ULTRAVIOLET SPECTROSCOPY AND REMOTE SENSING

CEDAR WORKSHOP

Boulder CO

June 22, 1993

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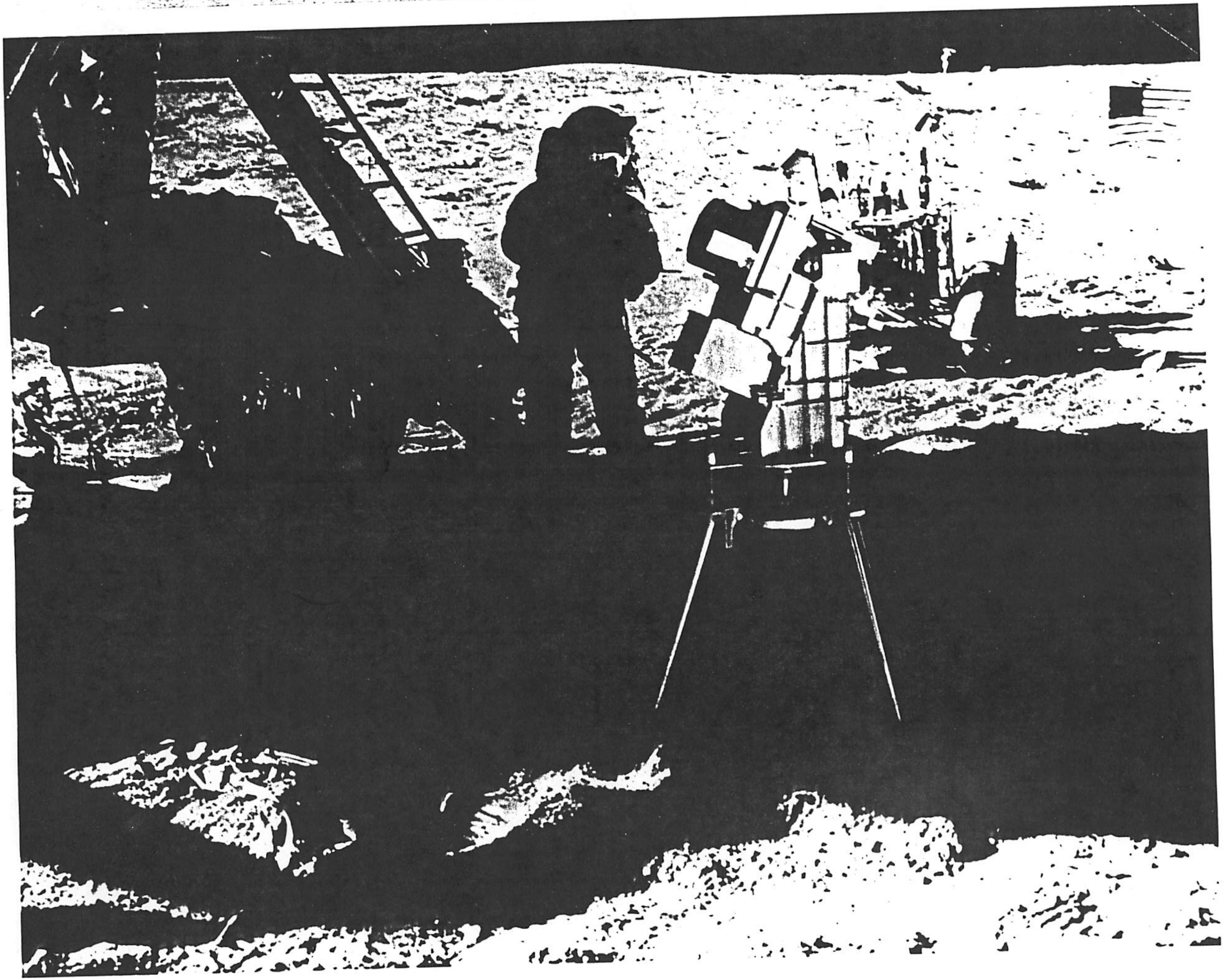
Code 7640
Naval Research Laboratory
202-767-2773

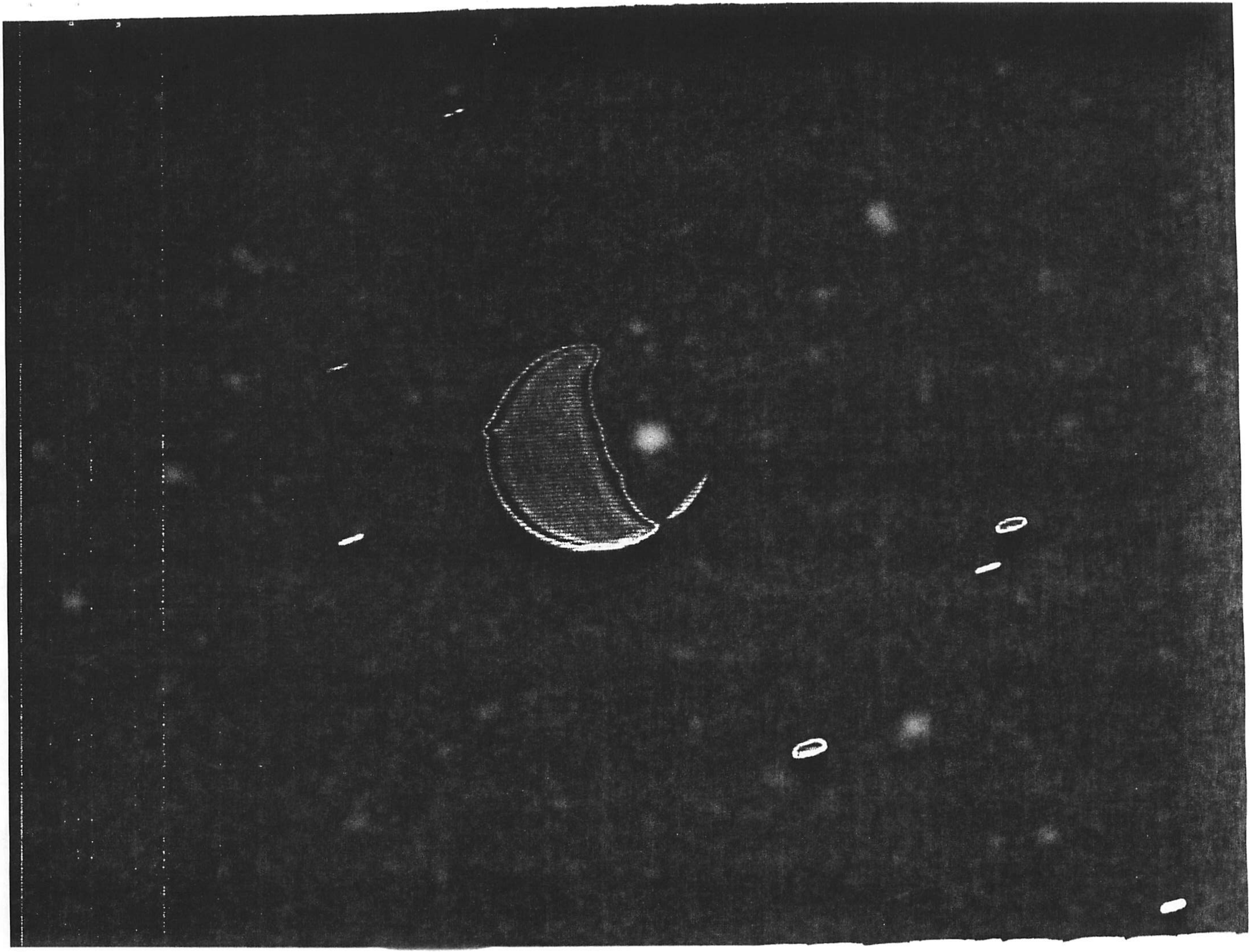
OVERVIEW

- *The Ultraviolet Earth: Images and Spectra*
- *Background and Early History*
- *Present Status of UV Remote Sensing*
    - *Global Imaging from High Altitude: DE*
    - *Limb Imaging from Low Altitude*
- *Inversion Techniques*
- *Global Change and Climatological Databases*
- *Summary*

NRL FUV CAMERA ON APOLLO-16

- *Observations: 21-23 April 1972*
- *Location: Lunar Surface*
- *Sun-Earth-Moon Angle: 105 deg*
- *Broadband Imagery:*
  - 1250 - 1600 Å
  - 1050 - 1600 Å
- *Spectroscopy: 500 - 1600 Å*



