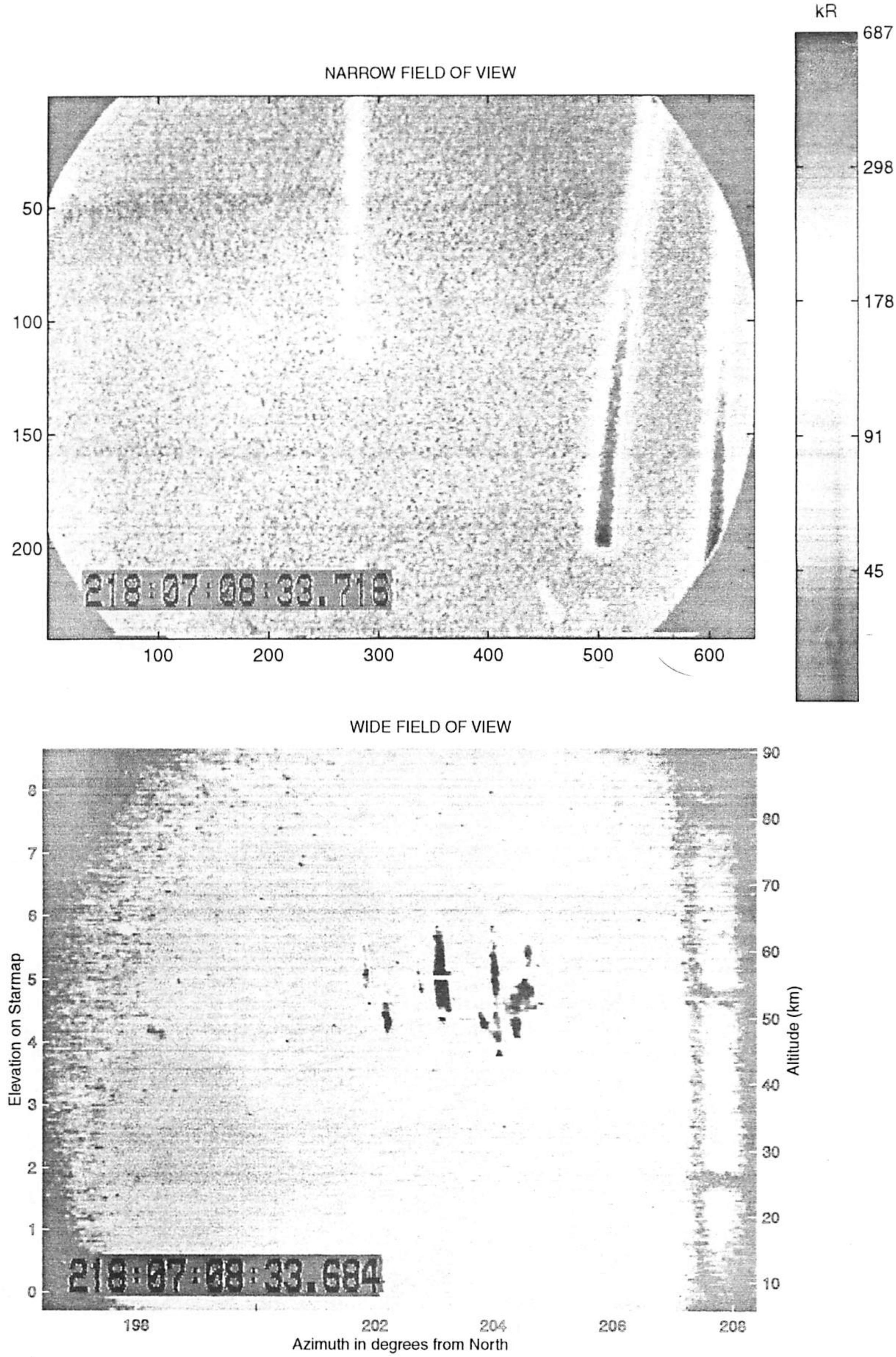


figure 4: August 6 sprite, NLDN data: 207degrees azimuth, 534km range, 71kA

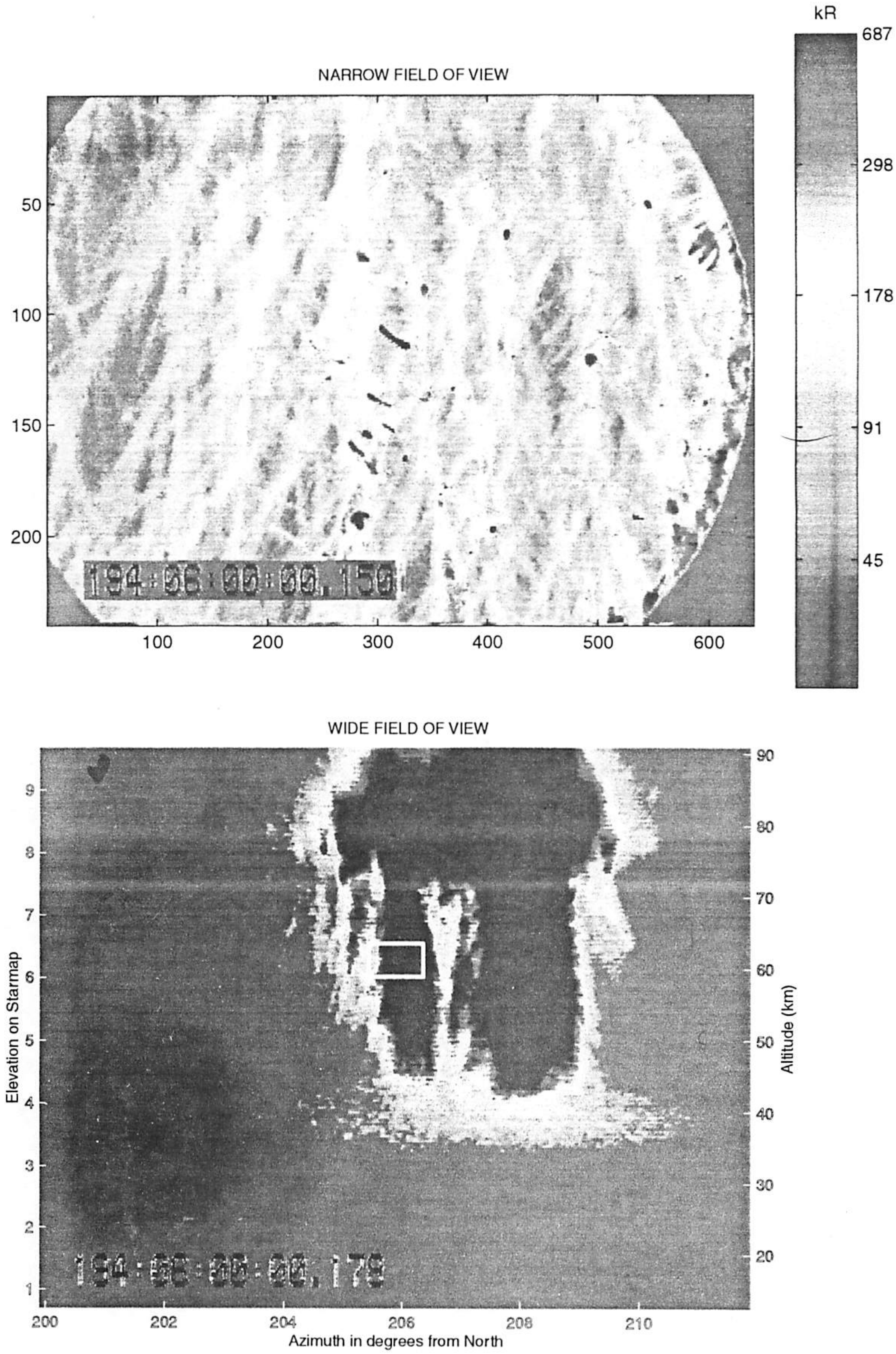
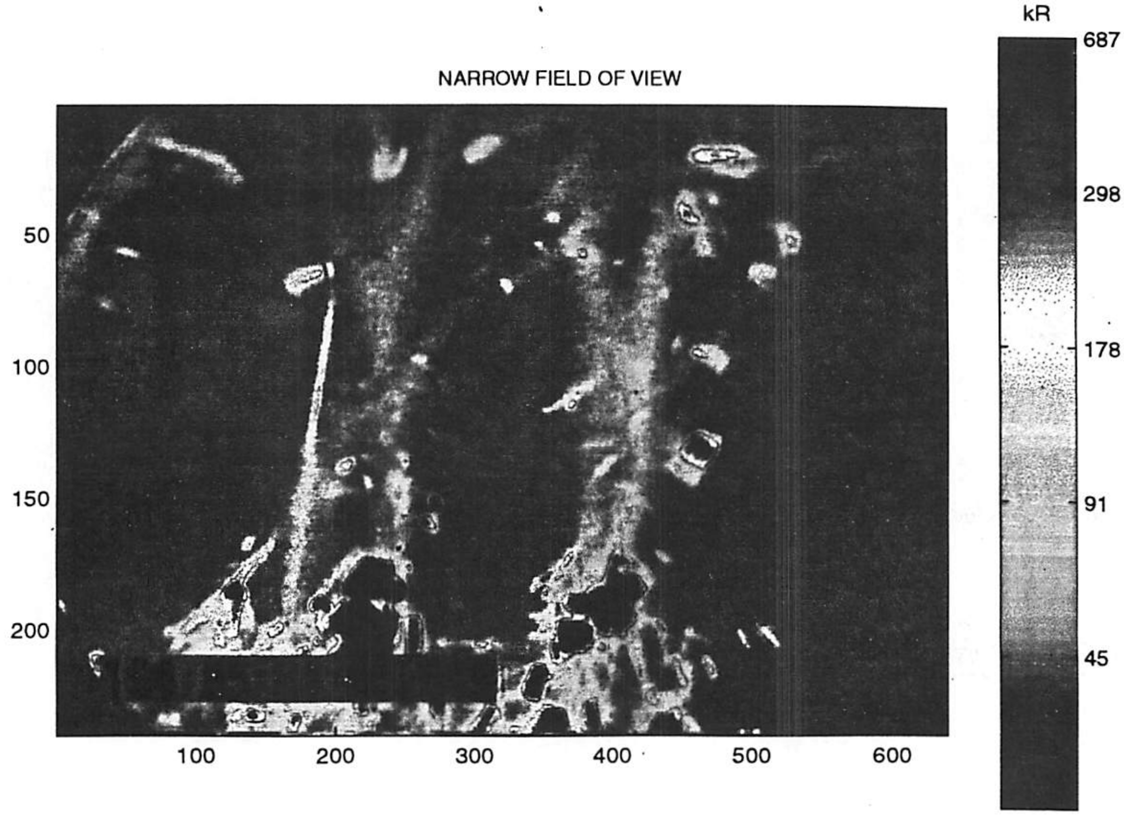


figure 3: July 13 sprite. NLDN data: .212degrees azimuth, 491km range,119kA



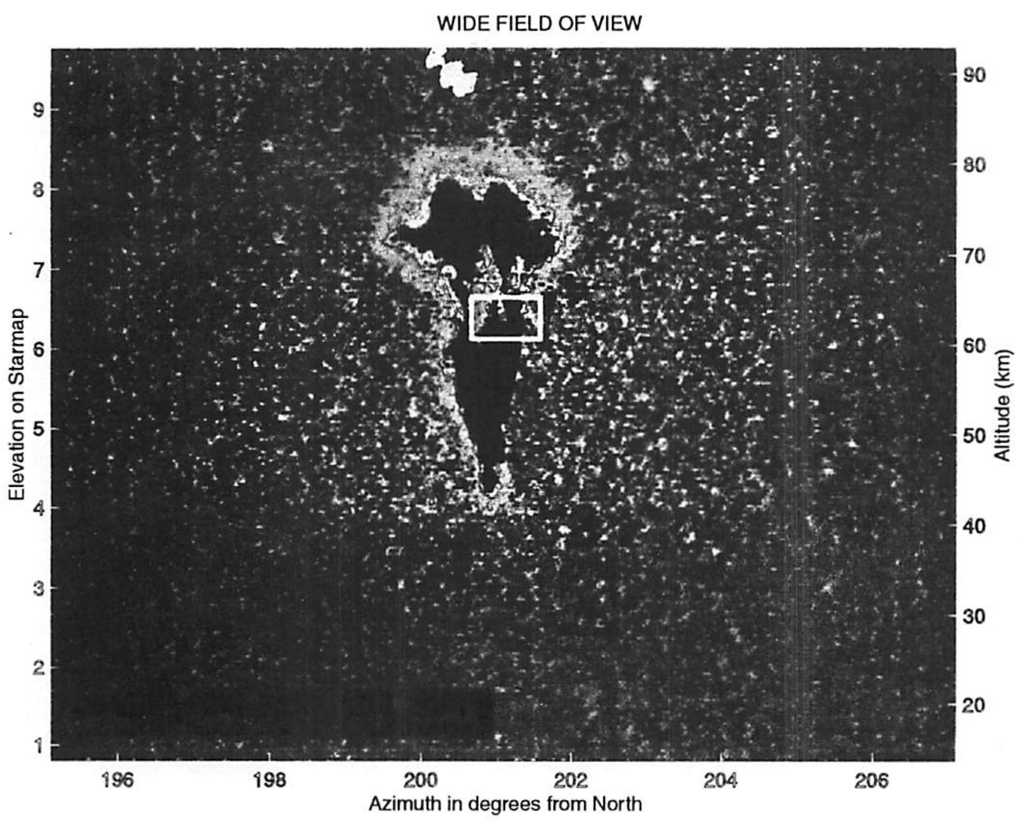
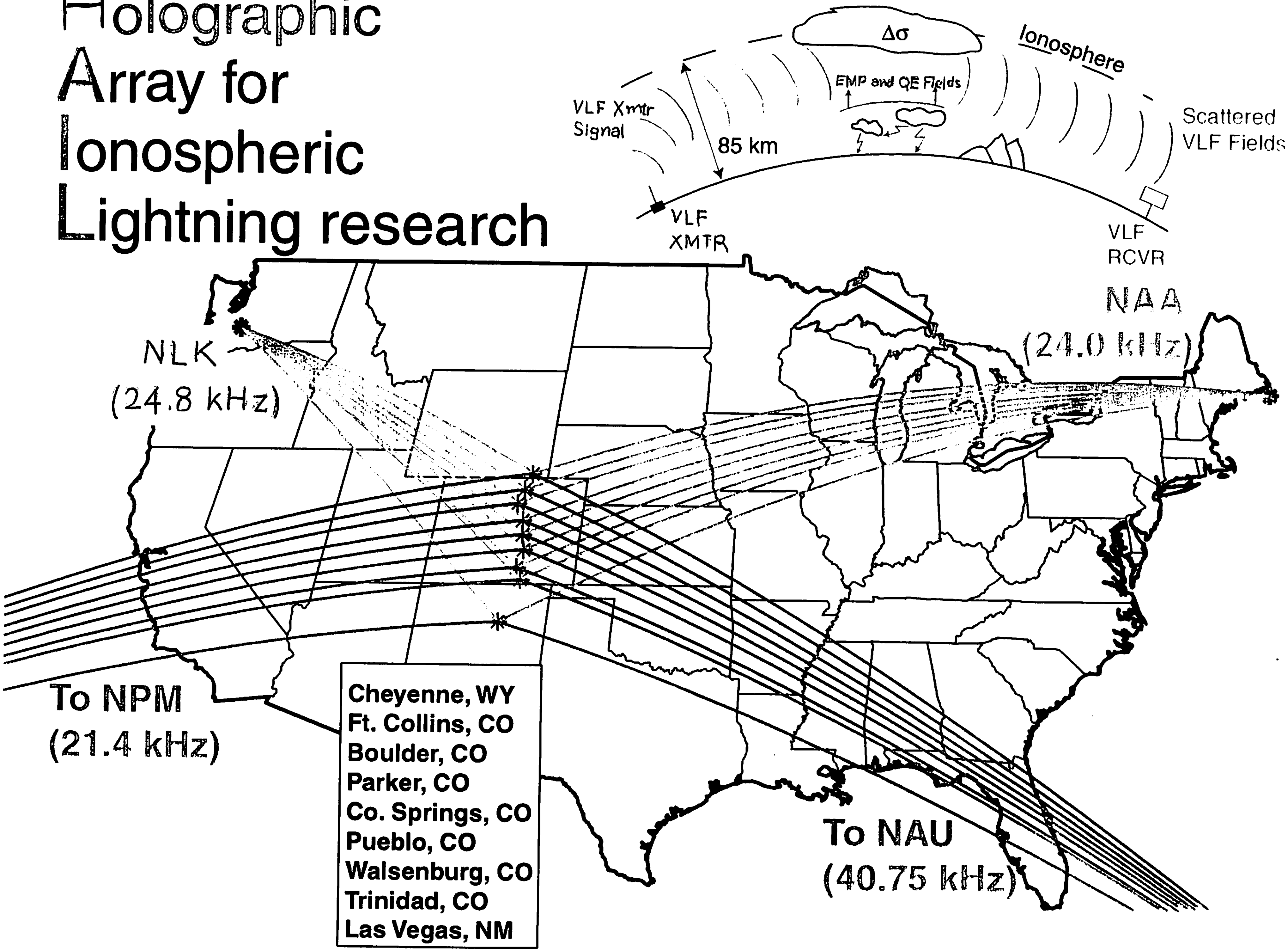
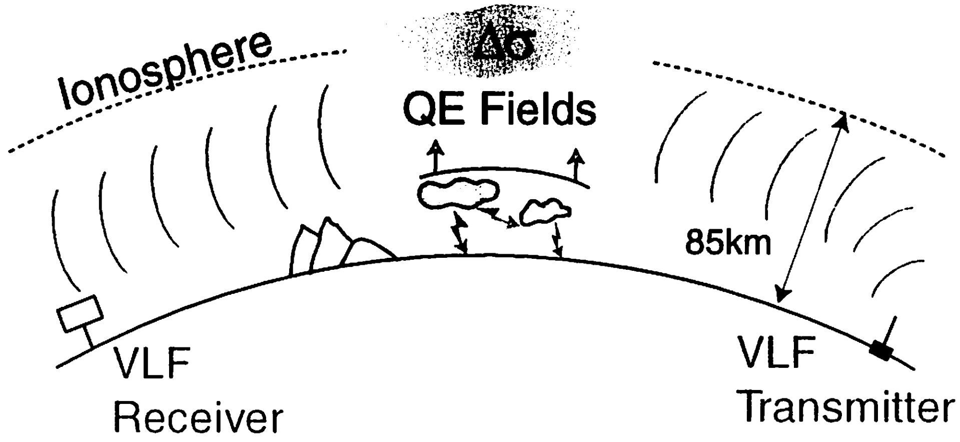


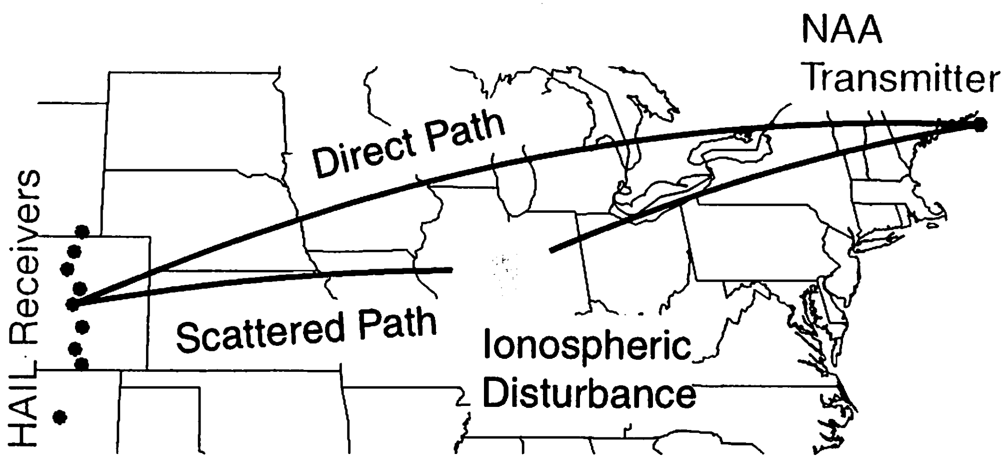
Figure 1: July 13 sprite. NLDN data: 204deg azimuth, 496km. range, 49kA