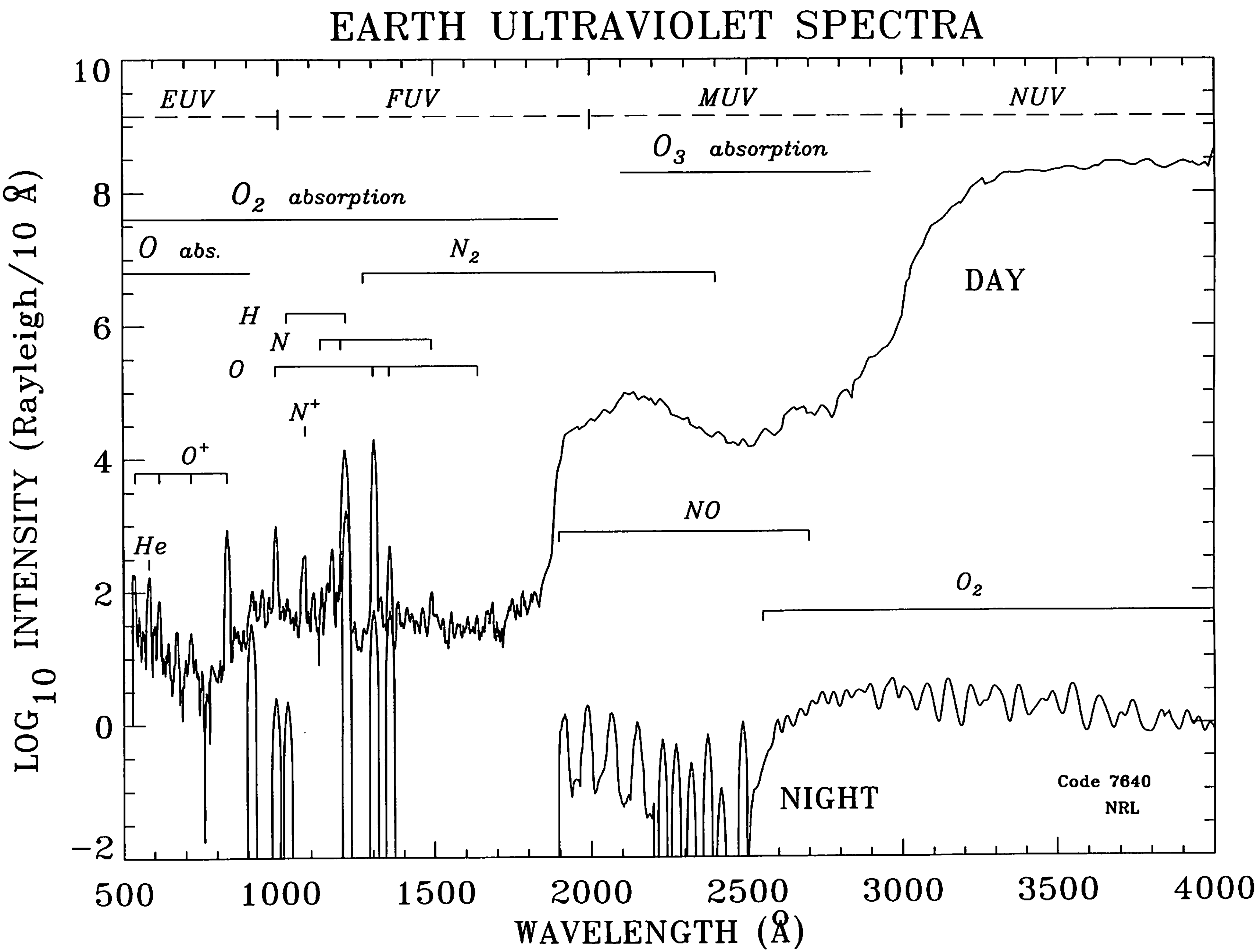


U. IOWA EXPERIMENT ON DYNAMICS EXPLORER (DE) - 1

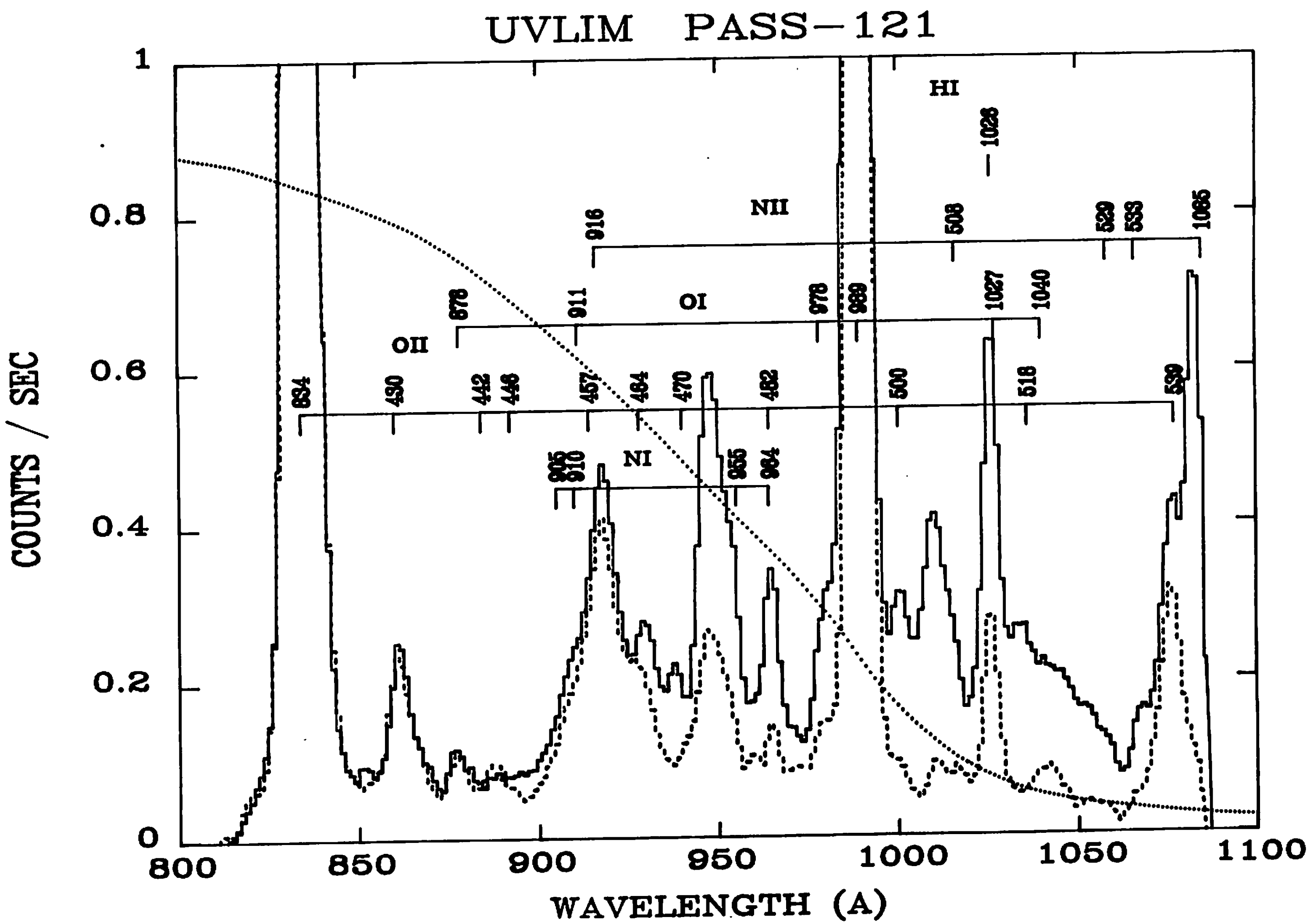
- *Launch: 3 August 1981*
- *Initial orbit: 570 km x 3.65 R_e*
- *Initial latitude of apogee: 78.2°*
- *Spin-scan imaging with about 12 min per image at apogee*
  - Photometer A: visible
  - Photometer B: visible
  - Photometer C: Far UV

    with 12 filters each

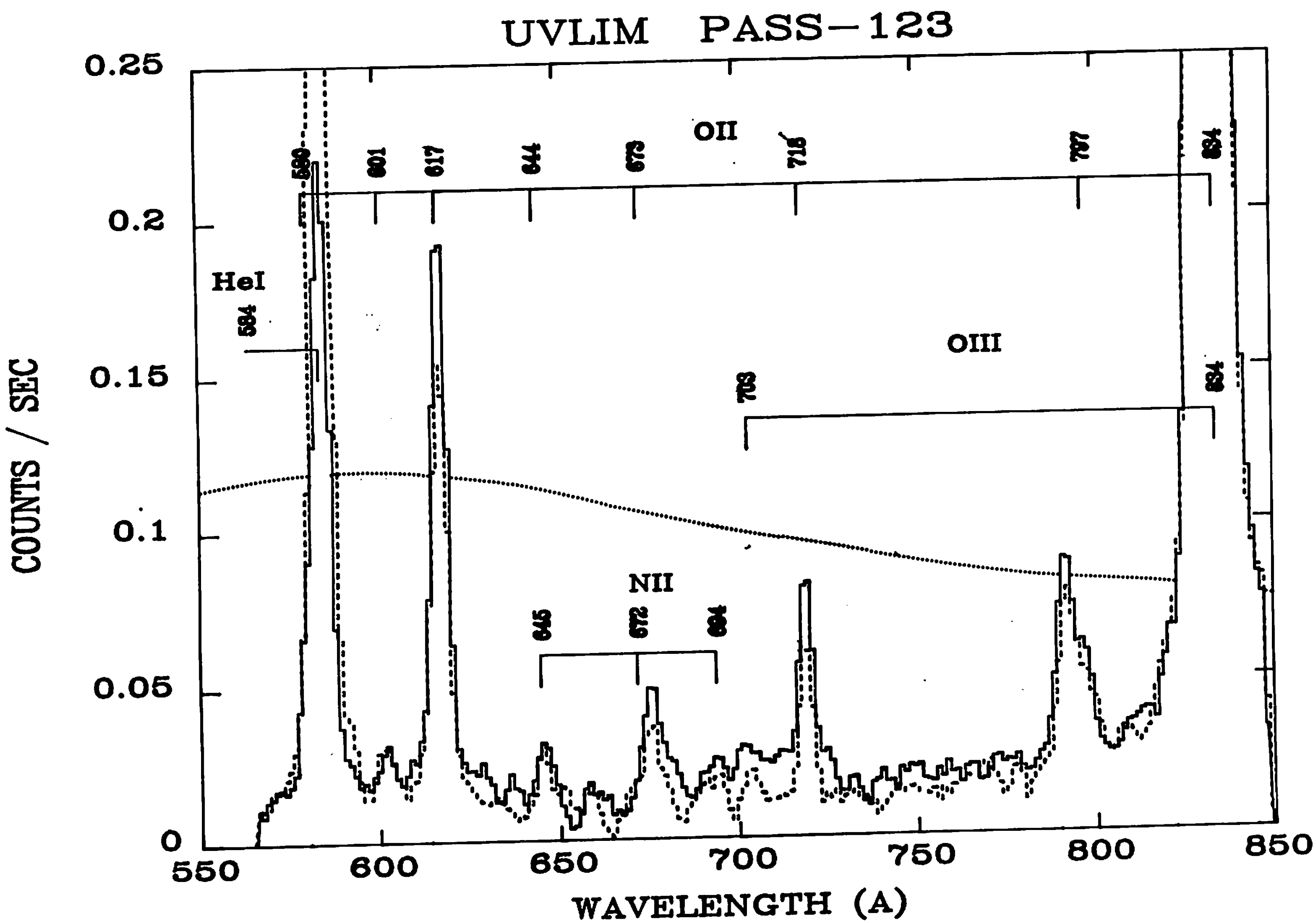
- *Photometer instantaneous field-of-view 0.32°*



EARTH ULTRAVIOLET SPECTRA
EUV
FUV
MUV
NUV
O3 absorption
O2 absorption
O abs.
N2
DAY
H
N
O
N+
O+
NO
He
O2
NIGHT
Code 7640
NRL
LOG10 INTENSITY (Rayleigh/10 Å)
WAVELENGTH (Å)
10
8
6
4
2
0
−2
500
1000
1500
2000
2500
3000
3500
4000

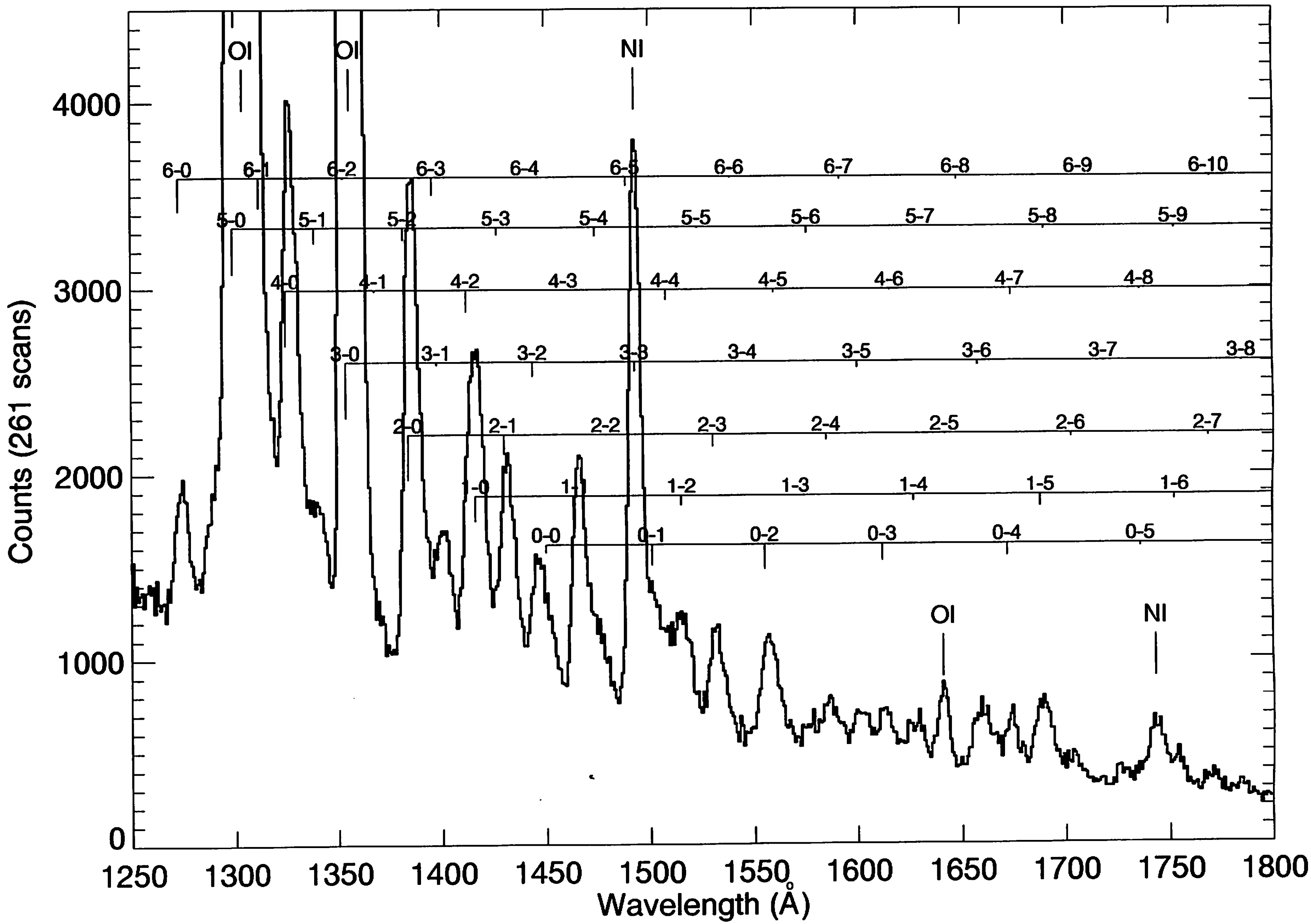


UVLIM PASS-121
COUNTS / SEC
WAVELENGTH (A)
HI
1026
NII
916
508
529
533
1085
OI
878
911
978
989
1027
1040
OII
834
430
442
446
457
464
470
482
500
518
539
NI
905
910
955
964
0
0.2
0.4
0.6
0.8
1
800
850
900
950
1000
1050
1100



UVLIM PASS-123
COUNTS / SEC
WAVELENGTH (A)
0.25
0.2
0.15
0.1
0.05
0
550
600
650
700
750
800
850
OII
601
617
644
673
718
797
834
HeI
584
OIII
703
834
NII
645
672
694