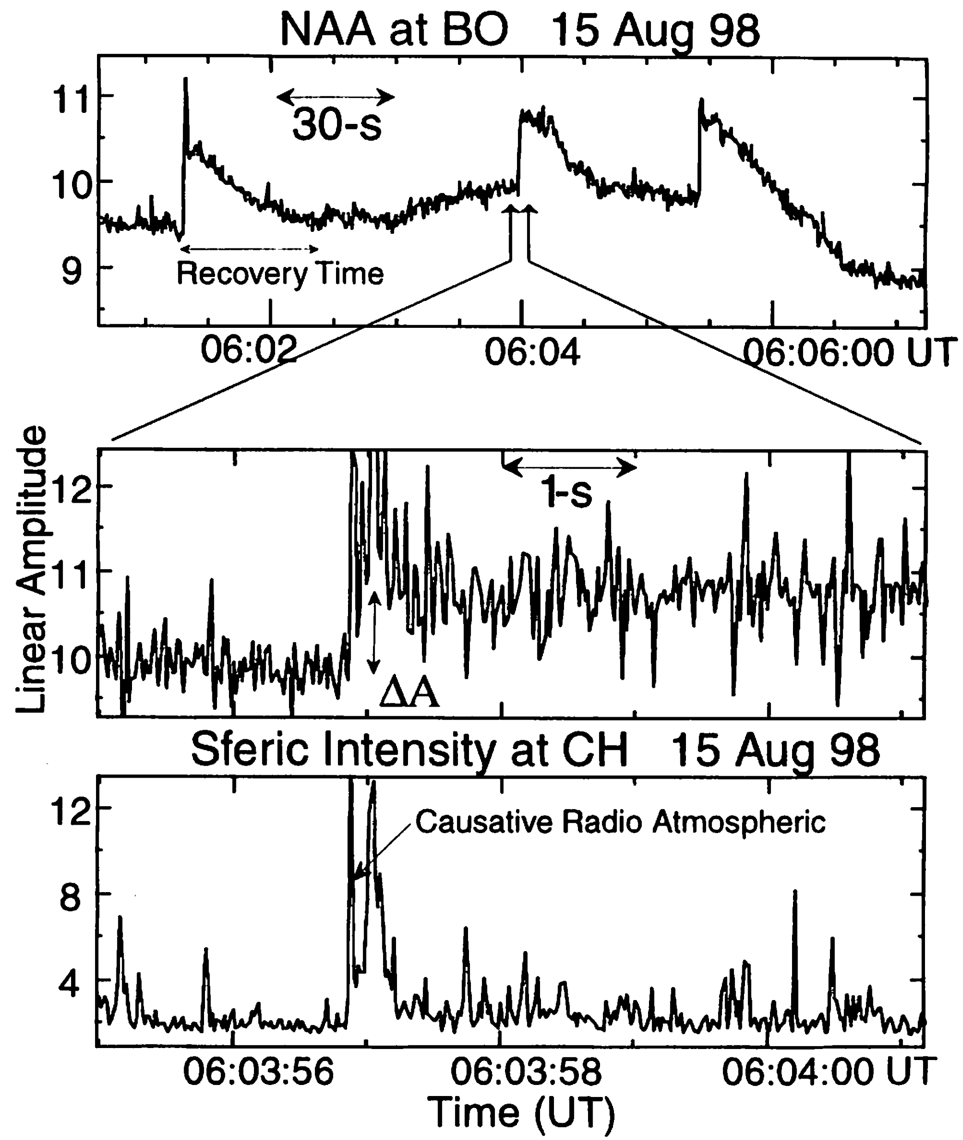
Holographic Array for Ionospheric Lightning research

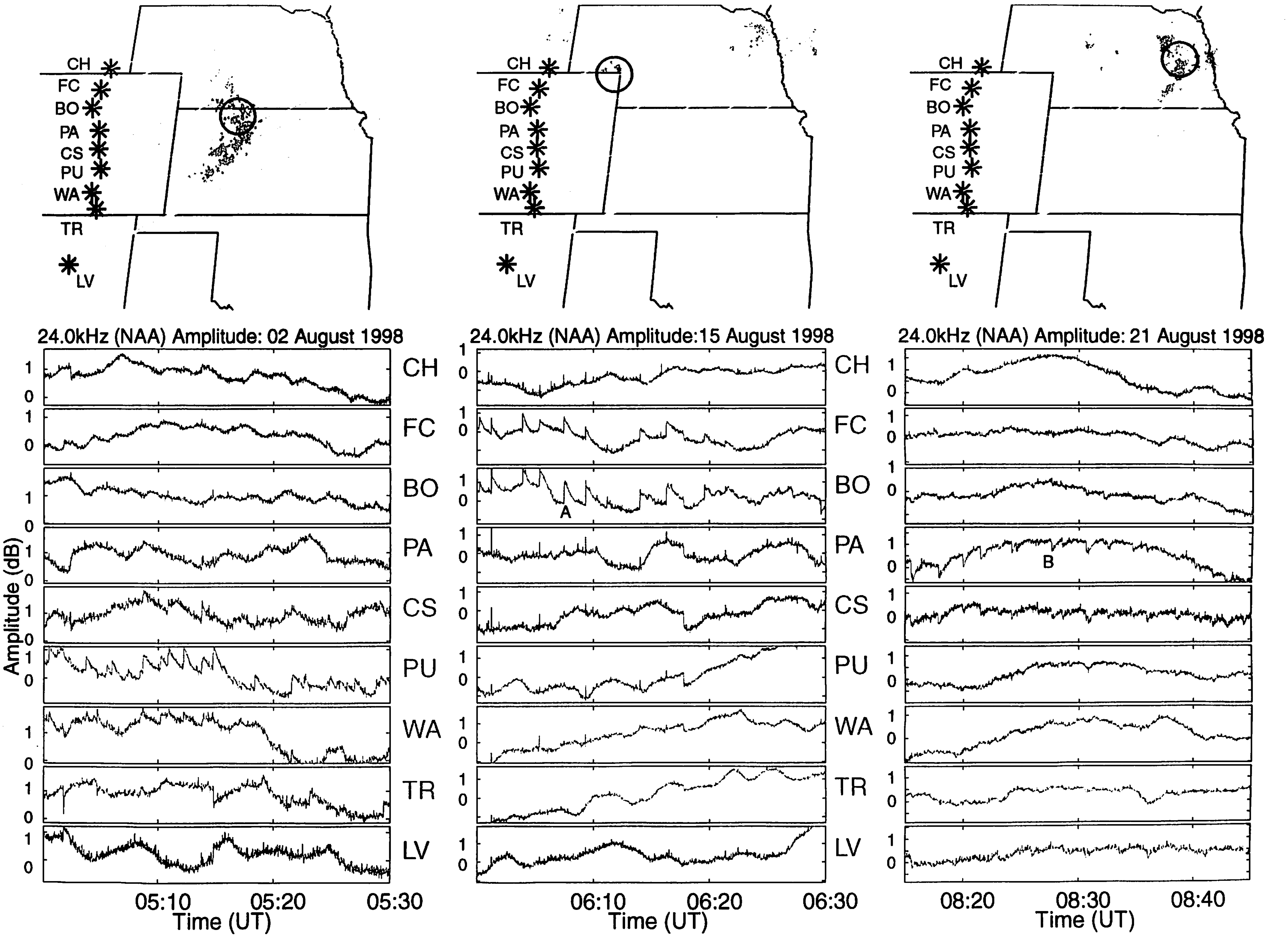


Early/Fast VLF Events (direct coupling)

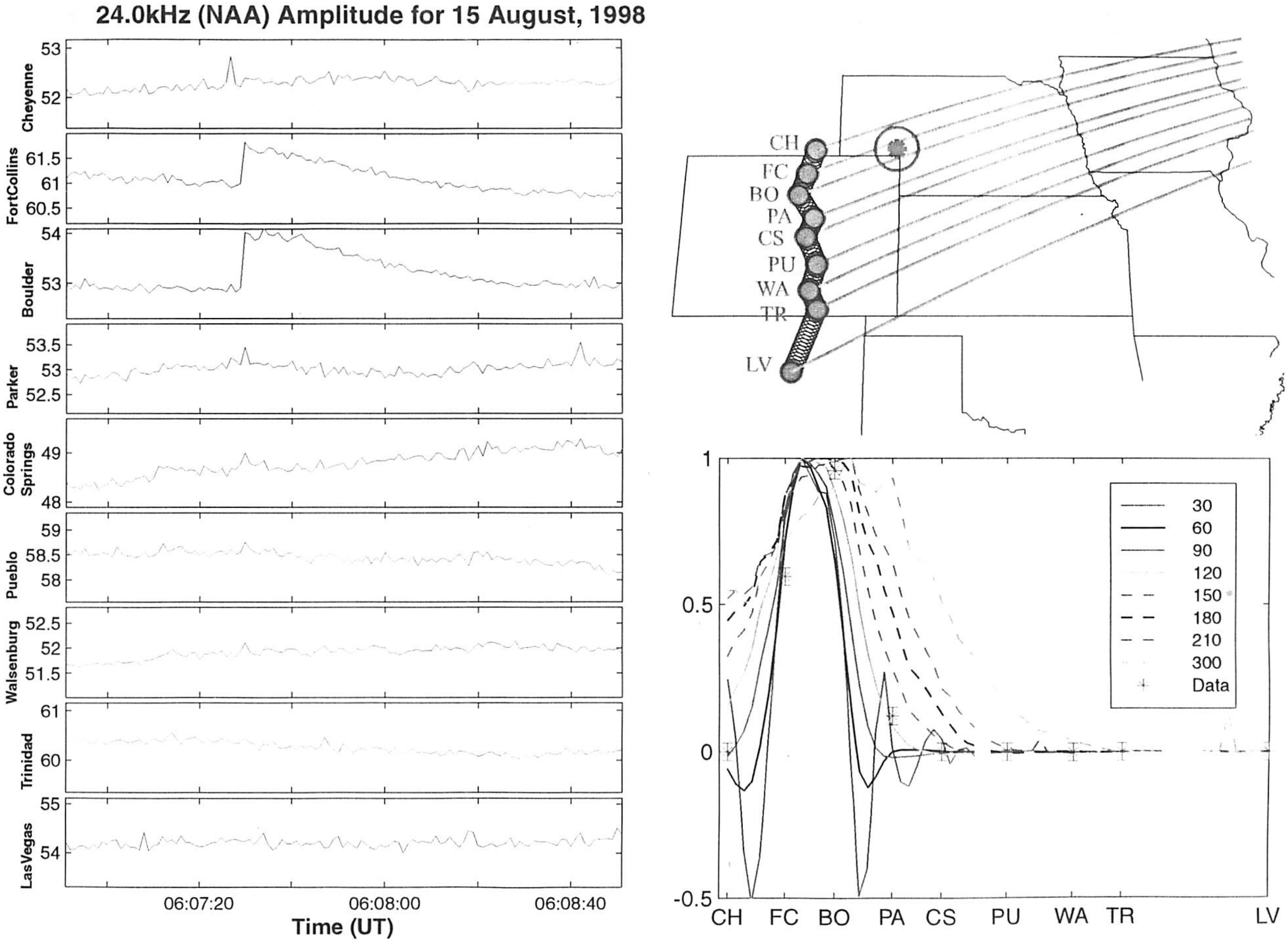




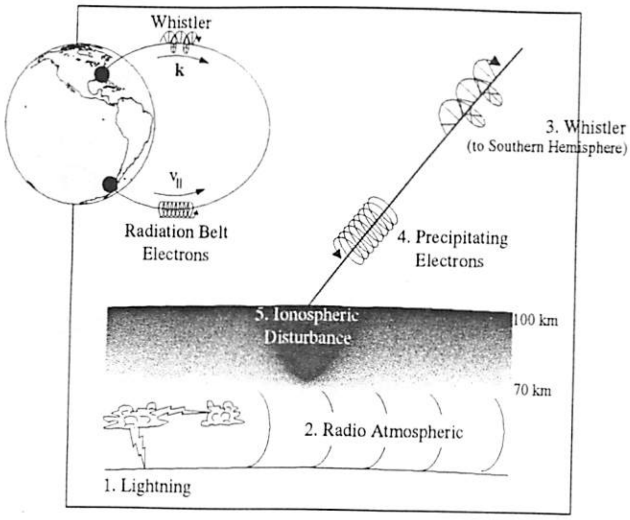


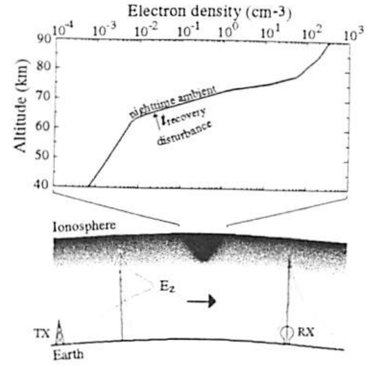


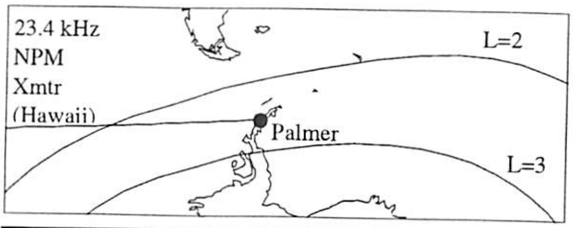
CH
FC
BO
PA
CS
PU
WA
TR
LV
24.0kHz (NAA) Amplitude: 02 August 1998
24.0kHz (NAA) Amplitude:15 August 1998
24.0kHz (NAA) Amplitude: 21 August 1998
Amplitude (dB)
A
B
05:10
05:20
05:30
06:10
06:20
06:30
08:20
08:30
08:40
Time (UT)

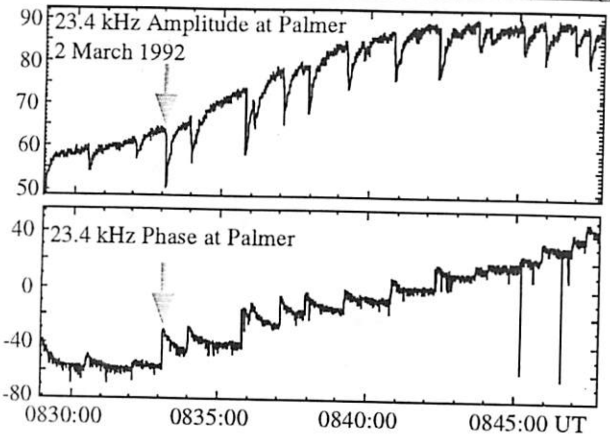


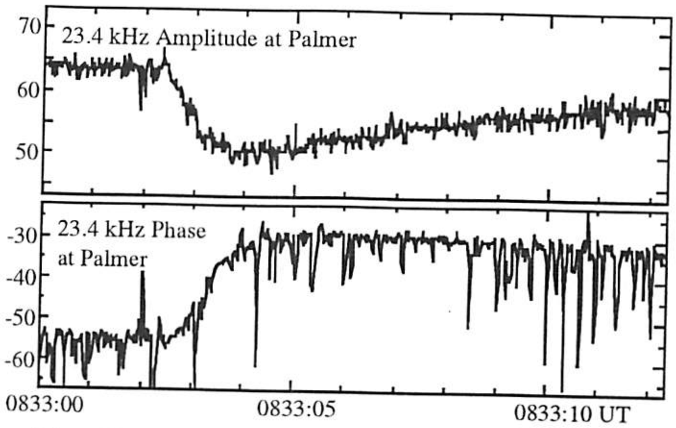
24.0kHz (NAA) Amplitude for 15 August, 1998
Cheyenne
FortCollins
Boulder
Parker
Colorado Springs
Pueblo
Walsenburg
Trinidad
LasVegas
06:07:20
06:08:00
06:08:40
Time (UT)
CH
FC
BO
PA
CS
PU
WA
TR
LV
30
60
90
120
150
180
210
300
Data

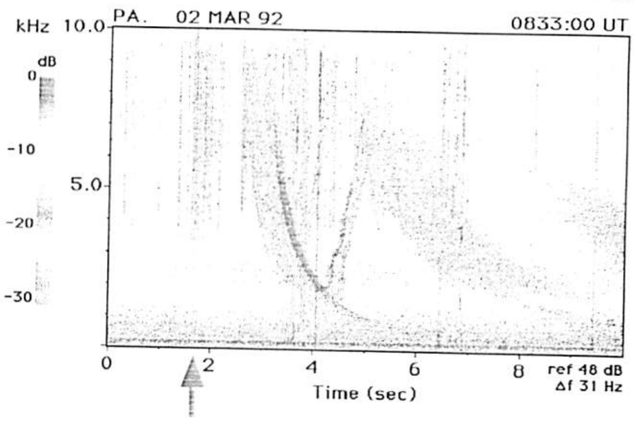

Whistler
k
$v_{||}$
Radiation Belt
Electrons
3. Whistler
(to Southern Hemisphere)
4. Precipitating
Electrons
5. Ionospheric
Disturbance
100 km
70 km
2. Radio Atmospheric
1. Lightning

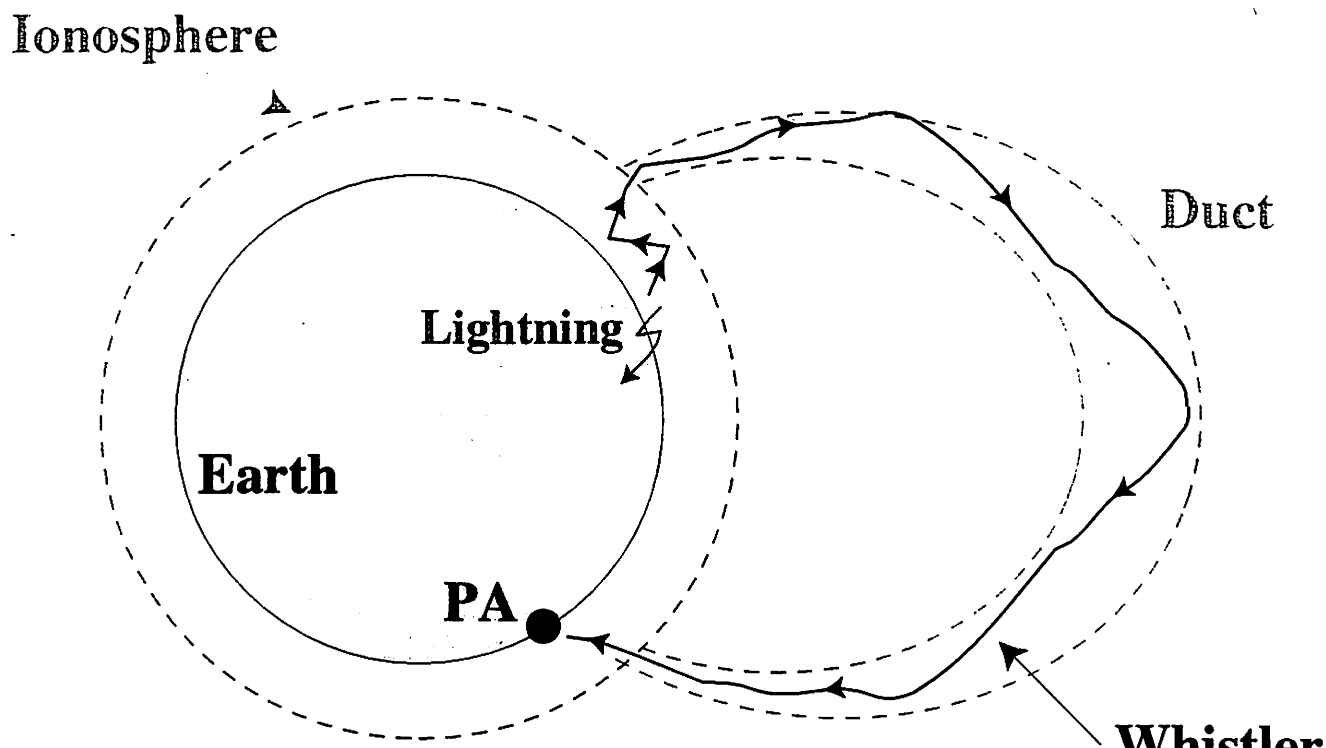

Electron density (cm-3)
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Altitude (km)
90 80 70 60 50 40
nighttime ambient
recovery
disturbance
Ionosphere
E_z
TX
RX
Earth


23.4 kHz
NPM
Xmtr
(Hawaii)
L=2
Palmer
L=3

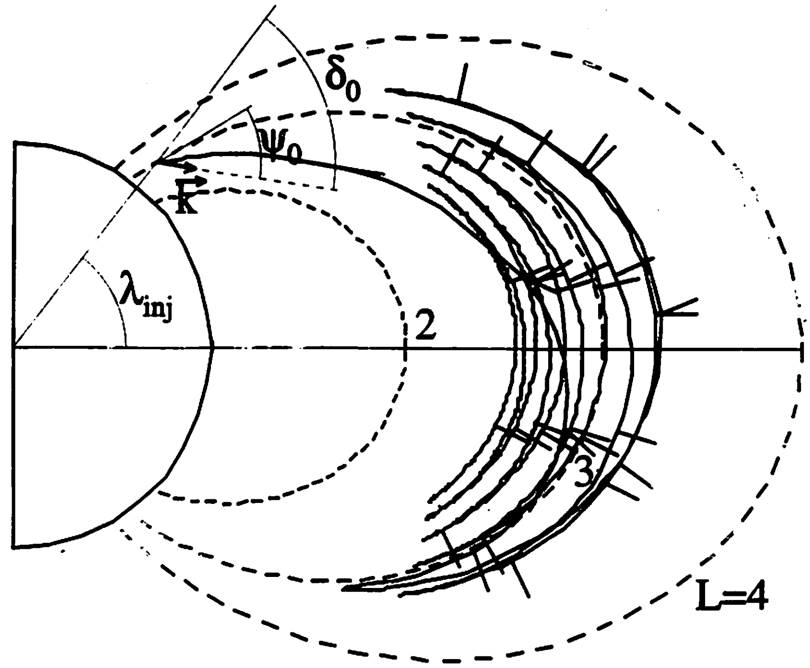

23.4 kHz Amplitude at Palmer
2 March 1992
90 80 70 60 50
23.4 kHz Phase at Palmer
40 0 -40 -80
0830:00
0835:00
0840:00
0845:00 UT


23.4 kHz Amplitude at Palmer
70 60 50
23.4 kHz Phase
at Palmer
-30 -40 -50 -60
0833:00
0833:05
0833:10 UT

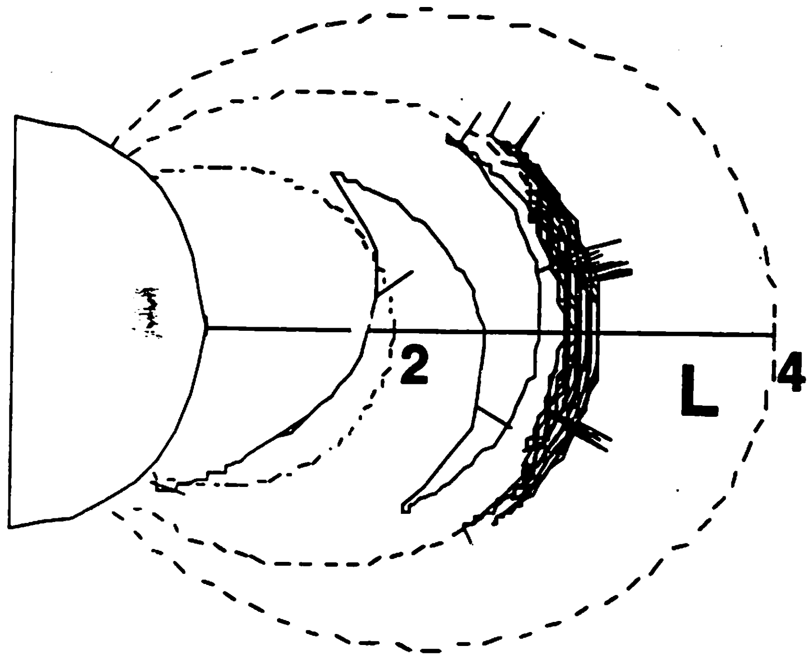

kHz 10.0
PA. 02 MAR 92
0833:00 UT
dB
0
-10
-20
-30
5.0
0 2 4 6 8
Time (sec)
ref 48 dB
Δf 31 Hz


Ionosphere
Duct
Lightning
Earth
PA
Whistler

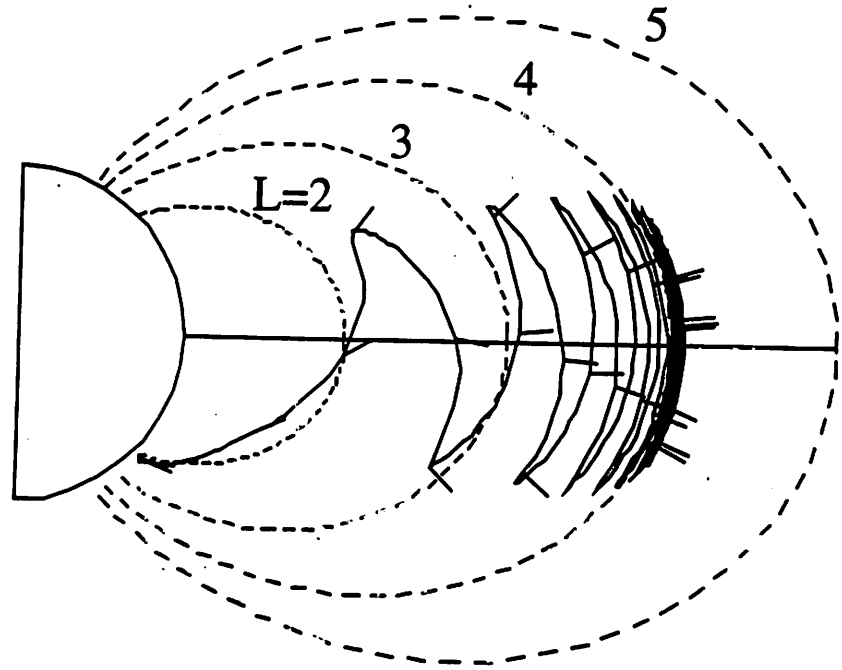
2 kHz



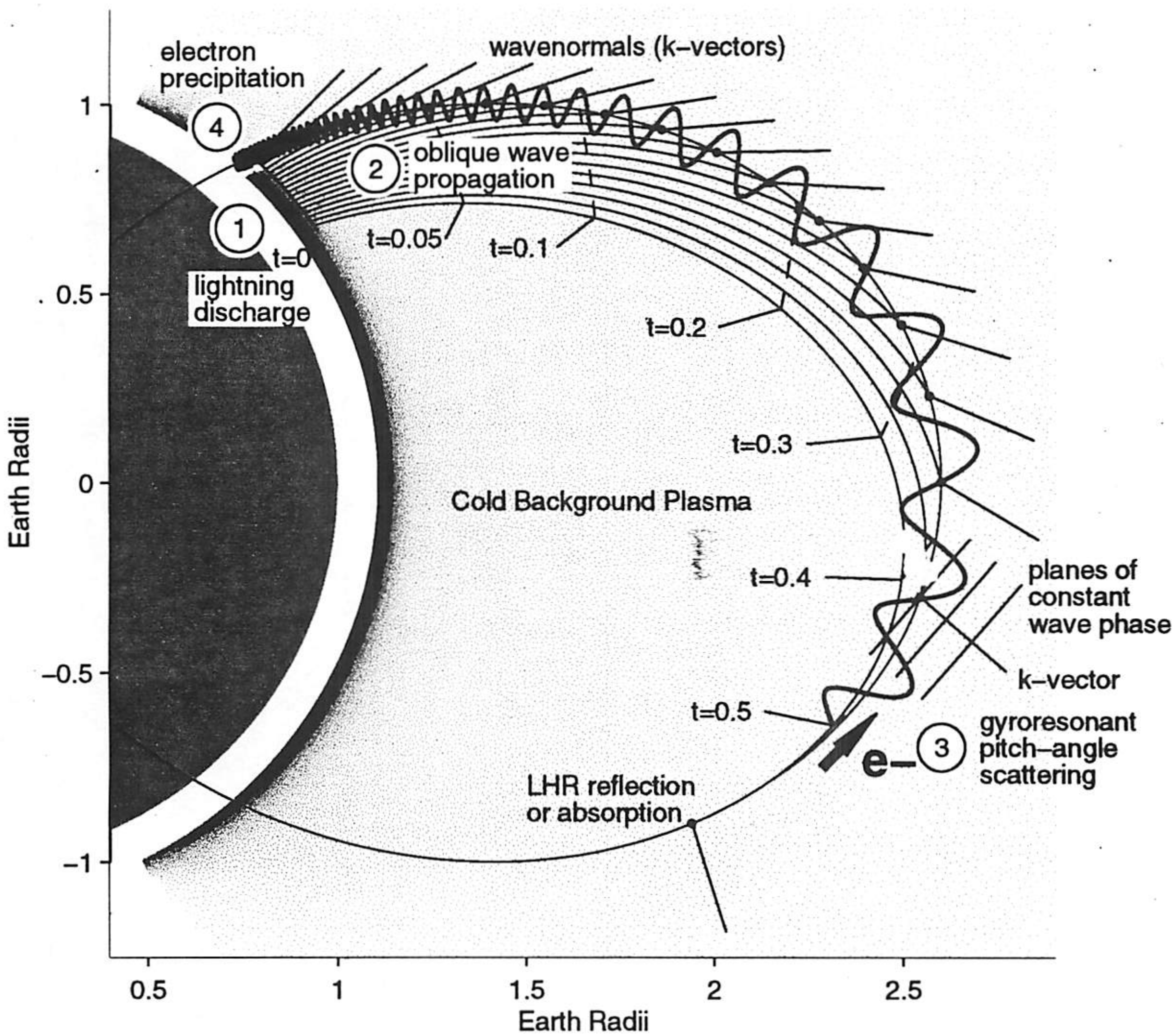
1 kHz

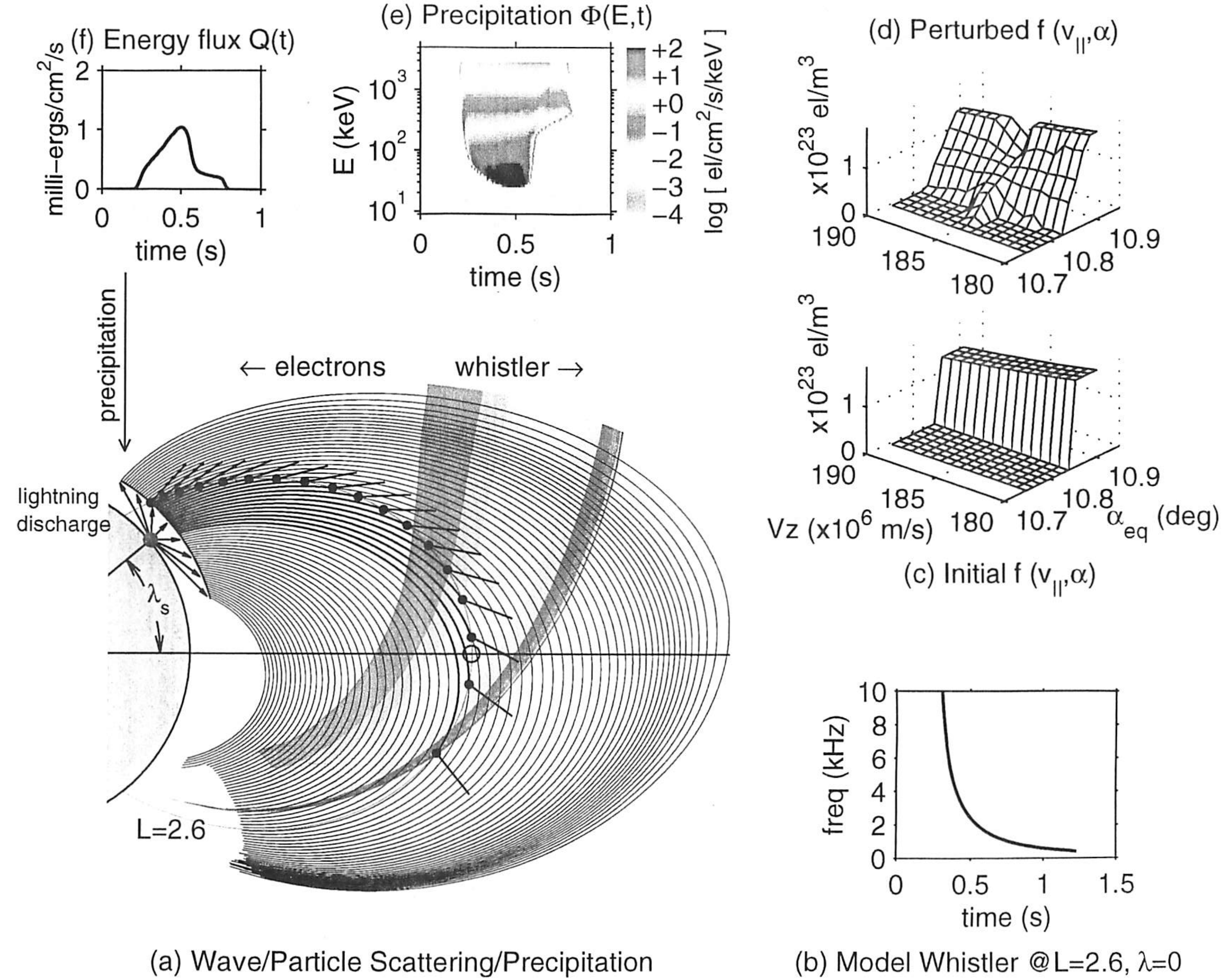


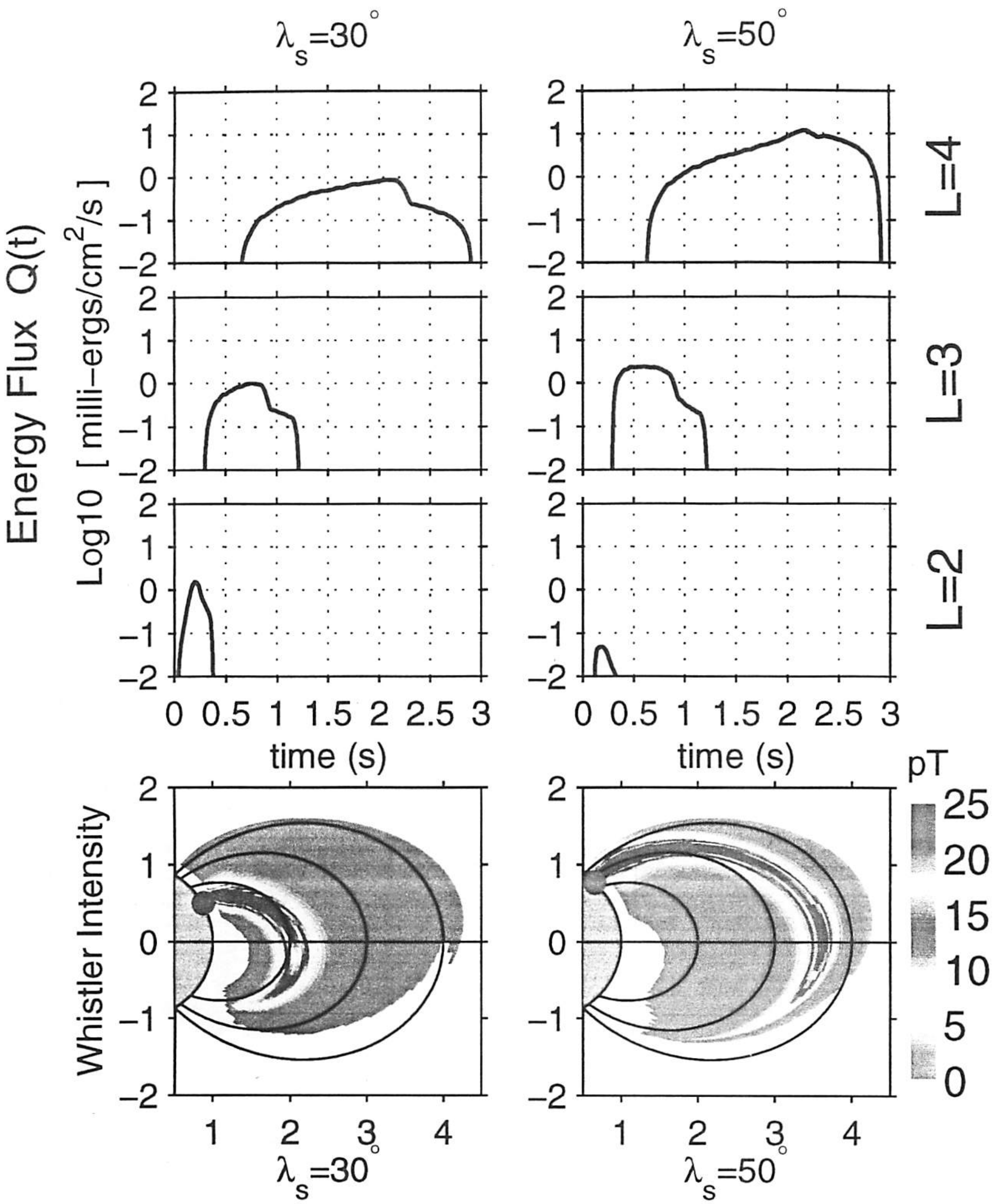
330 Hz



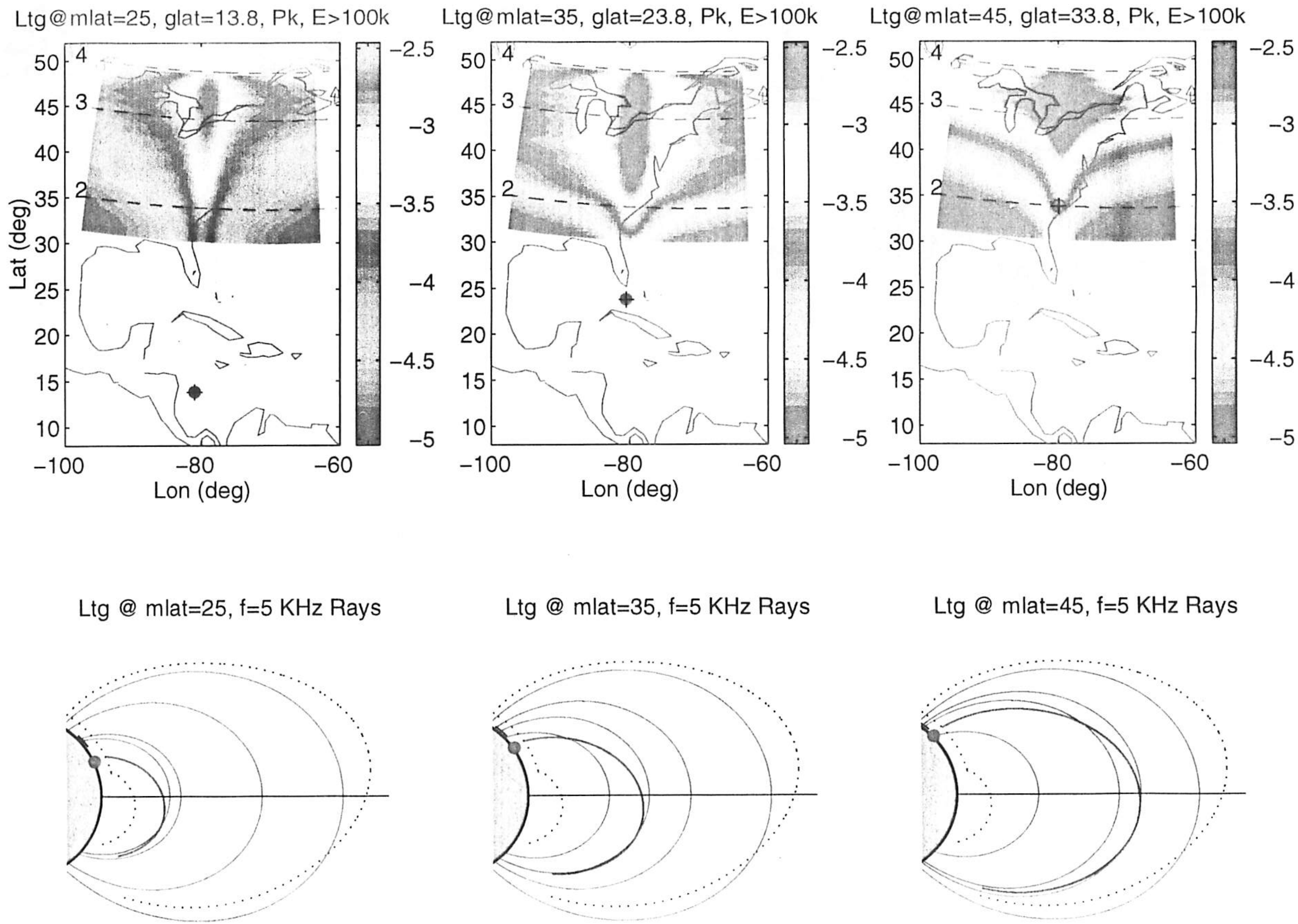
Oblique Wave / Energetic Particle Interaction