UVLIM



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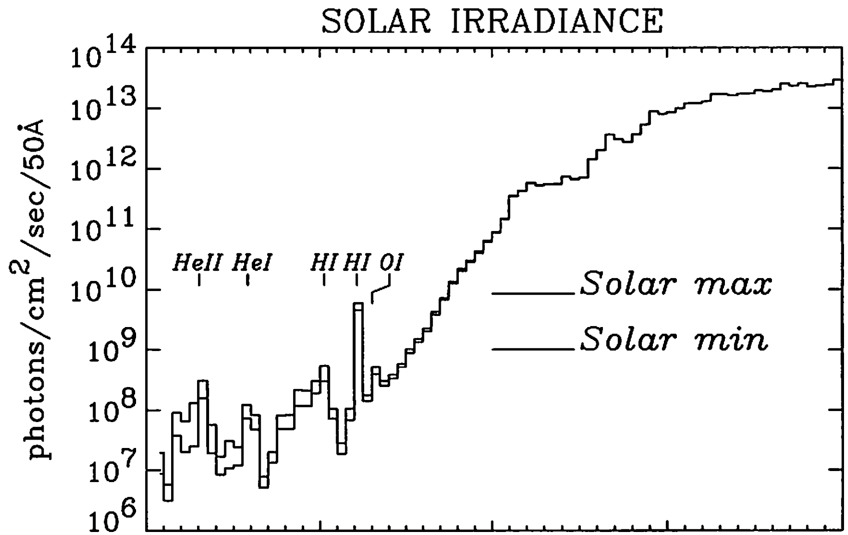
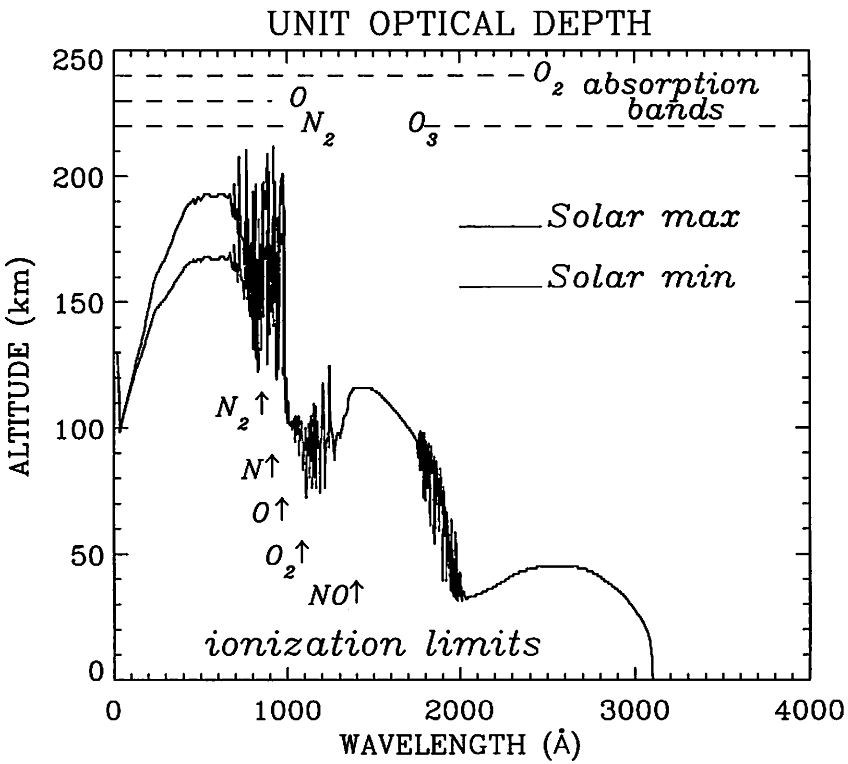
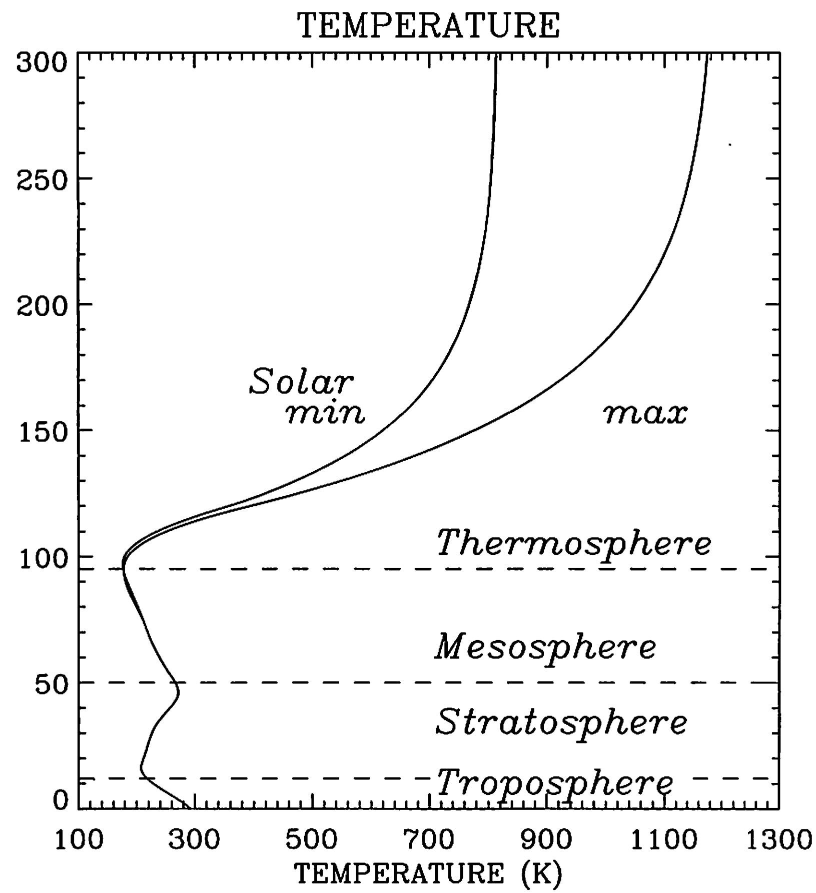
Heating of the Atmosphere by Variable Solar Ultraviolet Radiation

NRL Codes 7640 & 7670







EXCITATION MECHANISMS

- ***RESONANT SCATTERING OF SUNLIGHT***
  - SOLAR LINES: OI 1304, 1026; HI 1216, 1026; HeI 584, 540; HeII 304
  - SOLAR CONTINUUM: $NO\gamma$; N_2^+ 1NG

- ***ENERGETIC PARTICLE IMPACT***
  - PHOTO ELECTRONS: DAYGLOW
  - PRECIPITATING ELECTRONS (AND PROTONS): AURORA
  - HEAVY ATOM PRECIPITATION: NIGHTGLOW

- ***PHOTO/ION CHEMISTRY***
  - PHOTO-IONIZATION: $O + h\nu \rightarrow O^{*+} + e \rightarrow 834$ Å
  - RADIATIVE RECOMBINATION: $O^+ + e \rightarrow O$ (1356, 1304, 989, 911)
  - ION-ION RECOMBINATION: $O^+ + O^- \rightarrow O^* + O^*$
  - CHEMILUMINESCENCE: $N(^4S) + O\ (^3P) \Leftrightarrow NO\ (C)$

    $$O + O + M \rightarrow O_2\ (A)$$
  - DISSOCIATION: $O_2 + [h\nu \text{ or } e] \rightarrow O + O^*$

    $$N_2 + [h\nu \text{ or } e] \rightarrow N + N^* \text{ or } N + N^{+*} + e$$

EARLY HISTORY OF UV SPECTROSCOPY

1946	Sun observed to 2100 Å, O_3 observed to 55 km	*Baum et al.* [1946]
1949	O_2 extinction observed	*Friedman et al.* [1951]
1955	H Lyman α discovered	*Byram et al.* [1961]
1960, 1963	OI & N_2 LBH discovered	*Fastie et al.* [1961, 1964]

Other early contributors: T.M. Donahue, R. Tousey, J.W. Chamberlain, J. Brandt, F.S. Johnson, I.S. Shklovsky, C. Barth, V.G.Kurt, S.A. Kaplan

VERY LONG MATURATION TIME FOR ROUTINE UV REMOTE SENSING MISSIONS

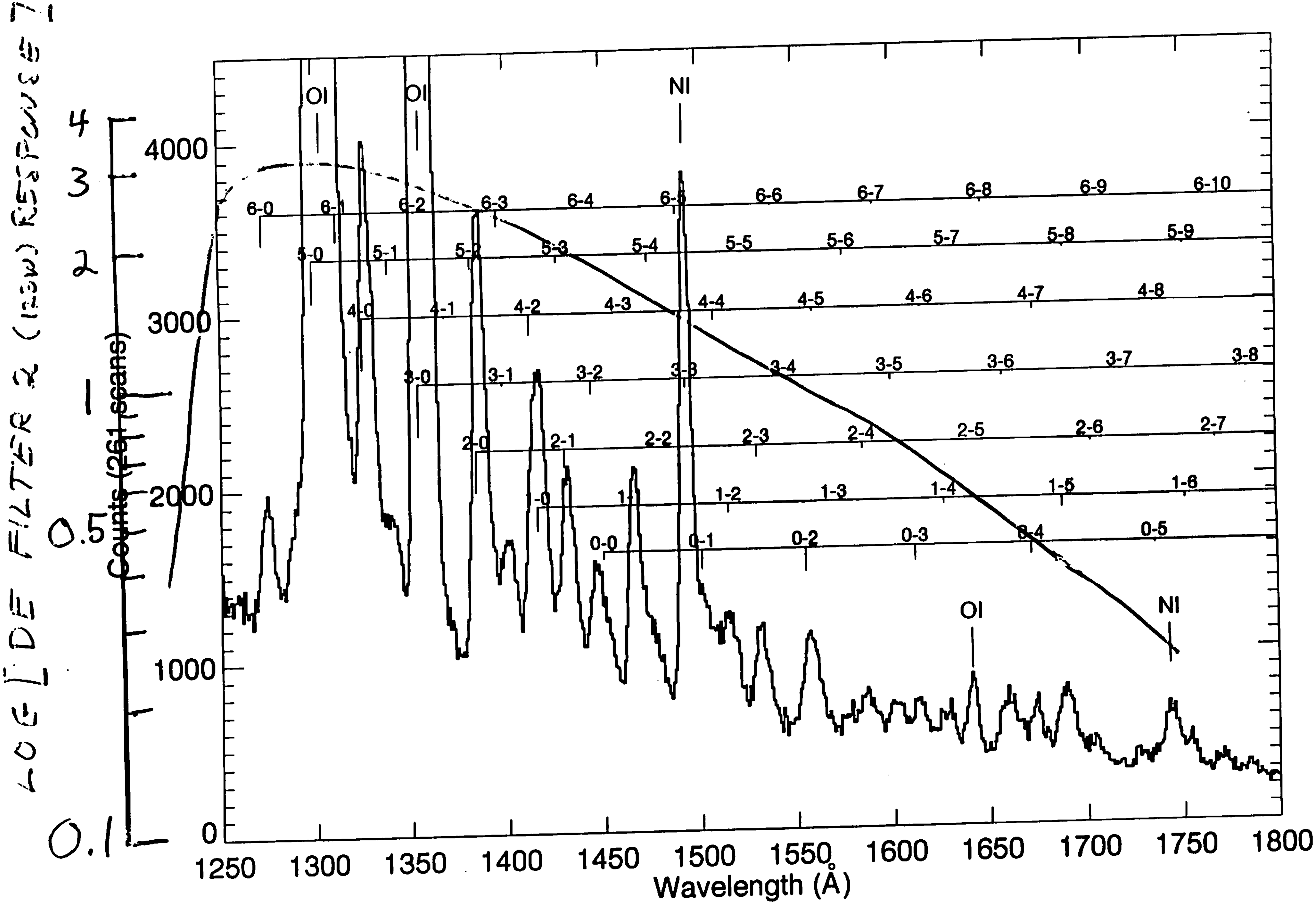
because:

- *Reliable cross sections, oscillator strengths... required*
- *High sensitivity imagers and spectrographs needed*
- *Science models had to be developed*
- *Retrieval algorithms necessary for parameter extraction*

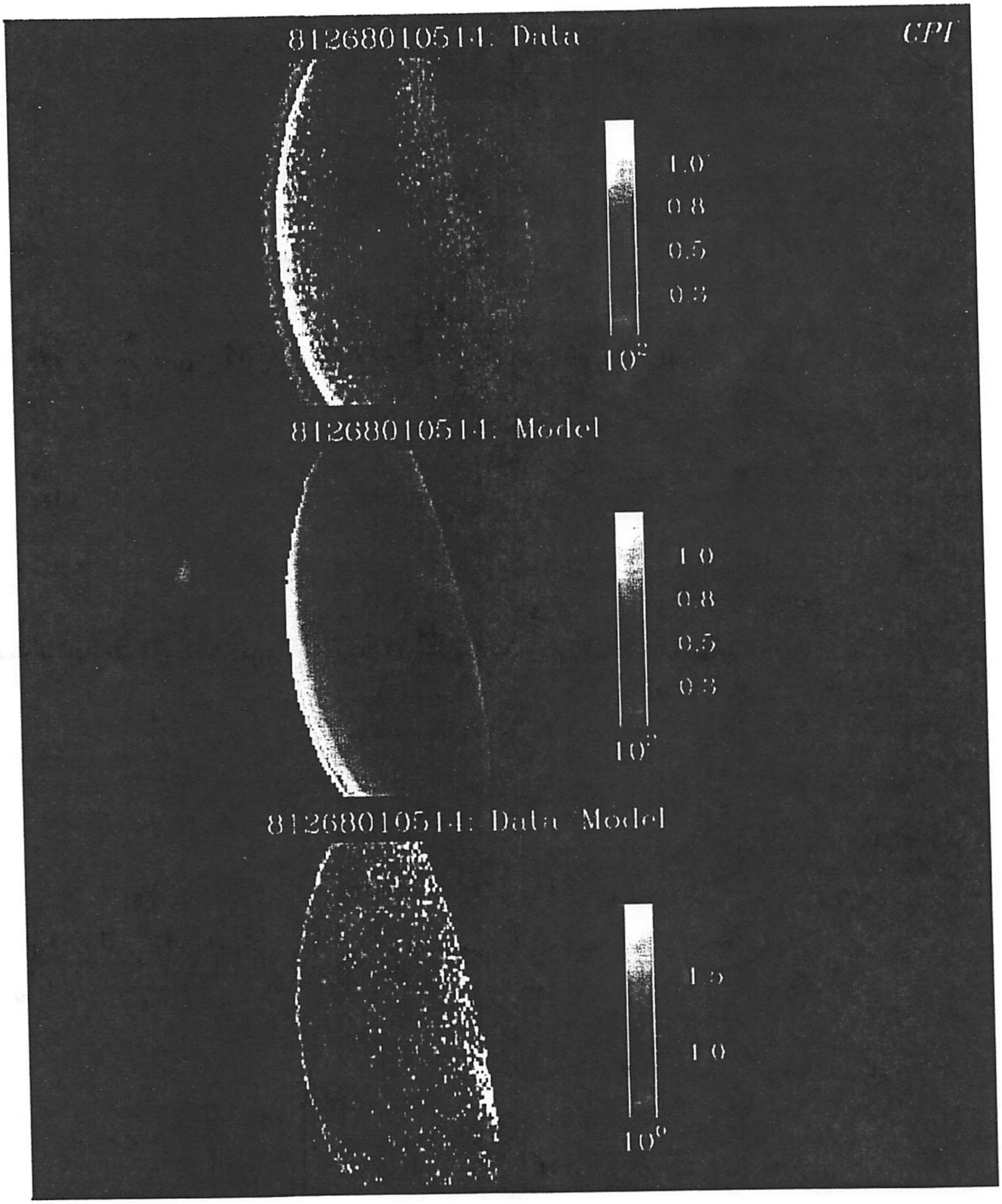
GLOBAL IMAGING MODEL

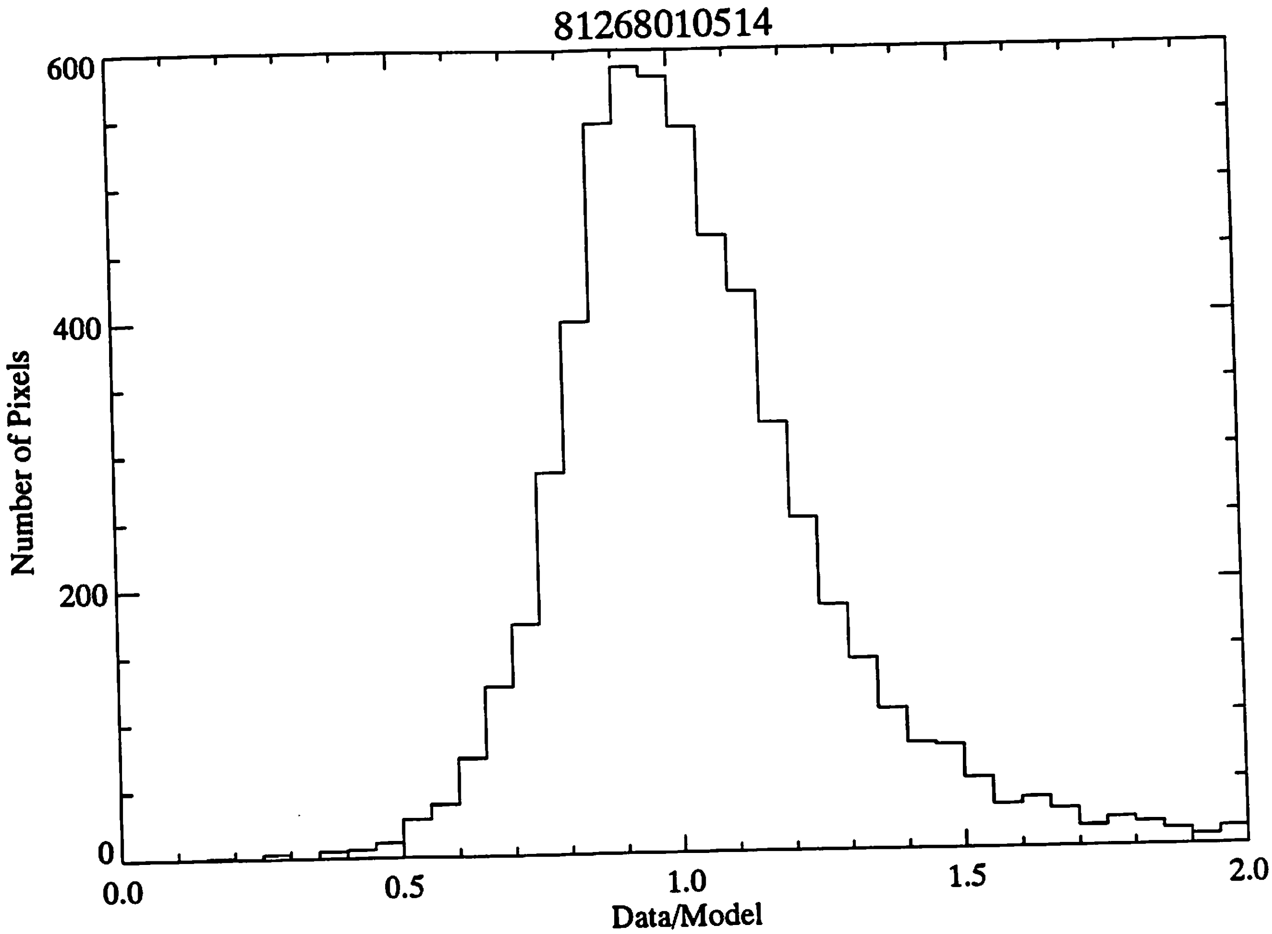
- *AIRGLOW MODEL*
  - MSIS-86 SPECIFIES GLOBAL CONCENTRATIONS
  - HINTEREGGER SOLAR EUV FLUX ALGORITHM
  - STRICKLAND AND MEIER PHOTOELECTRON MODEL
  - RADIATIVE TRANSPORT MODELS
    - OI 1356: Strickland and Anderson
    - OI 1304: Gladstone or Meier