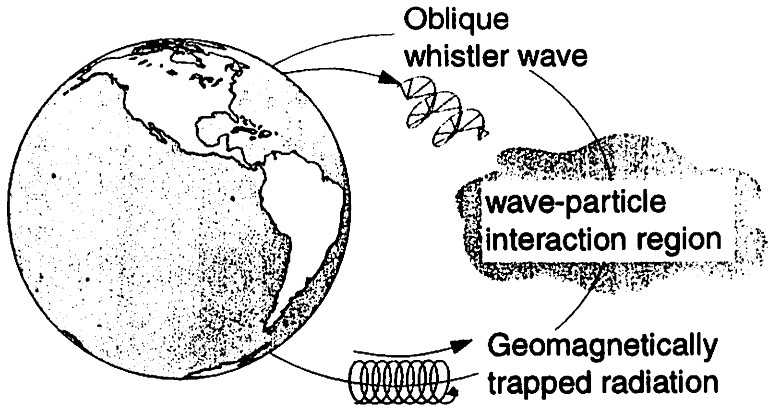

(f) Energy flux Q(t)
milli-ergs/cm^2/s
time (s)
(e) Precipitation Φ(E,t)
E (keV)
log [el/cm^2/s/keV]
+2
+1
+0
−1
−2
−3
−4
time (s)
(d) Perturbed f (v_||,α)
x10^23 el/m^3
190
185
180
10.7
10.8
10.9
Vz (x10^6 m/s)
α_eq (deg)
(c) Initial f (v_||,α)
precipitation
← electrons
whistler →
lightning
discharge
λ_s
L=2.6
(a) Wave/Particle Scattering/Precipitation
freq (kHz)
time (s)
(b) Model Whistler @L=2.6, λ=0

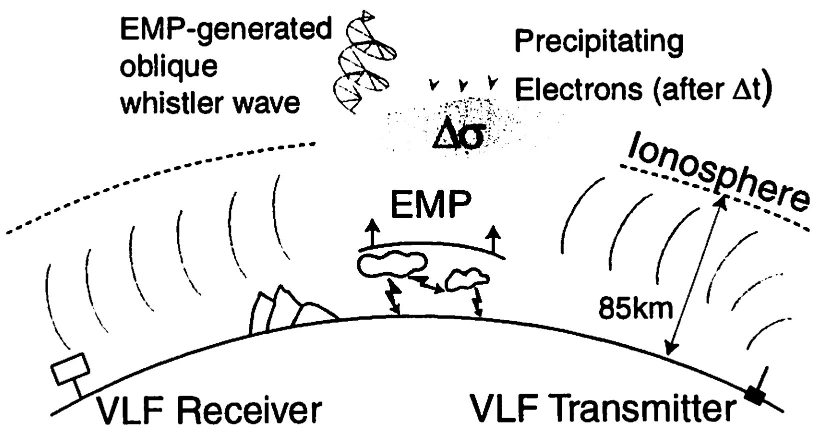


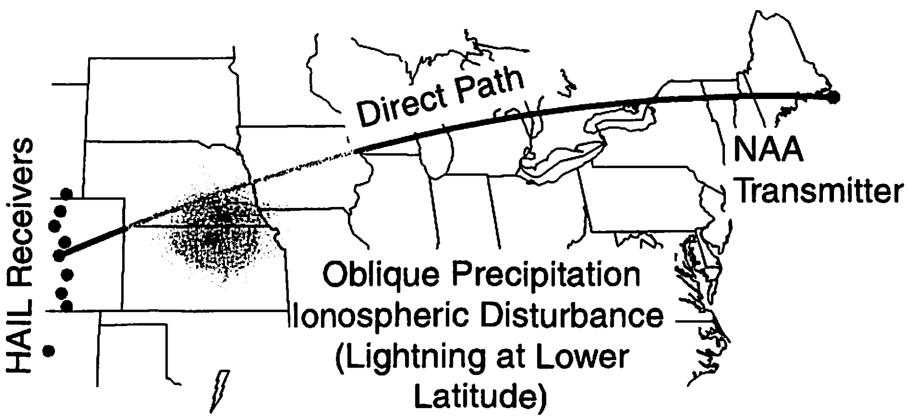
λs=30°
λs=50°
Energy Flux Q(t)
Log10 [milli-ergs/cm2/s]
L=4
L=3
L=2
time (s)
Whistler Intensity
pT
25
20
15
10
5
0
λs=30°
λs=50°

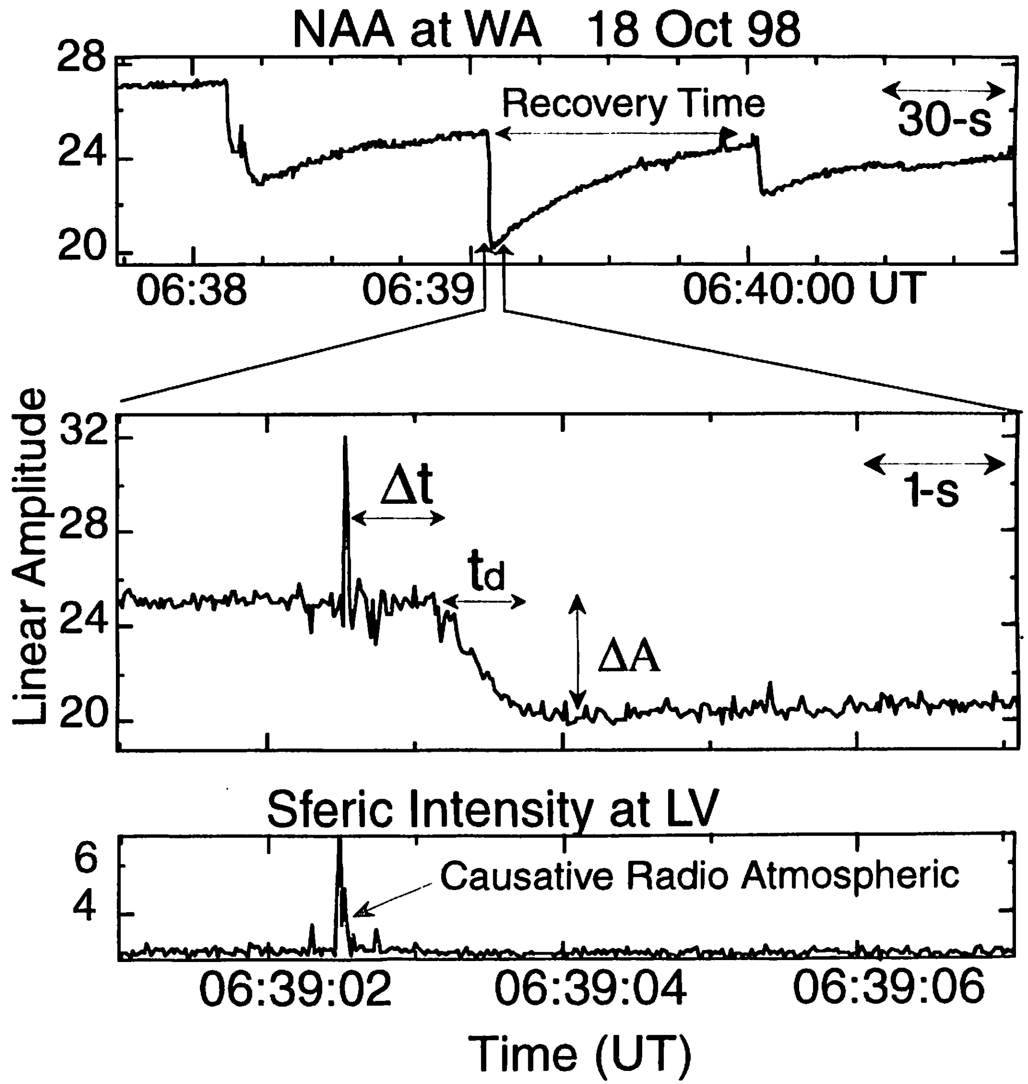

Ltg@mlat=25, glat=13.8, Pk, E>100k
Ltg@mlat=35, glat=23.8, Pk, E>100k
Ltg@mlat=45, glat=33.8, Pk, E>100k
Lat (deg)
Lon (deg)
-100
-80
-60
10
15
20
25
30
35
40
45
50
2
3
4
-2.5
-3
-3.5
-4
-4.5
-5
Ltg @ mlat=25, f=5 KHz Rays
Ltg @ mlat=35, f=5 KHz Rays
Ltg @ mlat=45, f=5 KHz Rays

Oblique Precipitation VLF Events (Indirect coupling)

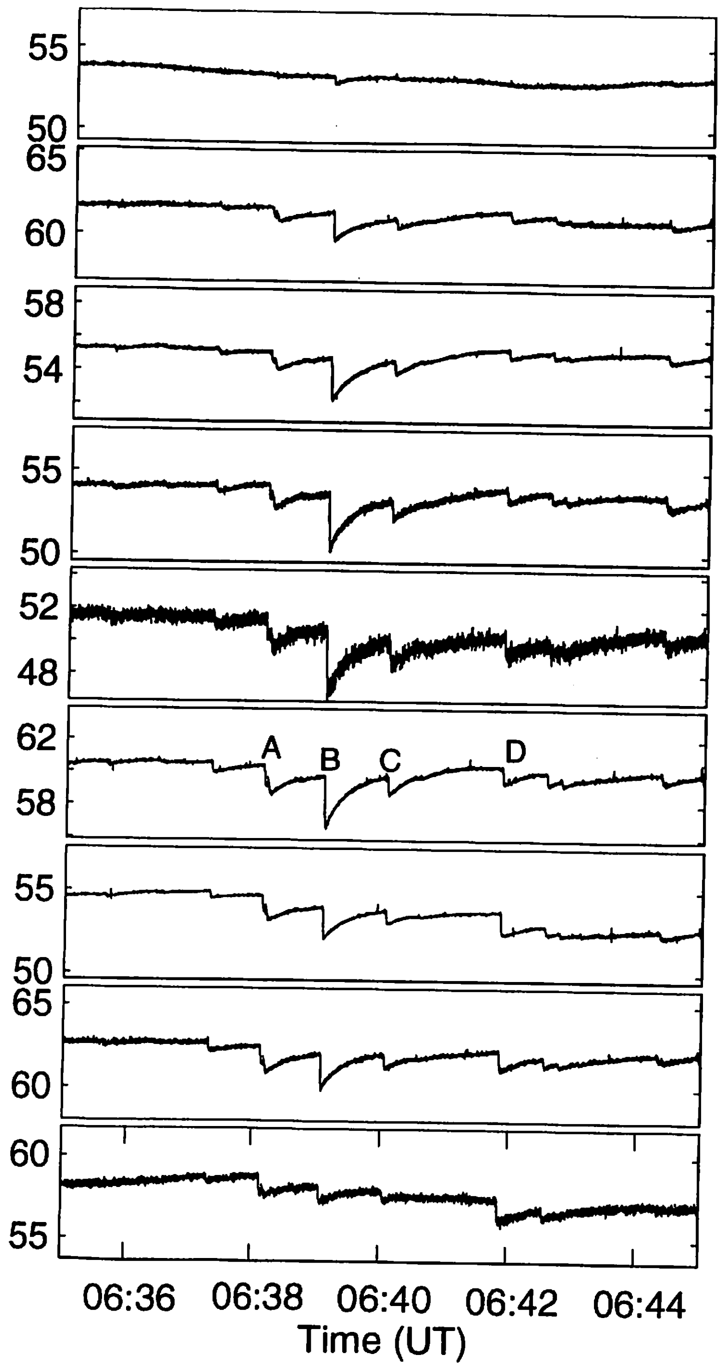




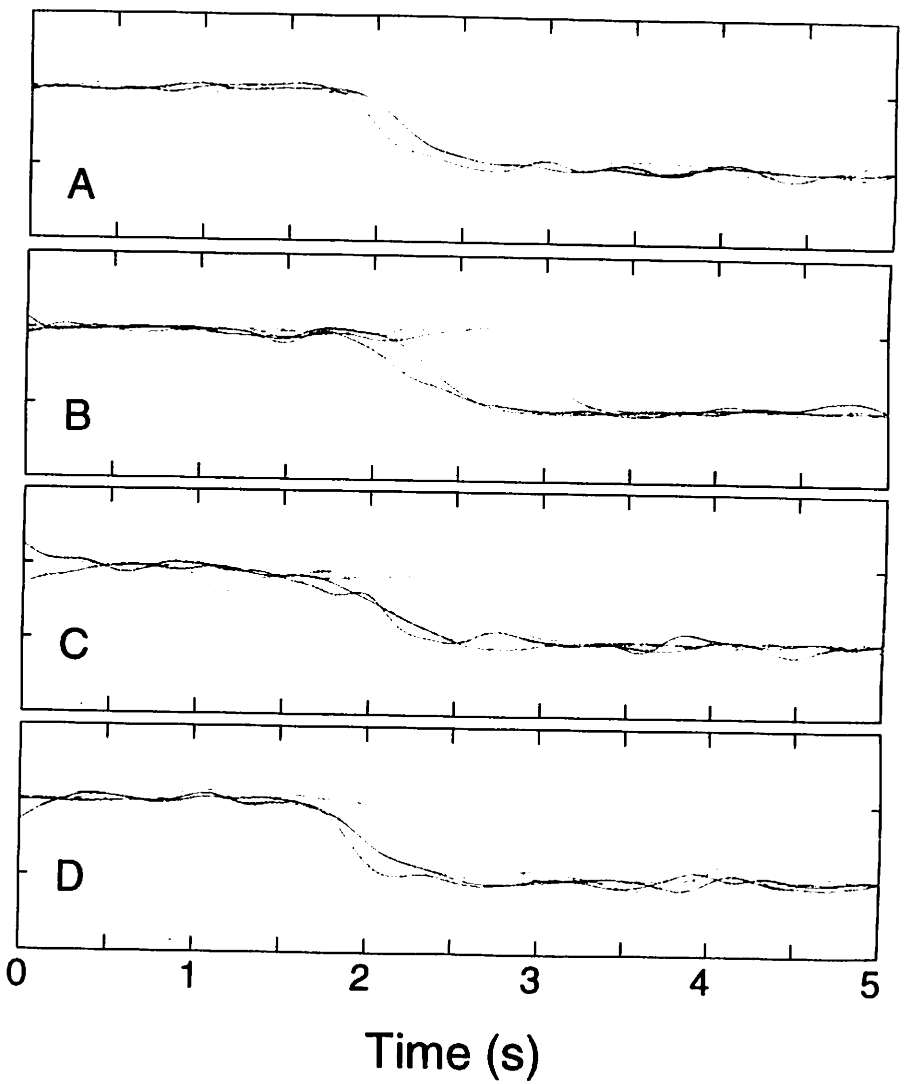




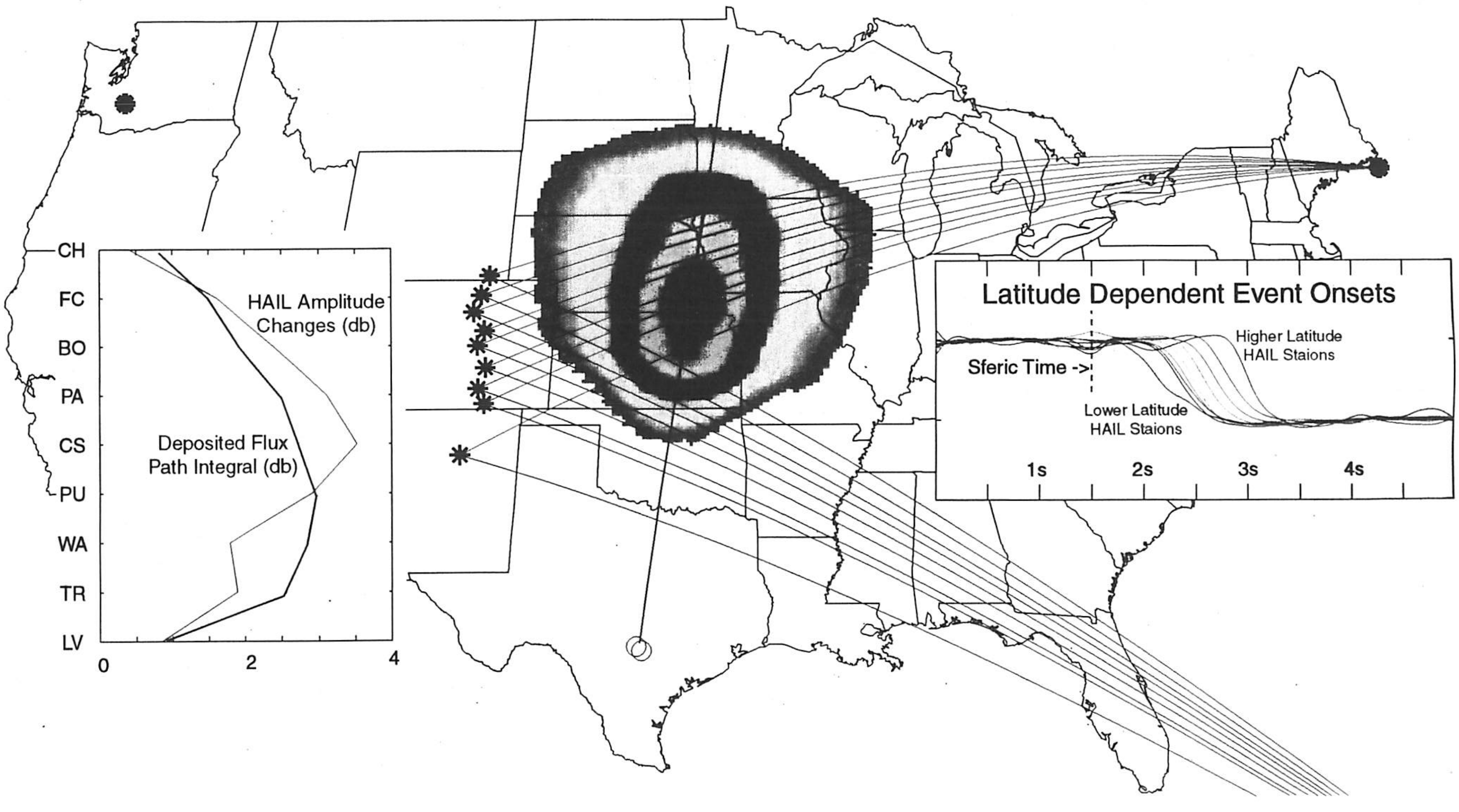
24.0kHz (NAA) Amplitude: 18 October 1998



Event Onset Delays



Modeled Flux Deposition and First Order Tomographic Comparison



Observation of an ionospheric disturbance caused by a gamma-ray burst

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* Space Science Laboratory, NASA/Marshall Space Flight Center, Huntsville, Alabama 35812, USA
† Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California 94305, USA

We report a first observation of an ionospheric disturbance from a gamma-ray burst. The burst, GB830801, occurred at 22:14:18 UT on 1 August 1983 and was one of the strongest ever observed. The total fluence was 2×10^{-3} erg cm^{-2}, most of which occurred in the first 4 s of the burst. Simultaneously, a change was observed in the amplitude of a very-low-frequency (VLF) radio signal from a transmitter in Rugby, England, monitored at Palmer Station, Antarctica, indicative of an ionospheric disturbance. Weaker disturbances were also recorded at the same receiving site on signals from VLF stations in Annapolis, Maryland and Lualualei, Hawaii. The times of the burst and the disturbances are coincident within the 10-s resolution of the VLF recording system. No similar disturbances were observed within 60 h around the time of the burst. In the future, a network of VLF burst monitors may provide

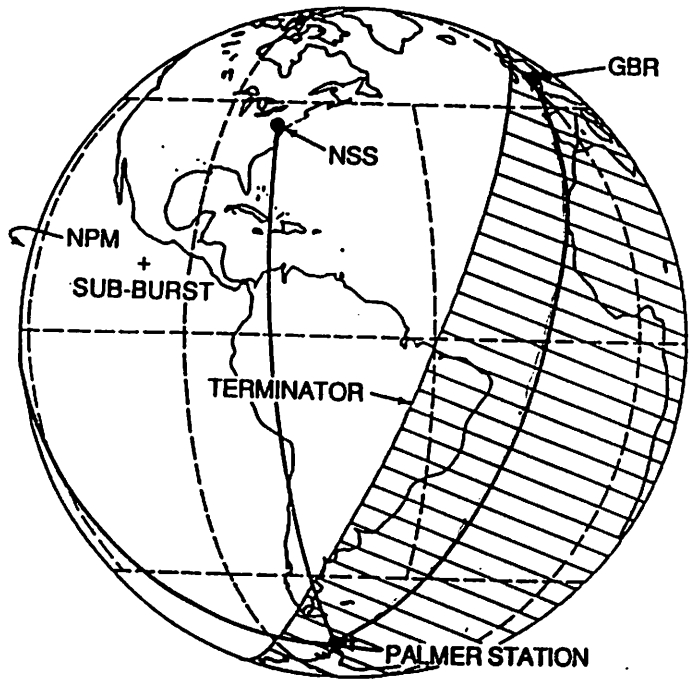


Fig. 1 The great-circle paths of the three VLF signals are shown along with the location of the sunset terminator at the time of the gamma-ray burst. The sub-burst position is indicated by a cross.

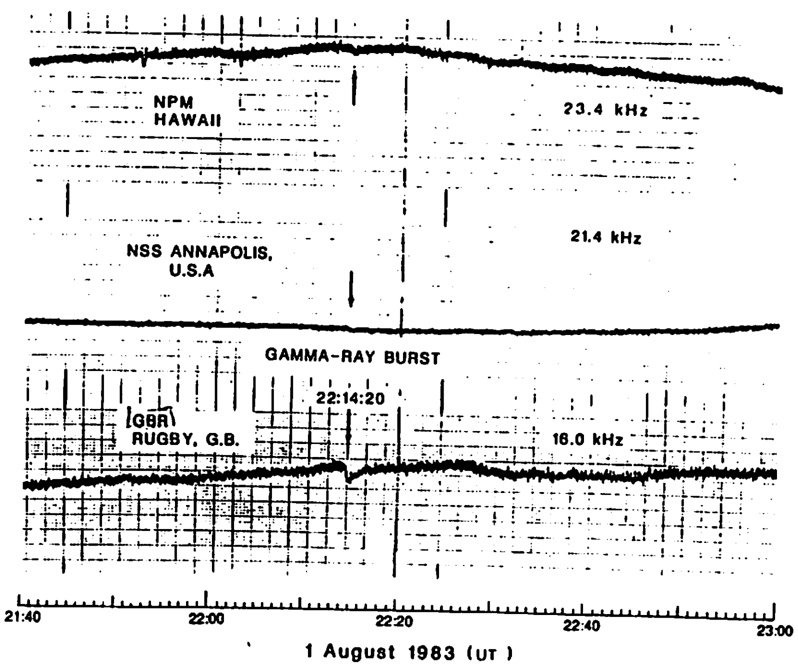
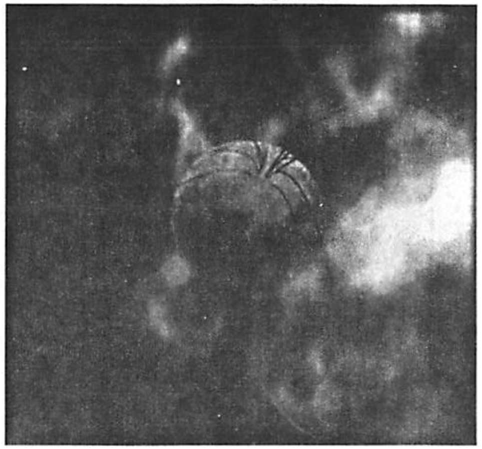


Fig. 2 Amplitude (arbitrary units) of the VLF radio signals received at Palmer, Antarctica from the three stations indicated. The ionospheric disturbances at the time of the gamma-ray burst are indicated by arrows.

Magnetar Gamma Ray Flare of 27 August 98 as Seen on a HAARP VLF Diagnostic Instrument

Artist's Rendition of a Magnetic Star (Magnetar)

ABC News



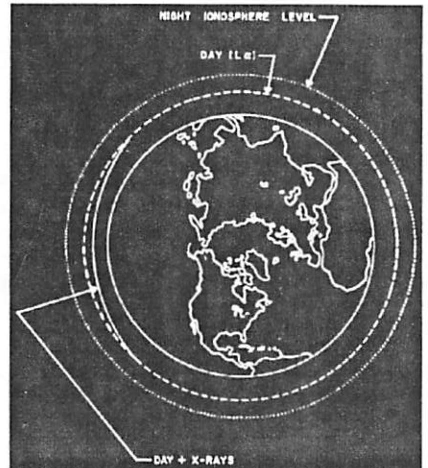
SGR 1900+14

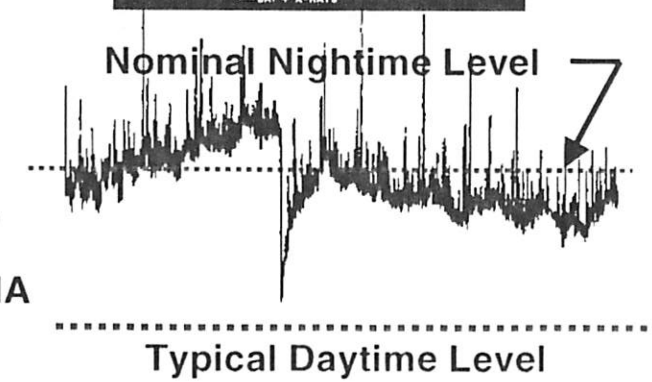
15-20,000 Light-Years Distance From the Earth

Release of Intense Gamma Rays Having as Much Energy as the Sun Would Put Out Over Hundreds of Years

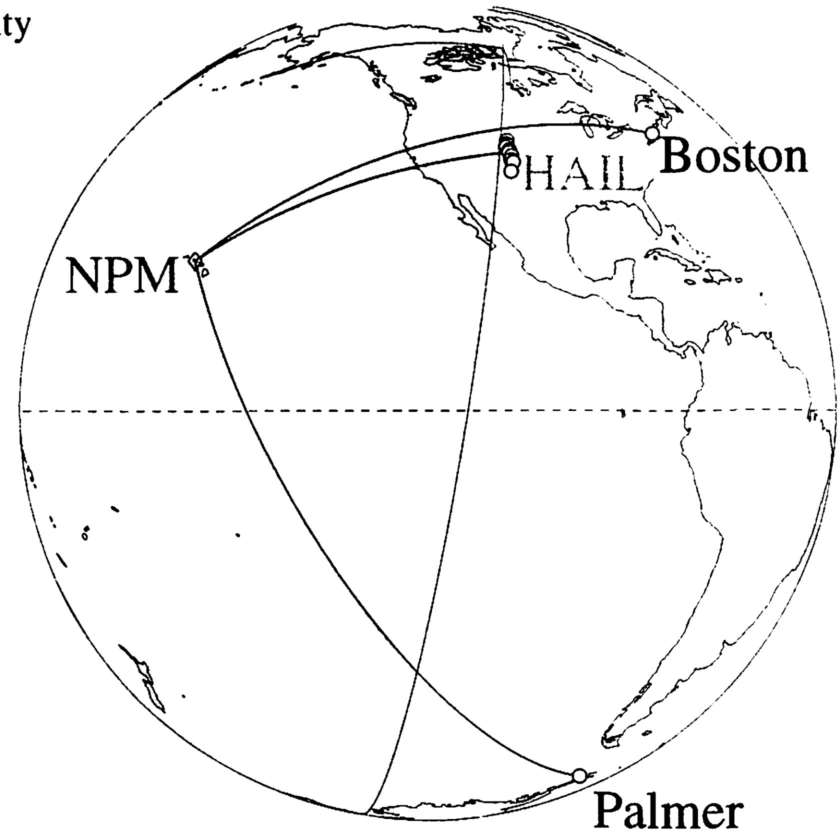
Effect of Gamma Ray Flare on VLF Signal Amplitude From NPM, Hawaii Observed at AFRL, Hanscom AFB, MA

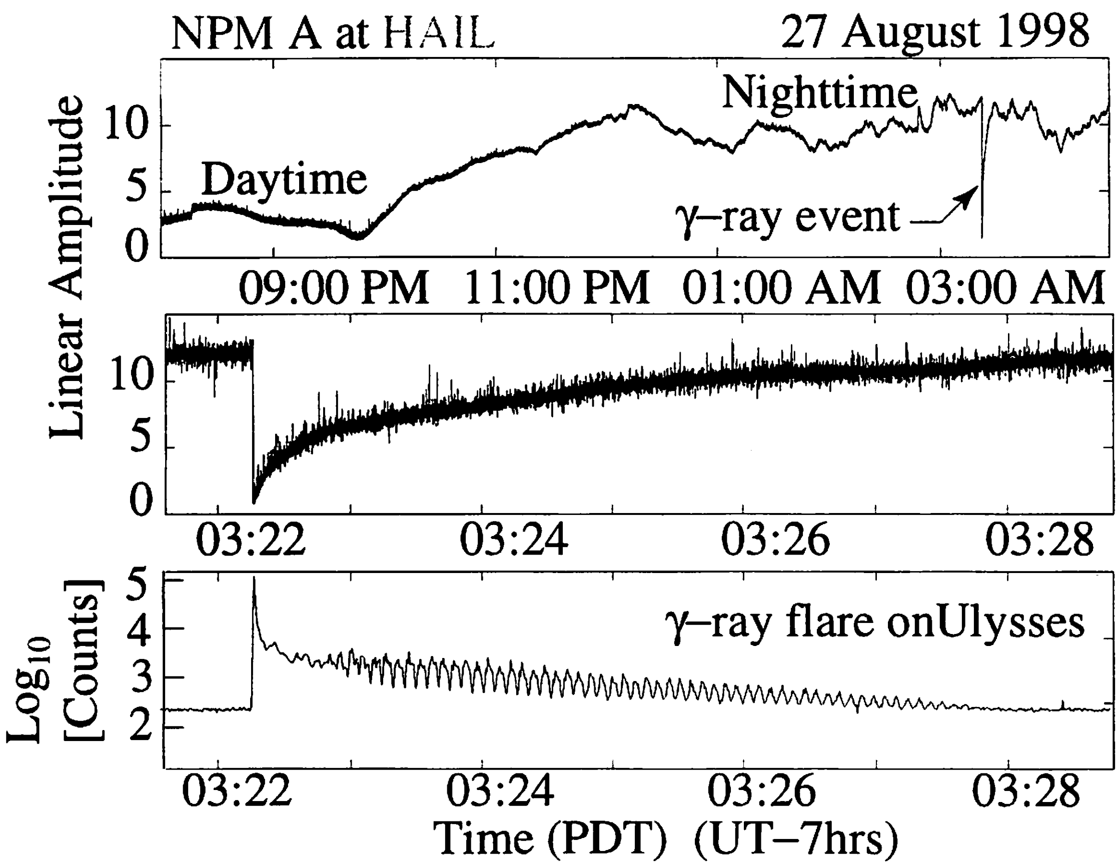
The Earth's Ionosphere as a Sensor of In-Coming X-Rays, Protons, Gamma Rays, etc.