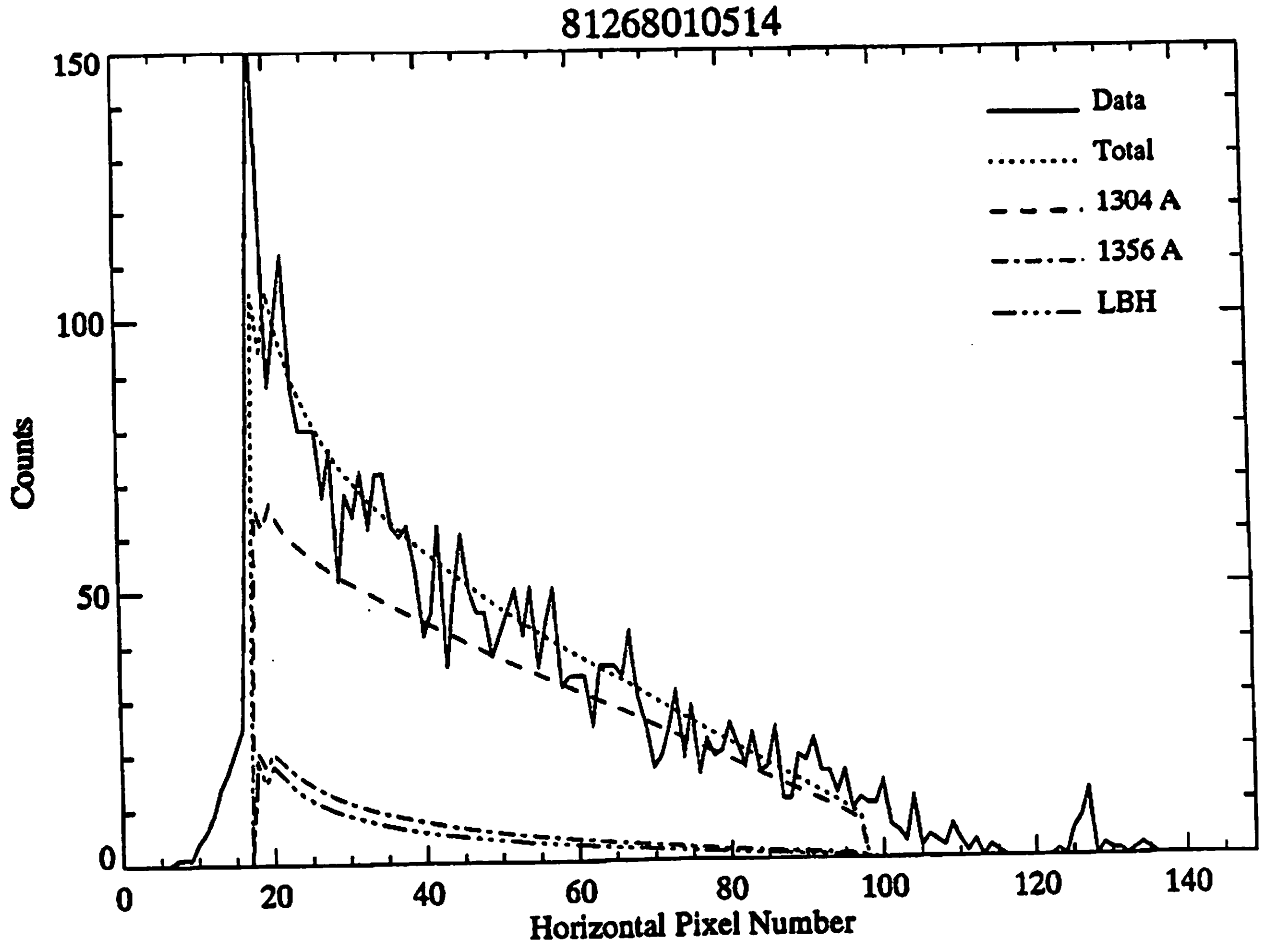
- *IMAGING MODEL*
  - MODEL DESCRIBED BY: Strickland, Cox, Barnes, Paxton, Meier, Thonnard
    -accepted in *Applied Optics [1993]*
  - USES GEOGRAPHIC GRID WITH VARIABLE SPACING IN SOLAR ZENITH AND AZIMUTH ANGLES
  - PRE-COMPUTES INTENSITIES VS LOOK ANGLE AT EACH GRID POINT AND INTERPOLATES TO DYNAMICS EXPLORER LOOK ANGLES



LOG [DE FILTER 2 (N3W) RESPONSE]
Counts (261 scans)
Wavelength (Å)
OI
OI
NI
OI
NI
0.1
0.5
1
2
3
4
0
1000
2000
3000
4000
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
1750
1800
6-0
6-1
6-2
6-3
6-4
6-5
6-6
6-7
6-8
6-9
6-10
5-0
5-1
5-2
5-3
5-4
5-5
5-6
5-7
5-8
5-9
4-0
4-1
4-2
4-3
4-4
4-5
4-6
4-7
4-8
3-0
3-1
3-2
3-3
3-4
3-5
3-6
3-7
3-8
2-0
2-1
2-2
2-3
2-4
2-5
2-6
2-7
1-2
1-3
1-4
1-5
1-6
0-0
0-1
0-2
0-3
0-4
0-5


81268010514: Data
CPI
1.0
0.8
0.5
0.3
10^2
81268010514: Model
1.0
0.8
0.5
0.3
81268010514: Data/Model
1.5
1.0
10^0

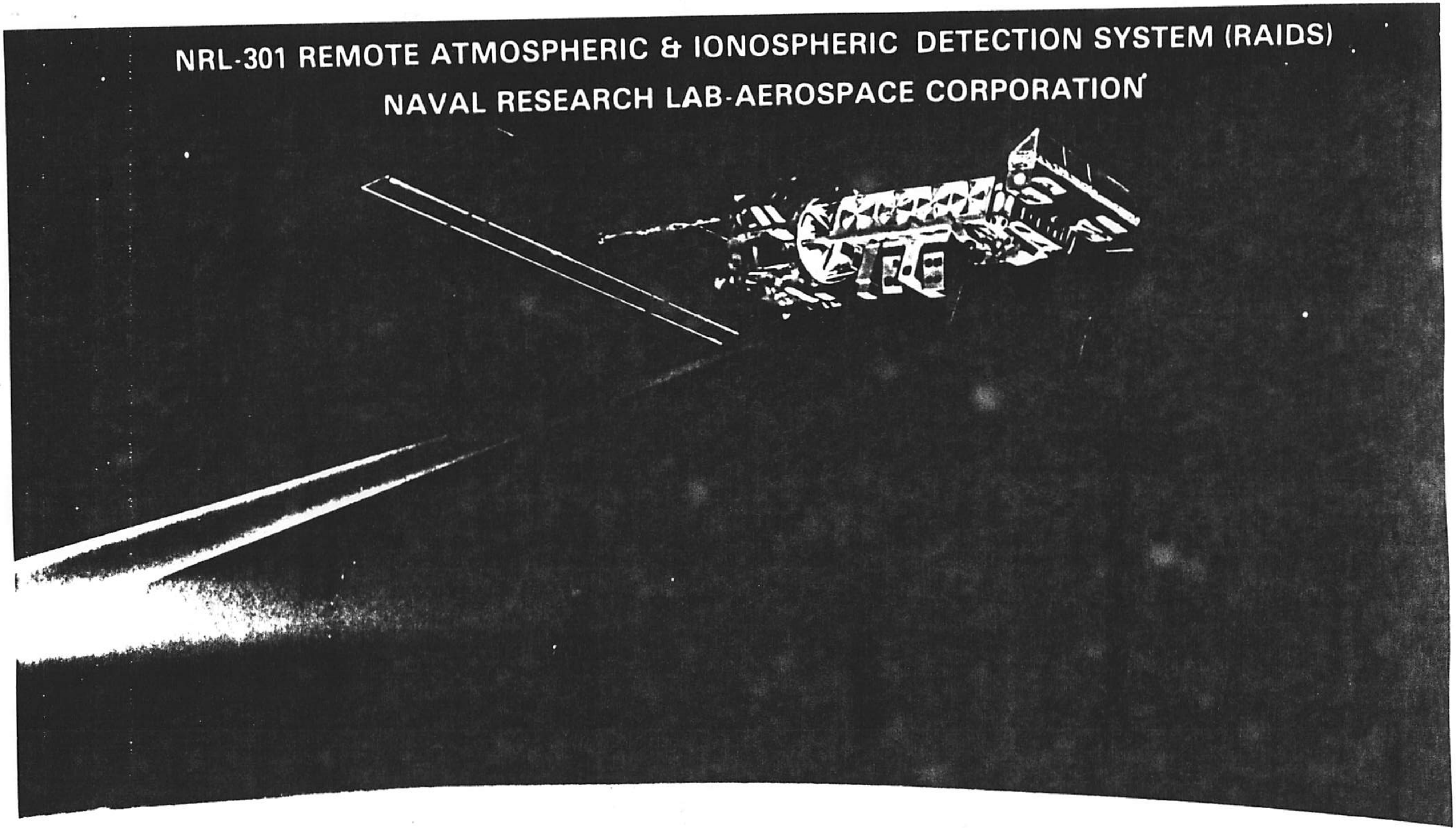

81268010514
Number of Pixels
600
400
200
0
0.0
0.5
1.0
1.5
2.0
Data/Model



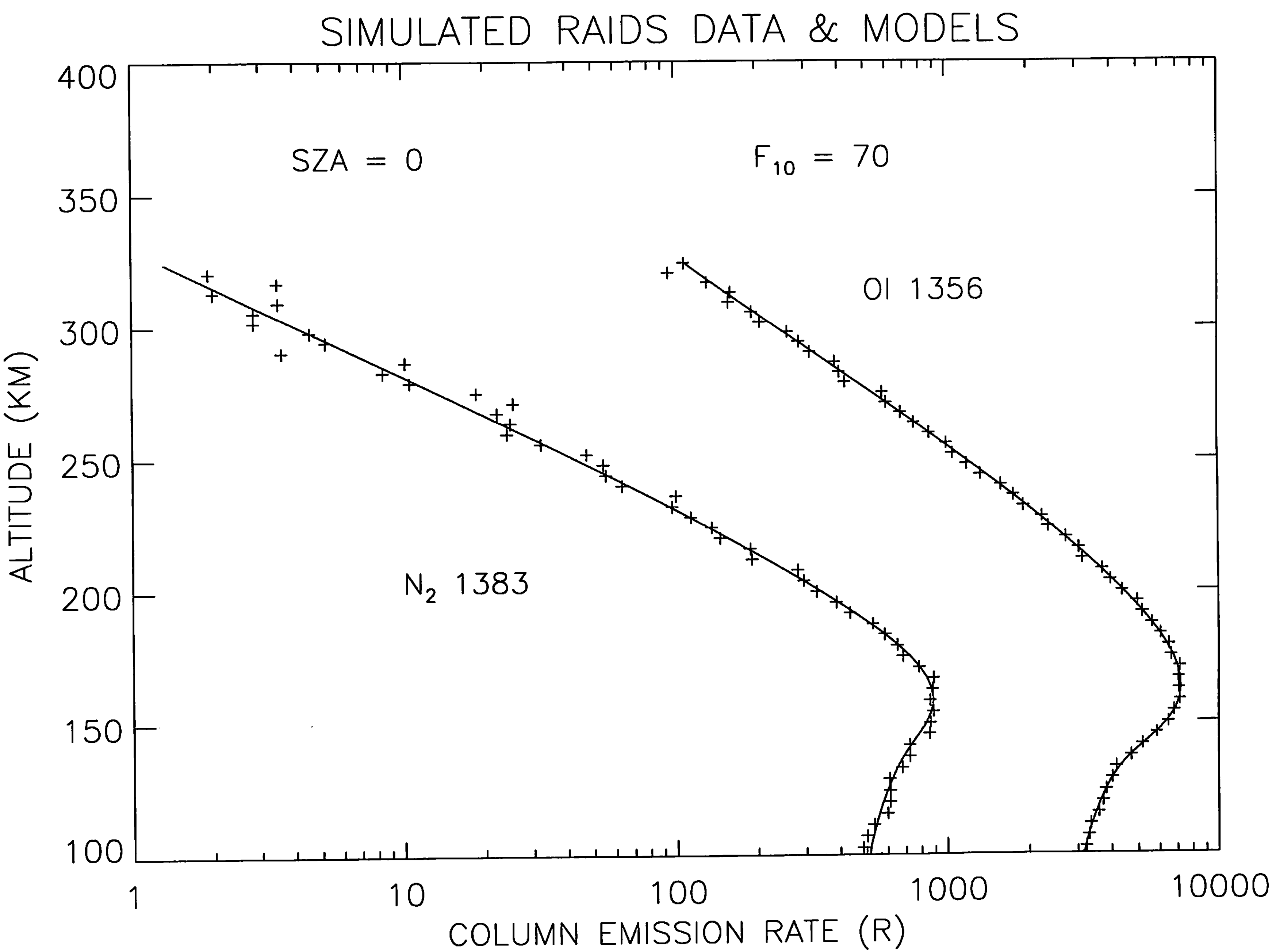
81268010514
Data
Total
1304 A
1356 A
LBH
Counts
150
100
50
0
0
20
40
60
80
100
120
140
Horizontal Pixel Number

CONCLUSIONS: 1230 - 1800 Å DATA

- ***MODEL REPRODUCES DATA TO WITHIN ± 17%***
    - model scaling for individual images: 0.92 - 0.99
    - deviations due to statistics or aurora
- ***SPATIAL VARIABILITY WELL-REPRODUCED BY MODEL***
- ***OI 1304 Å DOMINATES (~ 85 %) DISK PORTION OF (FILTER 2) IMAGES***
    - 60 % (photoelec.) + 25 % (solar res.scat.) = 85%
    - OI 1356 Å ~ 7 %
    - N_2 LBH bands ~ 7 %
- ***OI 1356 Å AND N_2 LBH BANDS DOMINATE AT LIMB***
- ***CAN PROCEED WITH CONFIDENCE TO DISTURBED-TIME IMAGES***



- EVALUATE CONCEPT OF GLOBAL UV REMOTE IONOSPHERIC SENSING
- OBTAIN ELECTRON DISTRIBUTION FROM AIRGLOW MEASUREMENTS
- MEASURE THE ALTITUDE DISTRIBUTION OF:
  O^{+}, O, N_2, O_2, N, NO, Na (75 750 km; 6 km RESOLUTION)
- FLY STATE OF THE ART IMAGING SPECTROSCOPIC INSTRUMENTATION
  (500 8700 Å)



SIMULATED RAIDS DATA & MODELS
SZA = 0
F_{10} = 70
OI 1356
N_2 1383
ALTITUDE (KM)
COLUMN EMISSION RATE (R)
400
350
300
250
200
150
100
1
10
100
1000
10000

O, O_2 AND N_2 CONCENTRATIONS FROM OI 1356 AND LBH

- **OI 1356 Å**

$$4\pi I_{1356} = \int n_O \, g_{1356} \, e^{-\tau_{O_2}} \, ds$$

- **N_2 LBH (2,0) 1383 Å**

$$4\pi I_{1383} = \int n_{N_2} \, g_{1383} \, e^{-\tau_{O_2}} \, ds$$

- **photoelectron g-factors are (non-linearly) proportional to total column density to sun, *N* through the photoelectron flux, Φ:**

$$g[z] = \int \sigma(E) \; \Phi(E, N[z]) \; dE$$

RAIDS ALGORITHM APPROACH:

DISCRETE INVERSE THEORY

- *Fast, rigorous, systematic inversion technique for obtaining environmental data records (EDR's) from UV limb scans*
- *Applicable to all RAIDS science data records (SDR's)*
- *Straightforward approach for obtaining uncertainties in EDR's*
- *Uncertainties from statistics in retrieved neutral densities of about 3-10% between 150 and 350 km, and 2% for exospheric temperature*
- *Validation will ultimately be with observational data and ground truth*

NONLINEAR DISCRETE INVERSE THEORY

- **Model Equation:**

$$G(m) = I^{pre}$$

I^{pre} = vector of length N, representing predictions of quantities which have been observed
G = vector function representing model
m = vector of length M, corresponding to the model parameters