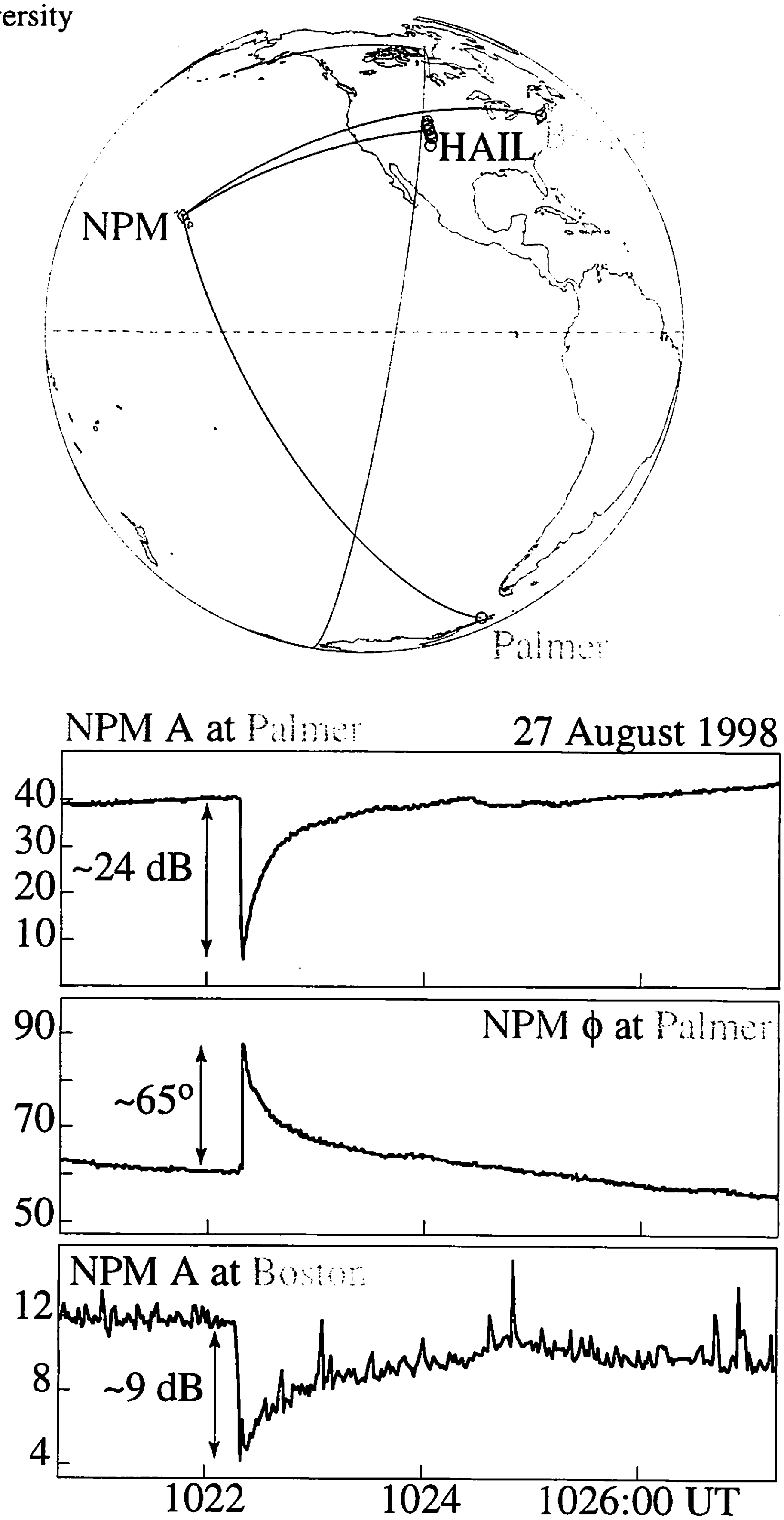


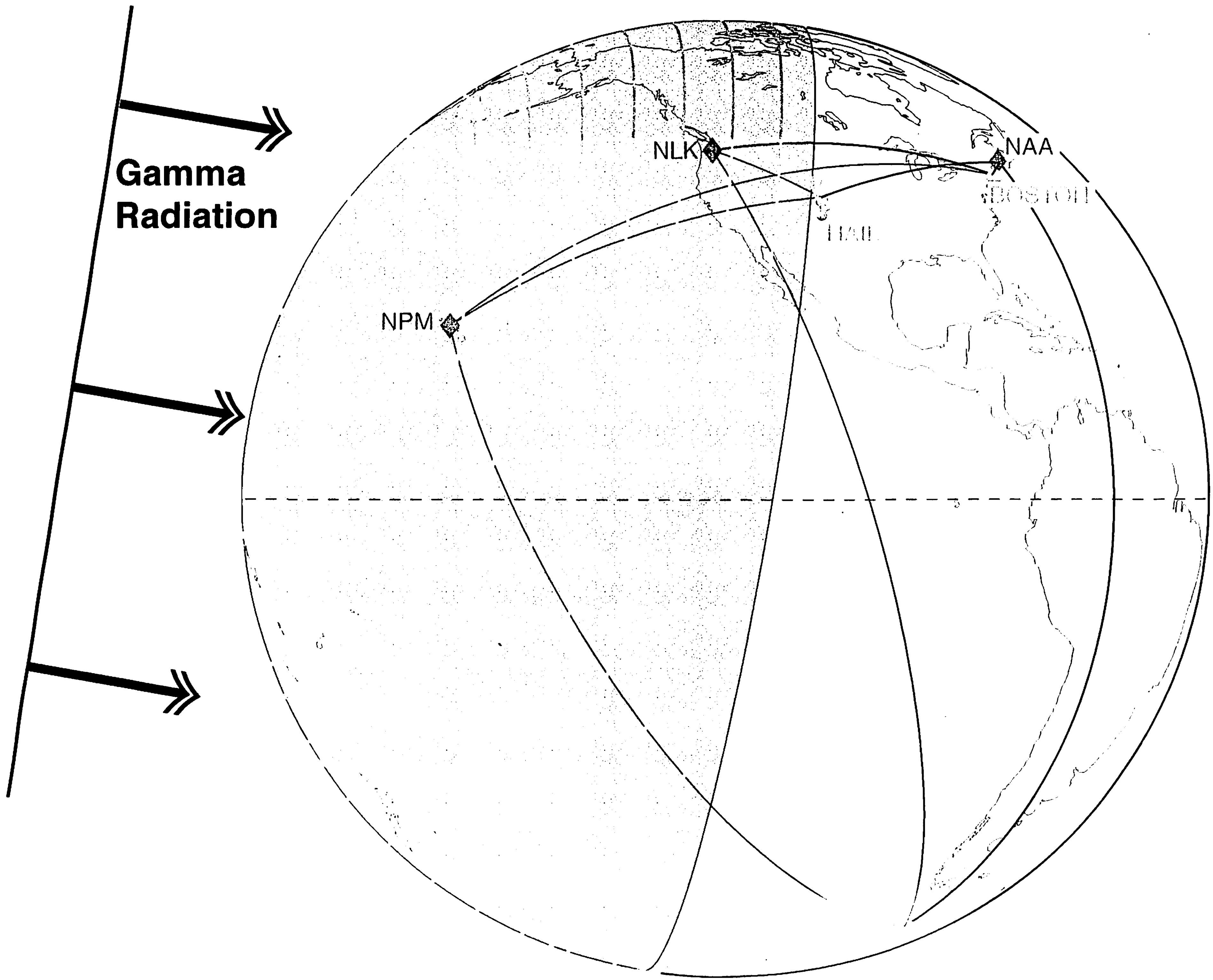
Umran Inan
Stanfor University

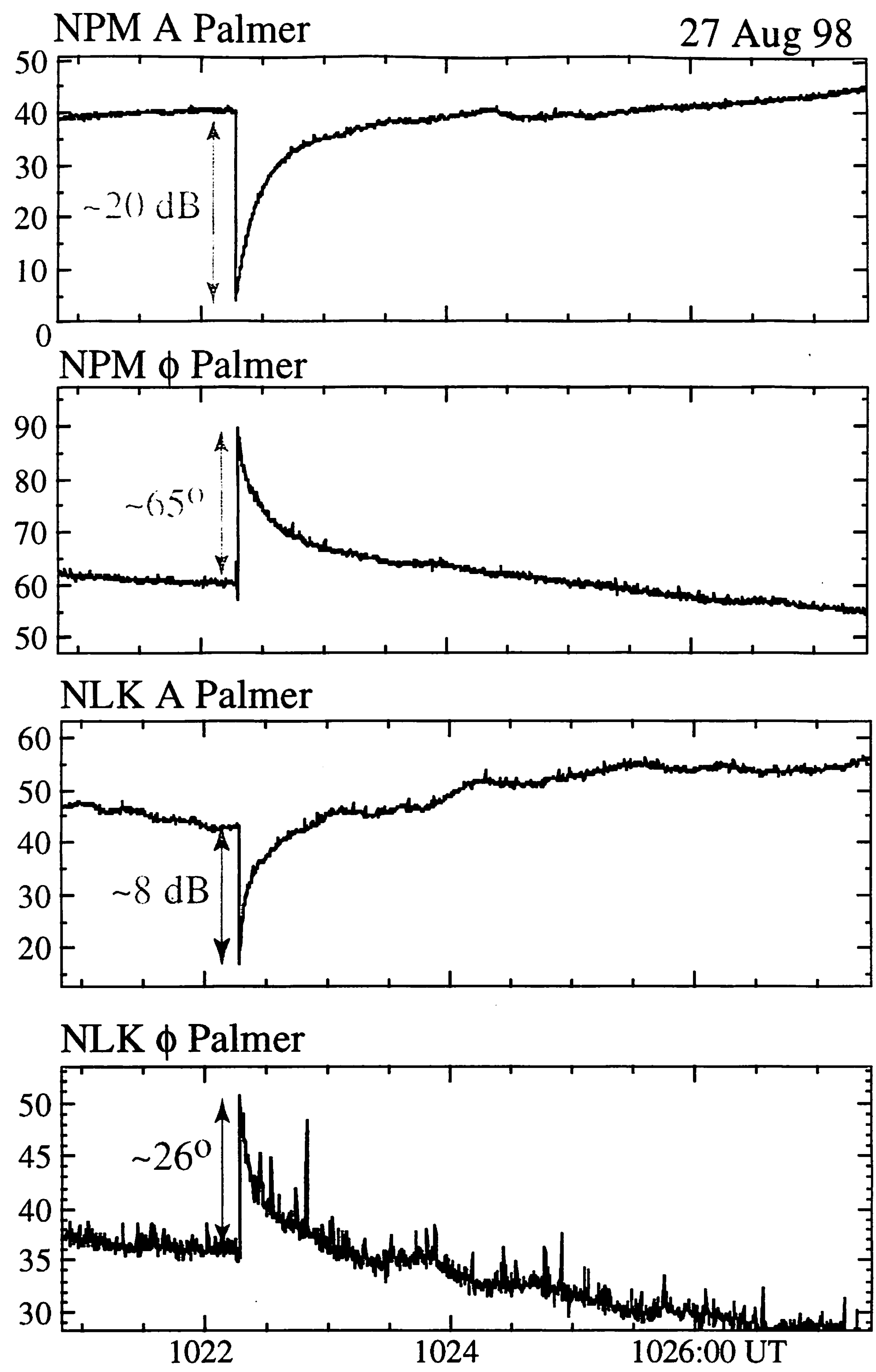




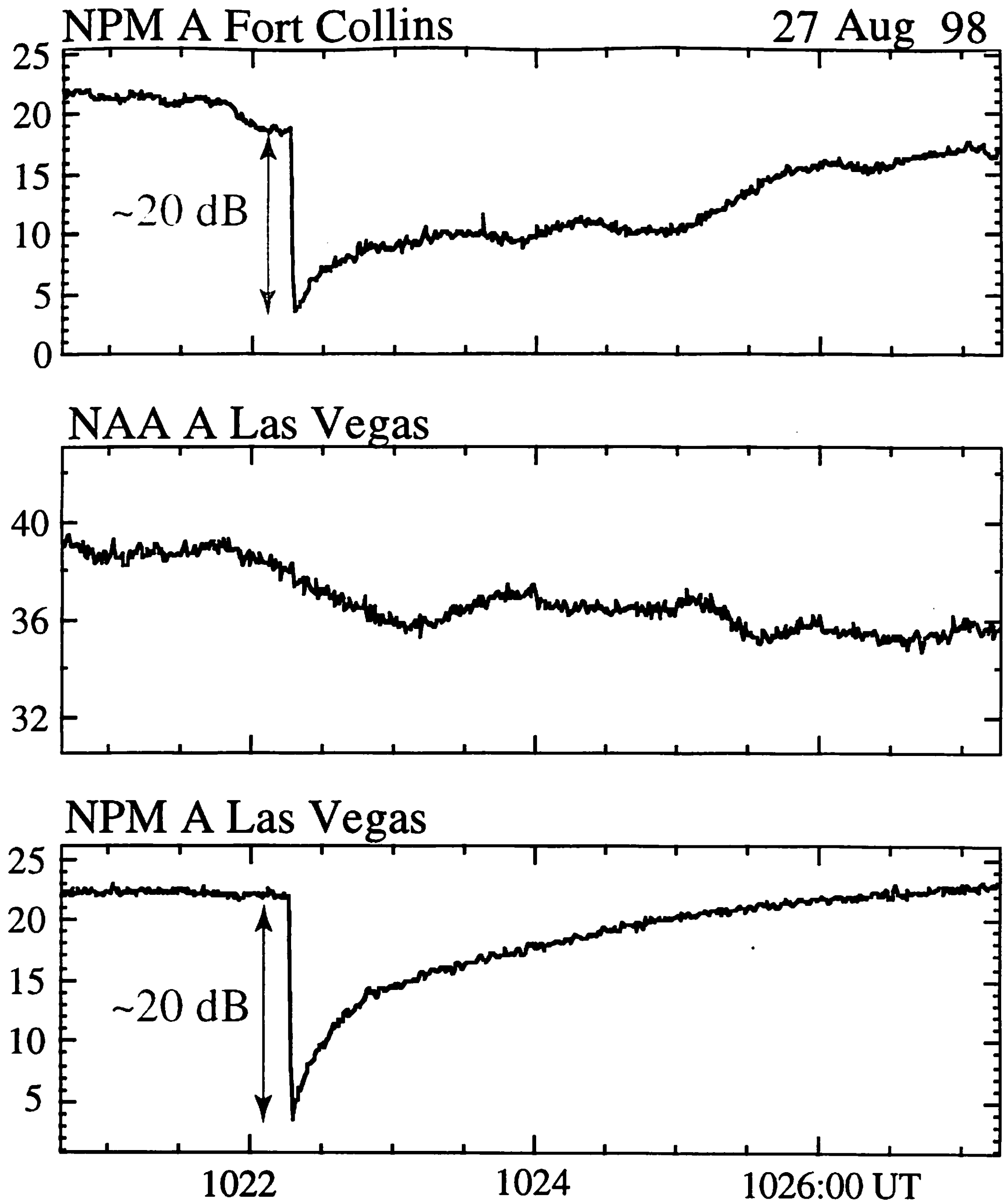
Umran Inan
Stanford University



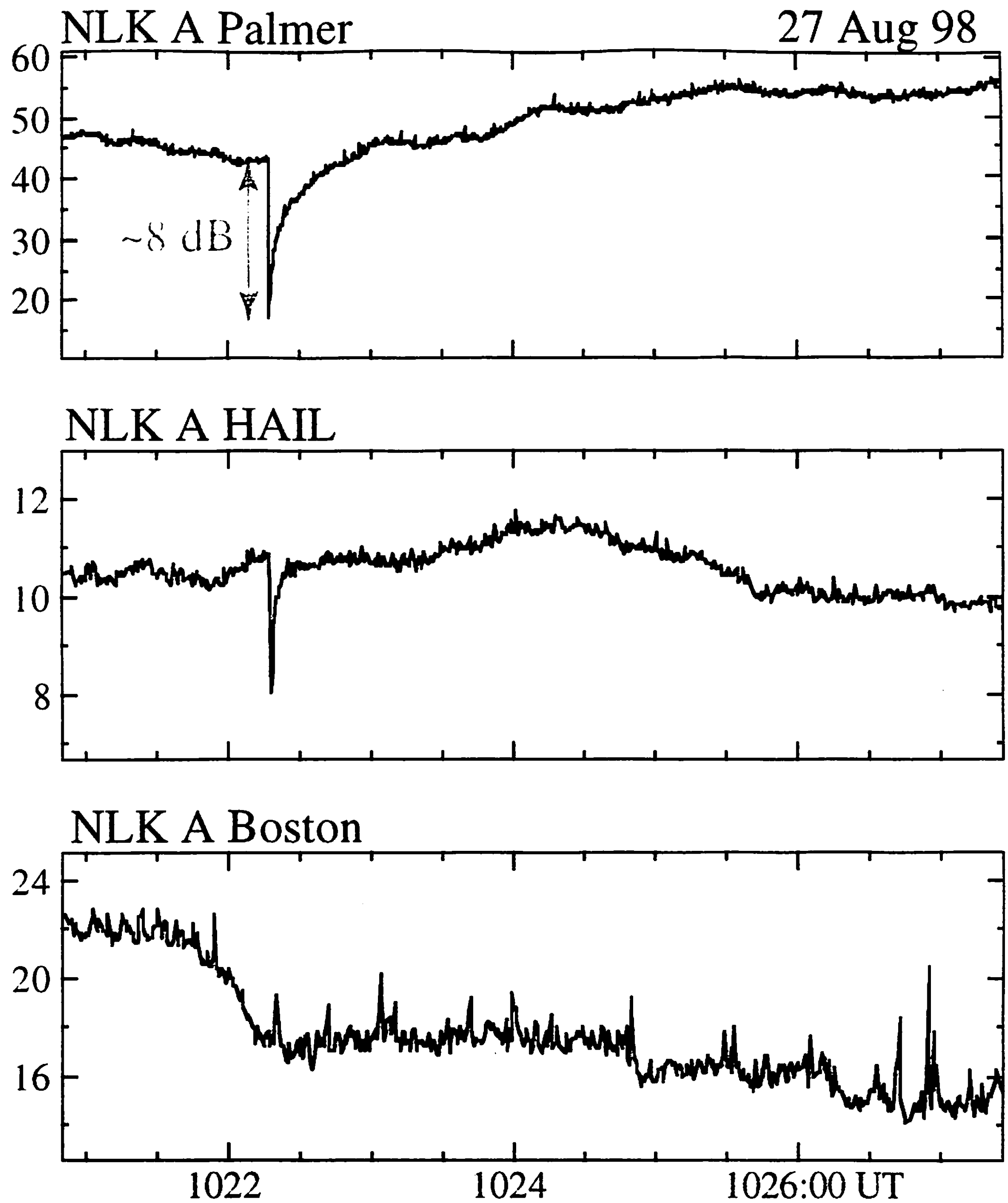

Gamma
Radiation
NLK
NAA
NPM



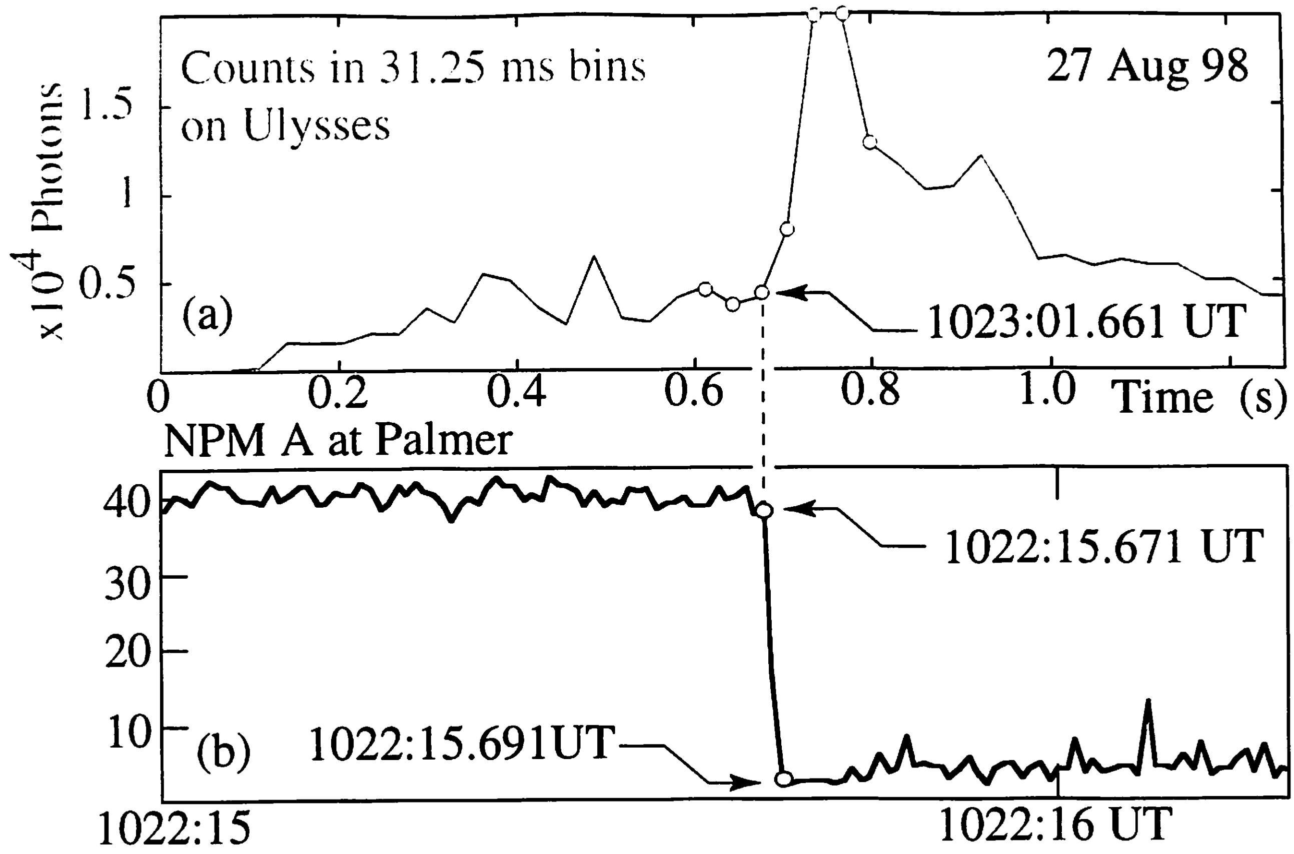
NPM A Palmer
27 Aug 98
~20 dB
NPM ϕ Palmer
~65°
NLK A Palmer
~8 dB
NLK ϕ Palmer
~26°
1022
1024
1026:00 UT

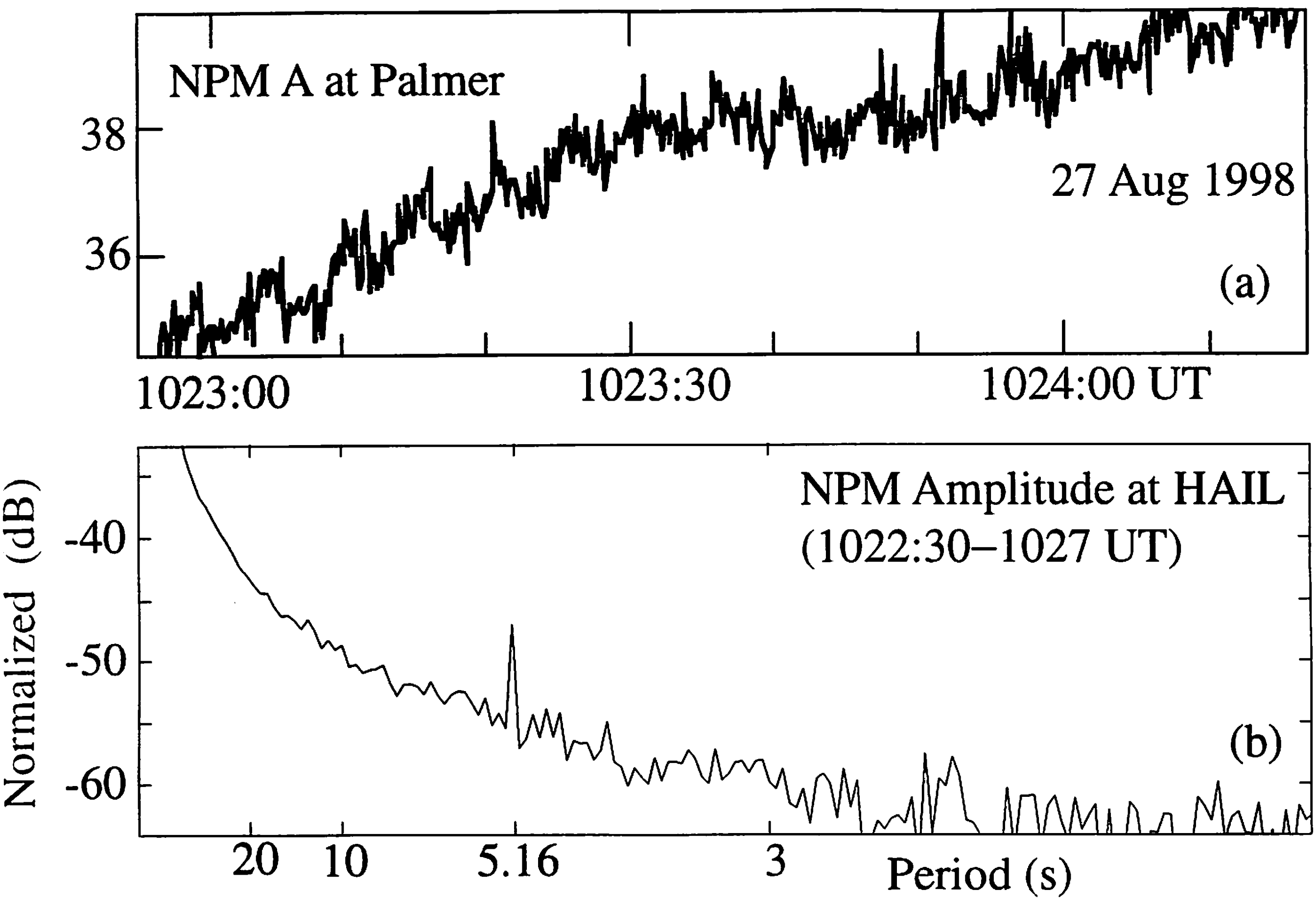


NPM A Fort Collins
27 Aug 98
~20 dB
NAA A Las Vegas
NPM A Las Vegas
~20 dB
1022
1024
1026:00 UT



NLK A Palmer
27 Aug 98
60
50
40
30
20
~8 dB
NLK A HAIL
12
10
8
NLK A Boston
24
20
16
1022
1024
1026:00 UT


Counts in 31.25 ms bins
on Ulysses
27 Aug 98
x10^4 Photons
1.5
1
0.5
(a)
1023:01.661 UT
0
0.2
0.4
0.6
0.8
1.0
Time (s)
NPM A at Palmer
40
30
20
10
(b)
1022:15.671 UT
1022:15.691UT
1022:15
1022:16 UT


NPM A at Palmer
38
36
27 Aug 1998
(a)
1023:00
1023:30
1024:00 UT
NPM Amplitude at HAIL
(1022:30–1027 UT)
Normalized (dB)
-40
-50
-60
(b)
20
10
5.16
3
Period (s)

Ionospheric Effects of the Gamma Ray Flare

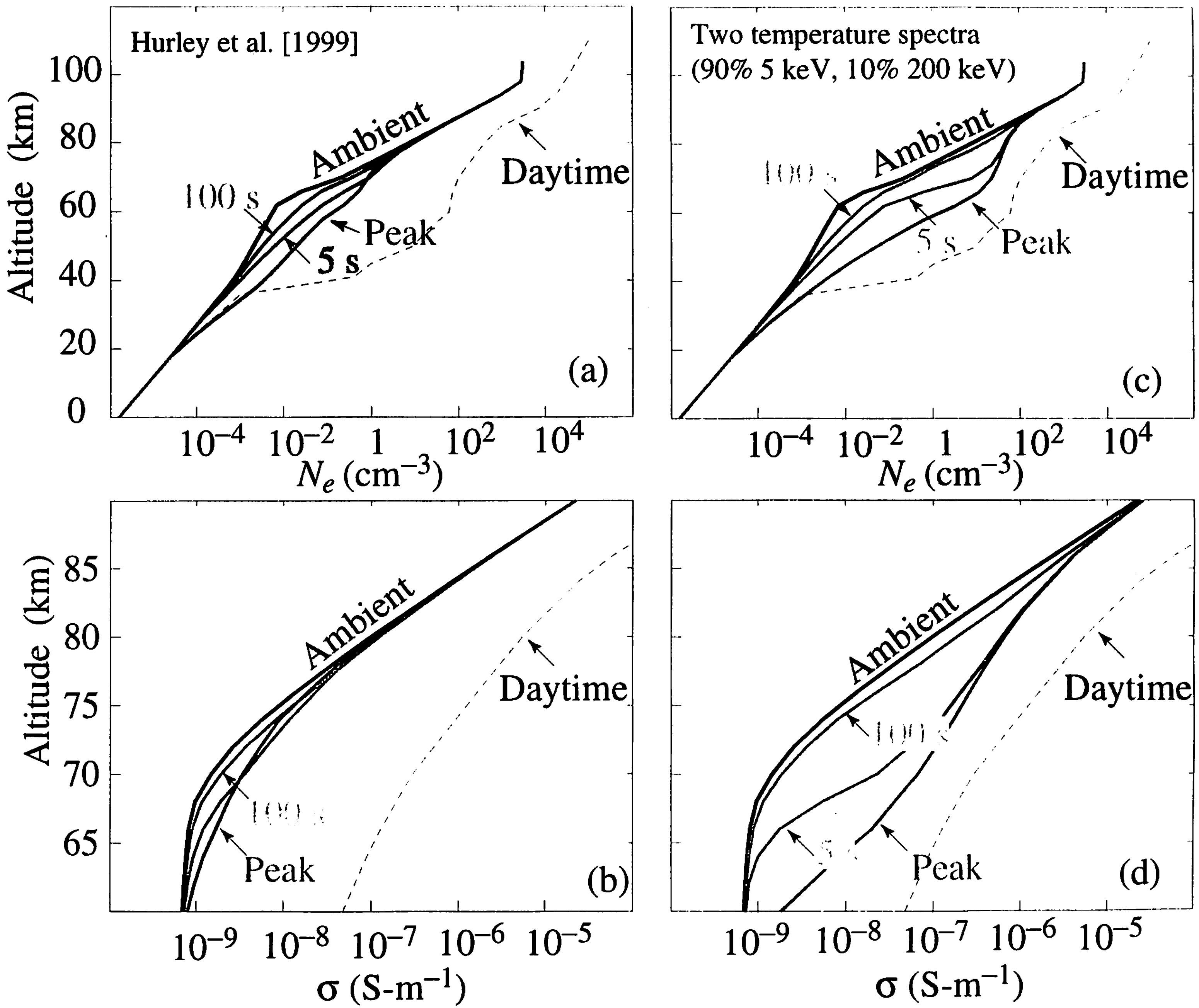
- Physical processes
  - *Compton scattering*: Elastic scattering of photons from charged particles [*Heitler,* 1954].
  - *Photoeffect*: Absorption of photon as it removes electrons from outer shell [Price et al, 1957; *Heitler*, 1954].
  - *Coherent (Rayleigh) scattering*: Photon scattering at small angles with no energy loss ($\sigma_{\mathrm{R}} \ll \sigma_{\mathrm{C}}$)
  - *Pair production:* Negligible ($T_{\max} = 240$ keV $\ll 2mc^2$).

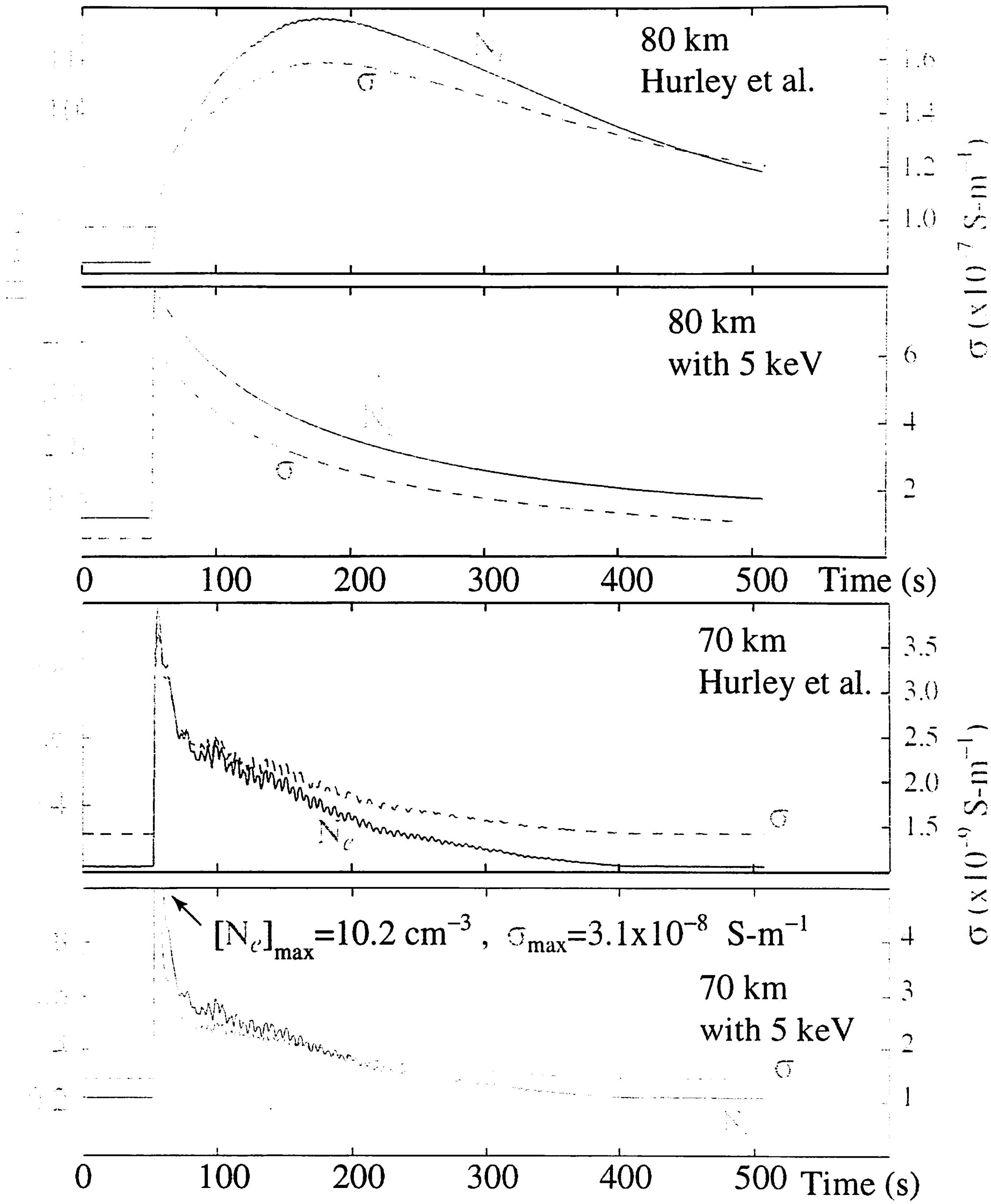
- Use Monte Carlo model using input data on gamma ray flux and spectra as a function of time from *Hurley et al.* [1999].
  - No pair production, and no significant bremmstrahlung. Consider photons one-by-one.
  - All photon energy is deposited within $\sim$1 km of collision. Assumed to all go into ionization.

- Time variation of electron density: $\dfrac{\partial N_e}{\partial t} = q - \alpha N_e^2$
  - Recombination rate α is as given by *Geldhill* [1986]
  - Ionization rate $q = q_{\gamma\text{-ray}} + q_{\text{ambient}}$

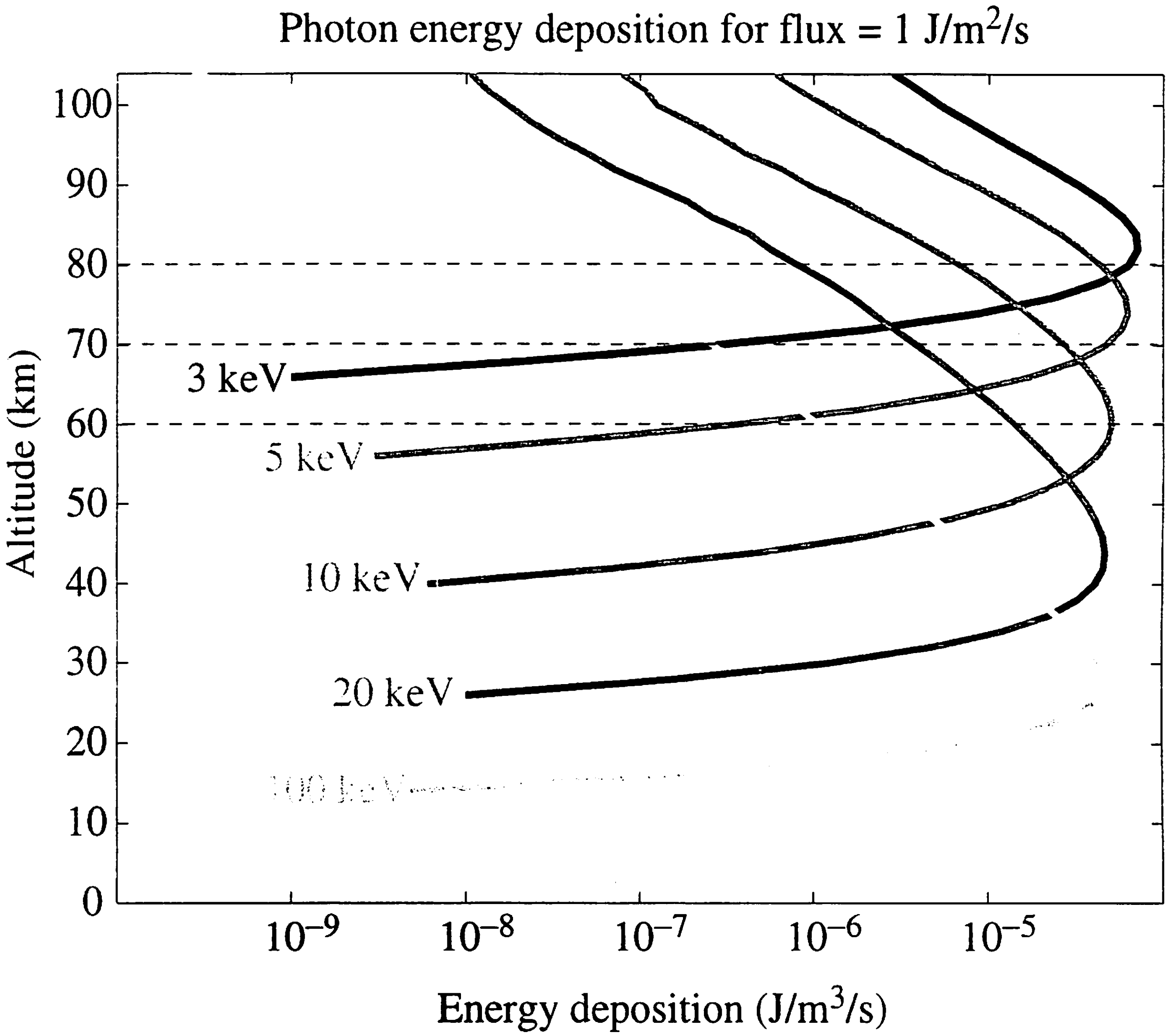
- Most of the energy is deposited at altitudes 20–30 km, but the largest ionization effect occurs at 70–80 km.

1. Gledhill, J. A., The effective recombination coefficient of electrons in the ionosphere between 50 and 150 km, *Radio Sci., 21*, 399, 1986.
2. Heitler, W. *The Quantum Theory of Radiation*, 3rd ed., Clarendon, Oxford, 1954.
3. Hurley, K., T. Cline, E. Mazets, S. Barthelmy, P. Butterworth, F. Marshall, D. Palmer, R. Aptekar, S. Golenetskii, V. Il'inski, D. Frederiks, J. McTiernan, R. Gold and J. Trombka, A giant periodic flare from the soft γ-ray repeater SGR1900+14, *Nature, 397*, 41, 1999.
4. Price, B. T., C. C. Horton, and K. T. Spinney, *Radiation Shielding*, Pergamon Press, 1957.

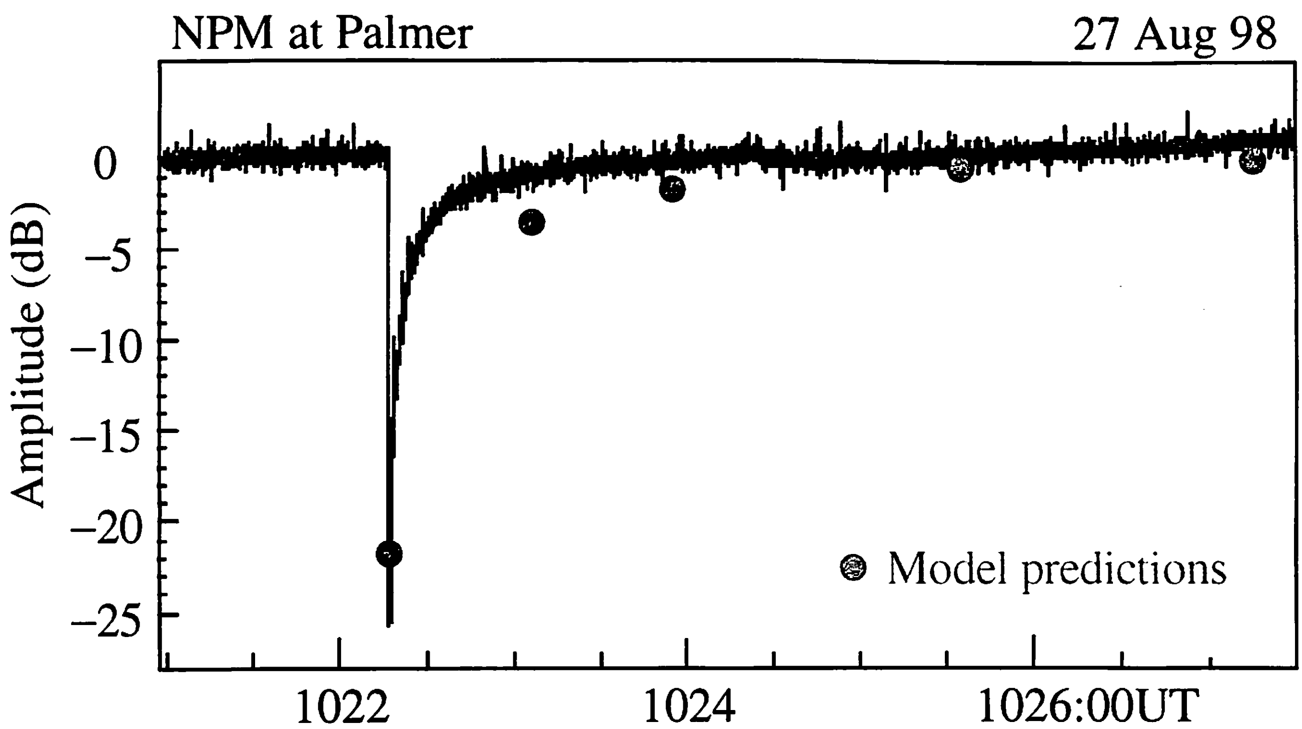

Hurley et al. [1999]
Altitude (km)
100
80
60
40
20
0
Ambient
Daytime
100 s
Peak
5 s
(a)
10^{-4} 10^{-2} 1 10^{2} 10^{4}
N_e (cm^{-3})
Two temperature spectra
(90% 5 keV, 10% 200 keV)
Ambient
Daytime
100 s
5 s
Peak
(c)
10^{-4} 10^{-2} 1 10^{2} 10^{4}
N_e (cm^{-3})
Altitude (km)
85
80
75
70
65
Ambient
Daytime
100 s
Peak
(b)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}
σ (S-m^{-1})
Ambient
Daytime
Peak
(d)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}
σ (S-m^{-1})



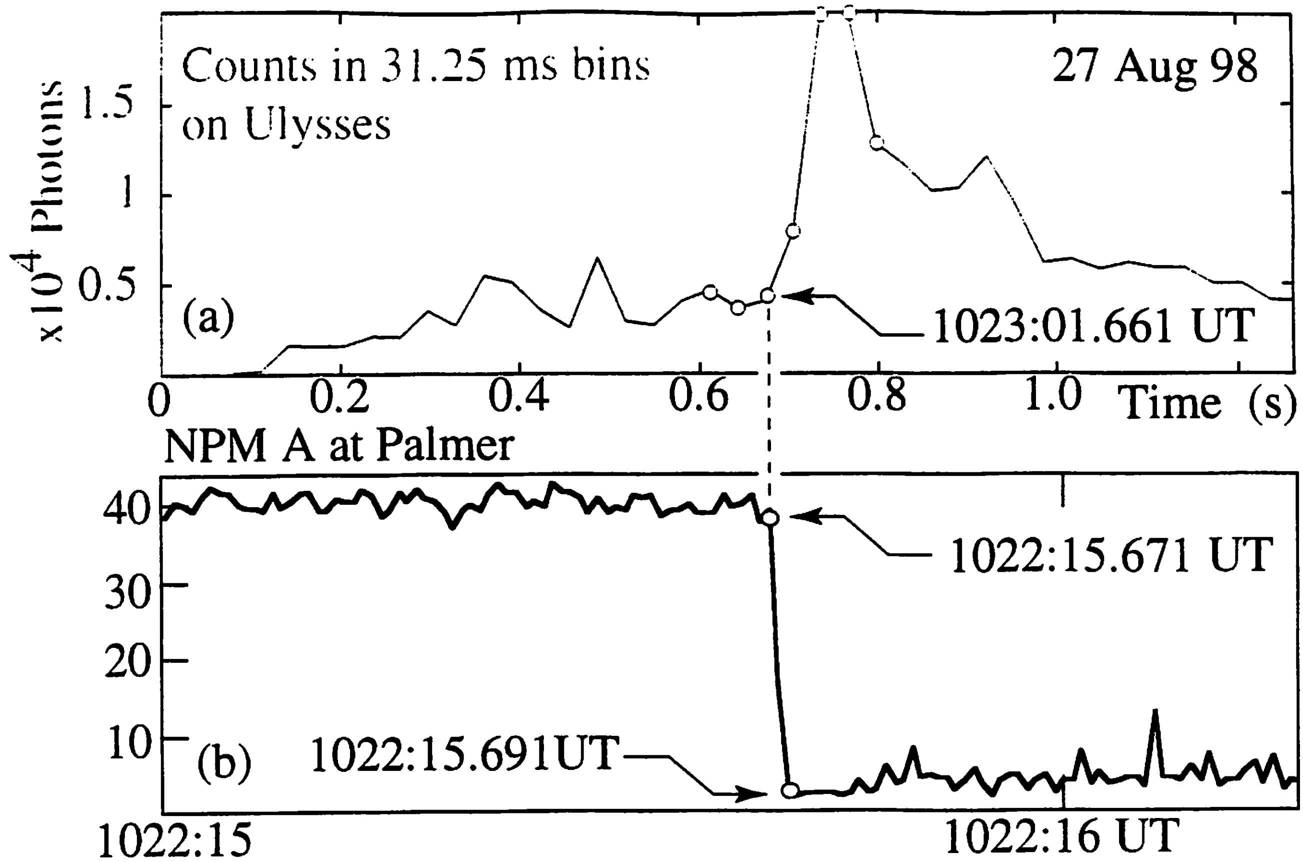
80 km
Hurley et al.
80 km
with 5 keV
0
100
200
300
400
500
Time (s)
70 km
Hurley et al.
$[N_e]_{max}$=10.2 cm^{-3} , σ_{max}=3.1x10^{-8} S-m^{-1}
70 km
with 5 keV
0
100
200
300
400
500
Time (s)
σ (x10^{-7} S-m^{-1})
σ (x10^{-9} S-m^{-1})

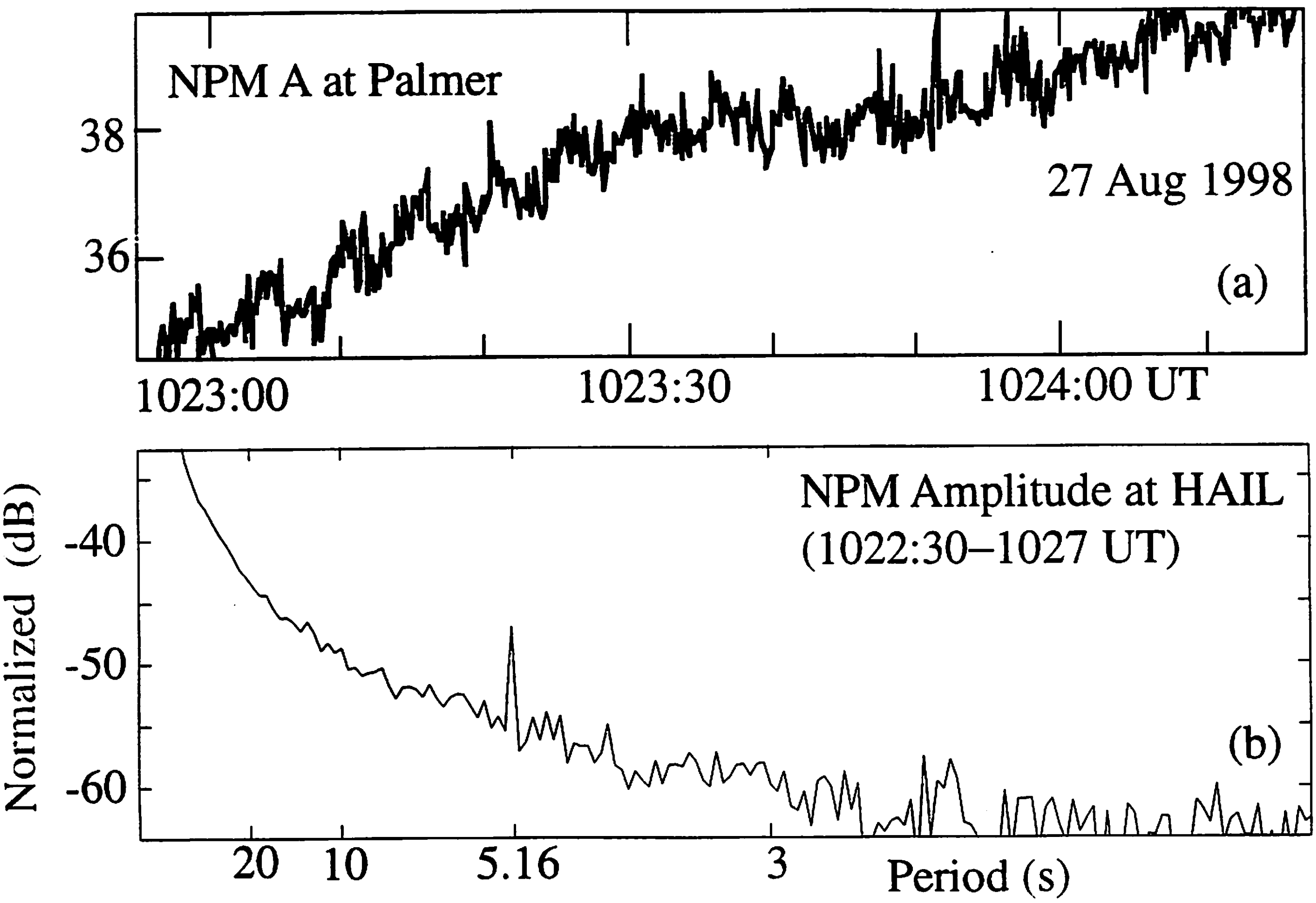


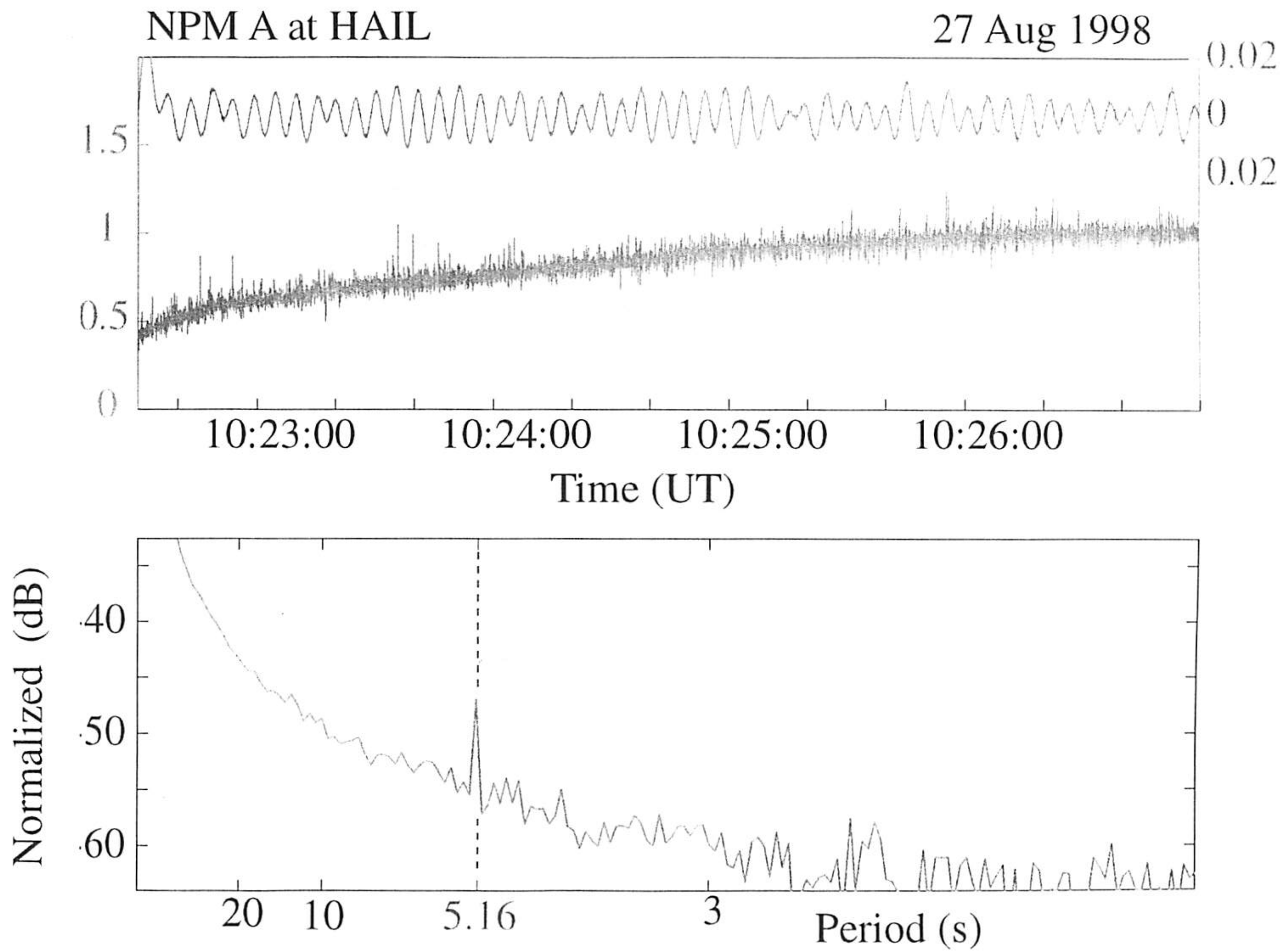
Photon energy deposition for flux = 1 J/m²/s
Altitude (km)
Energy deposition (J/m³/s)
3 keV
5 keV
10 keV
20 keV
100 keV
0
10
20
30
40
50
60
70
80
90
100
10⁻⁹
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵



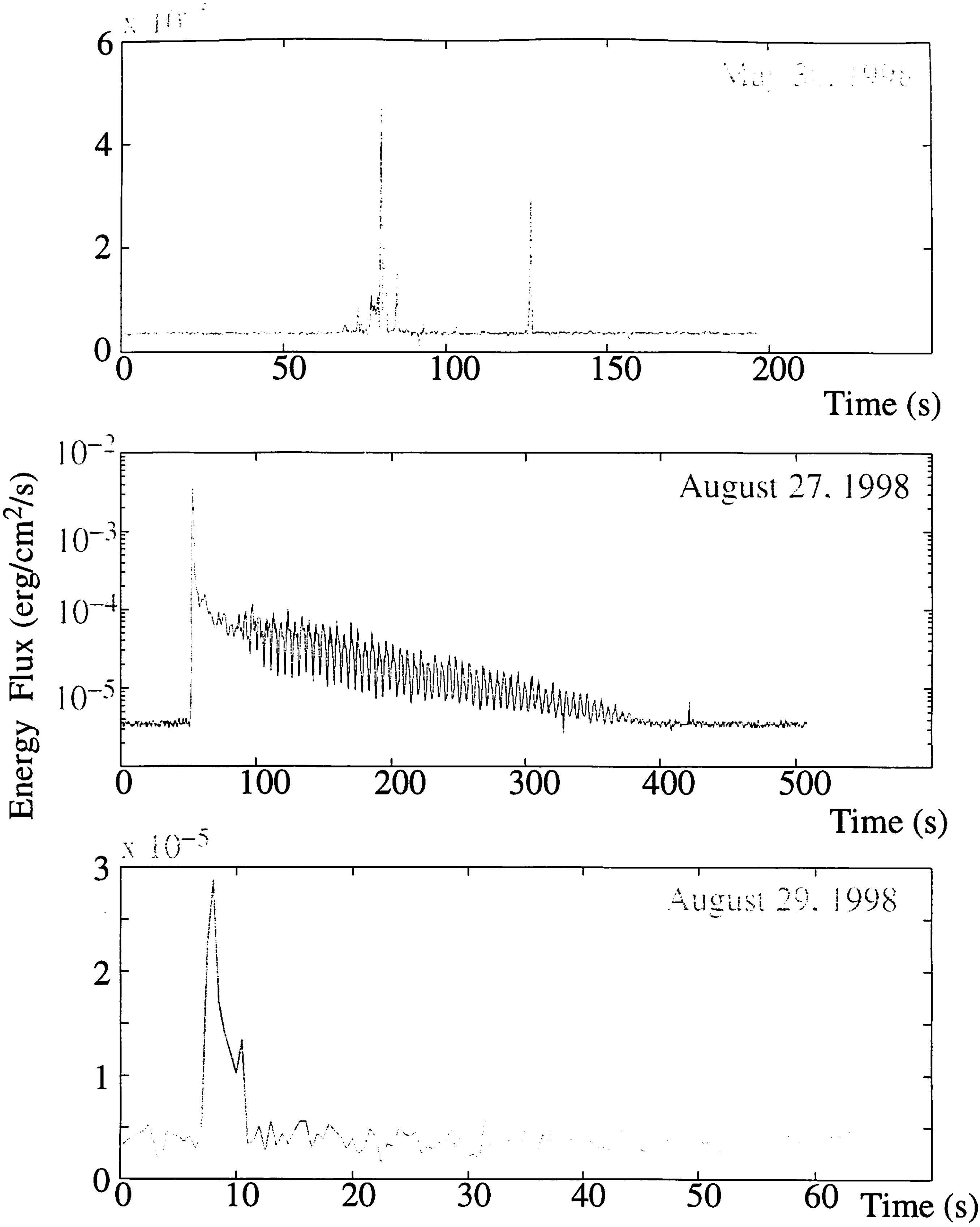
NPM at Palmer
27 Aug 98
Amplitude (dB)
0
−5
−10
−15
−20
−25
Model predictions
1022
1024
1026:00UT


Counts in 31.25 ms bins
on Ulysses
27 Aug 98
x10^4 Photons
(a)
1023:01.661 UT
Time (s)
NPM A at Palmer
1022:15.671 UT
(b)
1022:15.691UT
1022:15
1022:16 UT

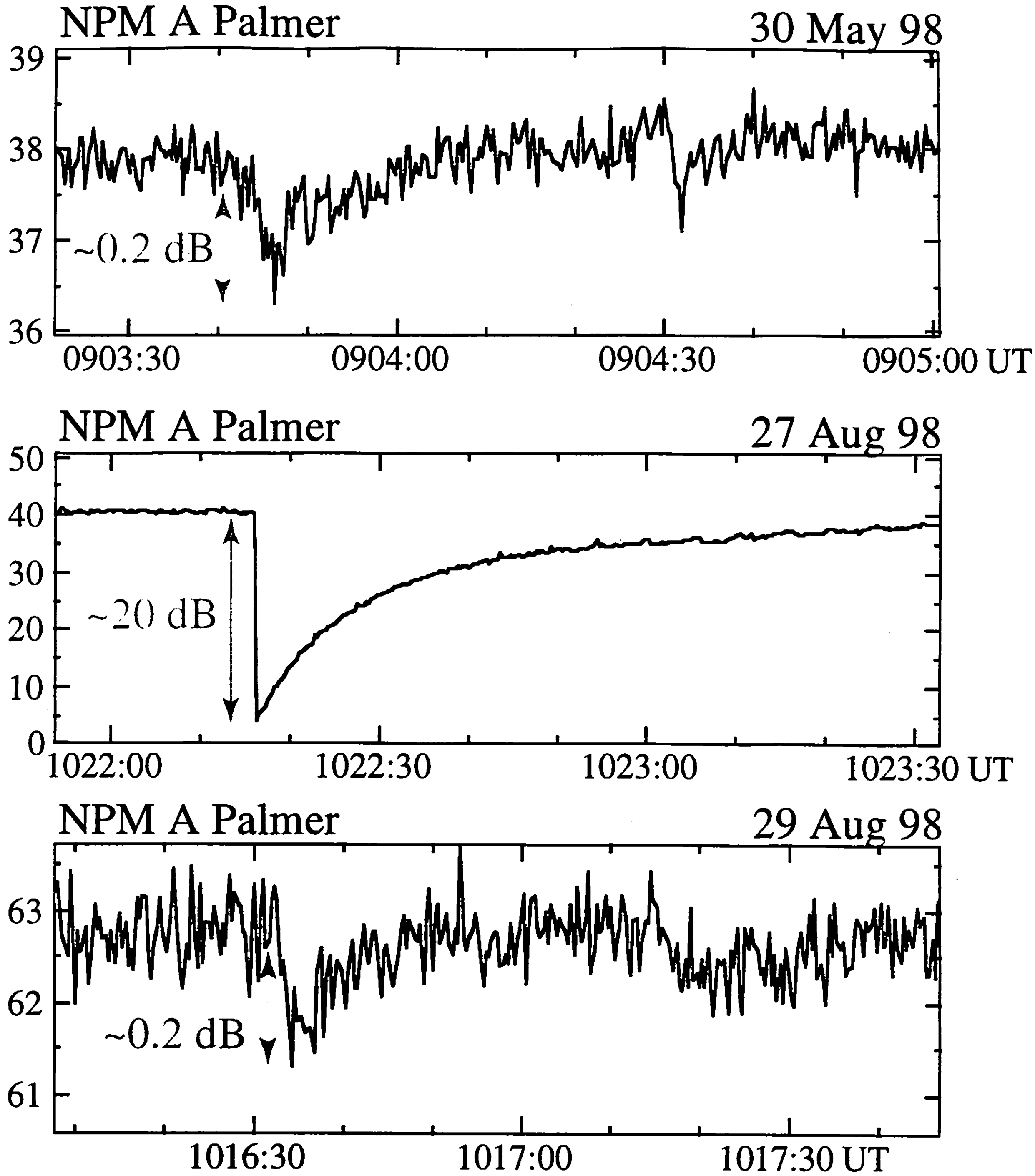

NPM A at Palmer
27 Aug 1998
(a)
1023:00
1023:30
1024:00 UT
NPM Amplitude at HAIL
(1022:30–1027 UT)
Normalized (dB)
(b)
Period (s)



NPM A at HAIL
27 Aug 1998
0.02
0
0.02
1.5
1
0.5
0
10:23:00
10:24:00
10:25:00
10:26:00
Time (UT)
Normalized (dB)
-40
-50
-60
20
10
5.16
3
Period (s)



May 30, 1998
August 27, 1998
August 29, 1998
Energy Flux (erg/cm^2/s)
Time (s)


NPM A Palmer
30 May 98
39
38
37
36
~0.2 dB
0903:30
0904:00
0904:30
0905:00 UT
NPM A Palmer
27 Aug 98
50
40
30
20
10
0
~20 dB
1022:00
1022:30
1023:00
1023:30 UT
NPM A Palmer
29 Aug 98
63
62
61
~0.2 dB
1016:30
1017:00
1017:30 UT