- **Simple Iterative Approach; Use Taylor's Theorem:**

$$\nabla G[m_{i+1}^{e} - m_{i}^{e}] = I^{obs} - G(m_{i}^{e})$$

- **Taking inverse (overdetermined case):**

$$m_{i+1}^{e} = m_{i}^{e} + \nabla G_{inv}[I^{obs} - G(m_{i}^{e})]$$

- **Generalized inverse:**

$$\nabla G_{inv} = \{ \nabla G^{T}[cov I^{obs}]^{-1} \nabla G \}^{-1} \nabla G^{T}[cov I^{obs}]^{-1}$$

- **Covariance of Model Parameters:**

$$[cov\ m] = \nabla G_{inv}[cov I^{obs}]\ \nabla G_{inv}^{T}$$

- **Equivalent to Maximum Likelihood Method**

DISCRETE INVERSE THEORY ALGORITHM FOR OI 1356 Å AND N_2 LBH

EXAMPLES: **Limb scans from 65 to 325 km tangent altitude**

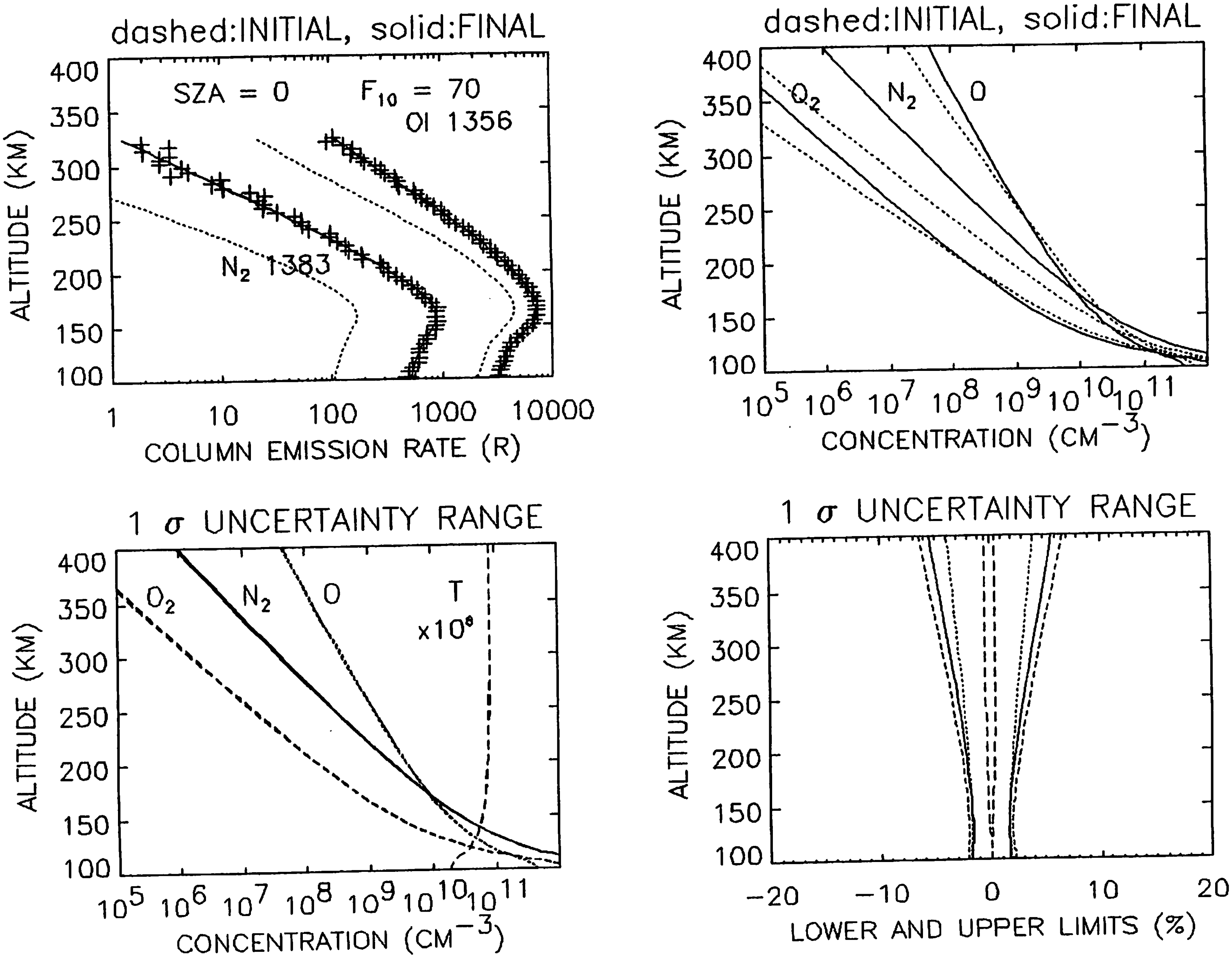
- **65 measurement for each line**
- **Synthetic data with Gaussian noise (1 ct/s/R)**
- **Solar min, max; 0, 70 deg solar zenith angle, 850 km satellite**

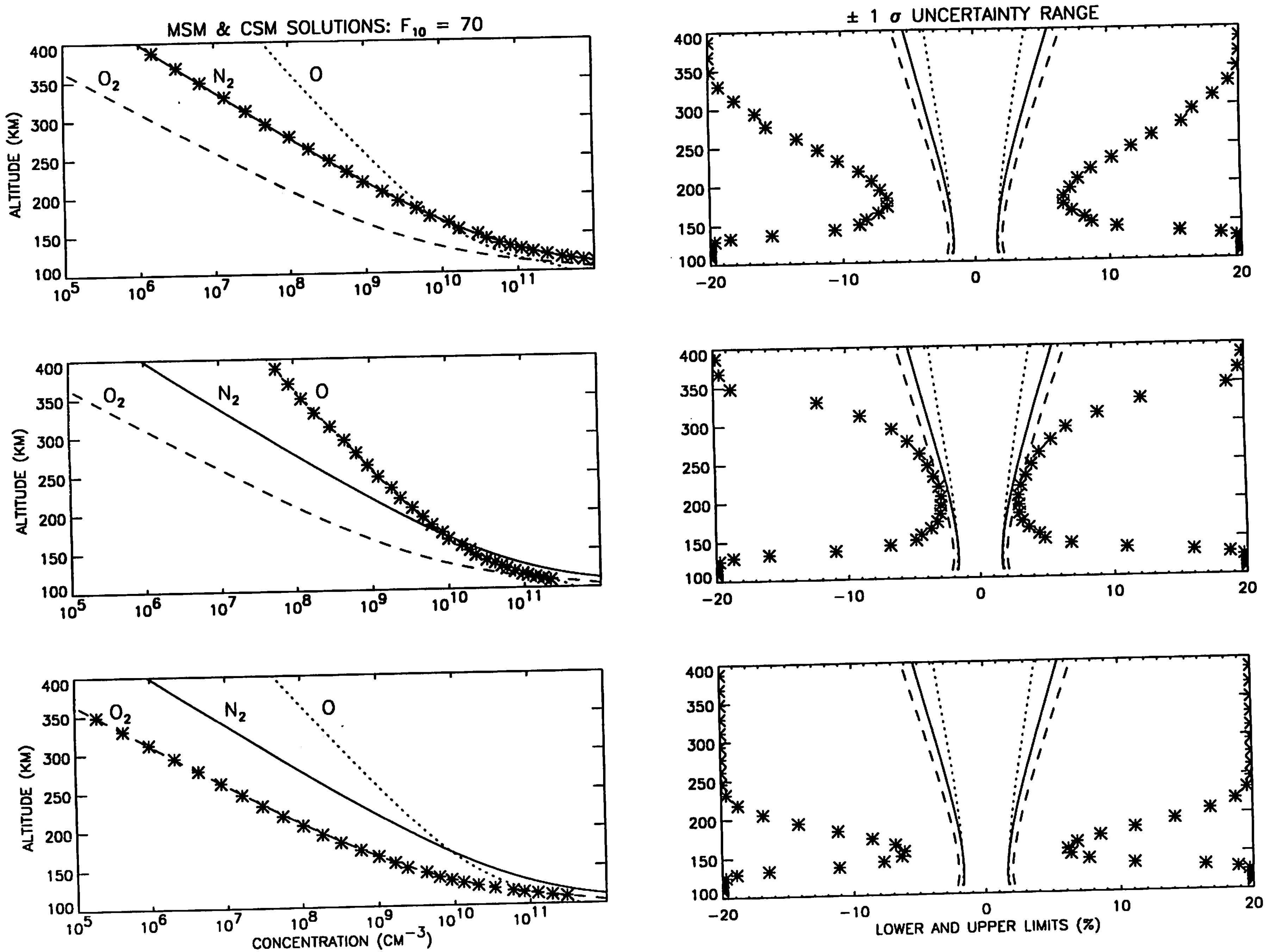
CASE 1: *m represents 5 scaling parameters describing the MSIS model:*

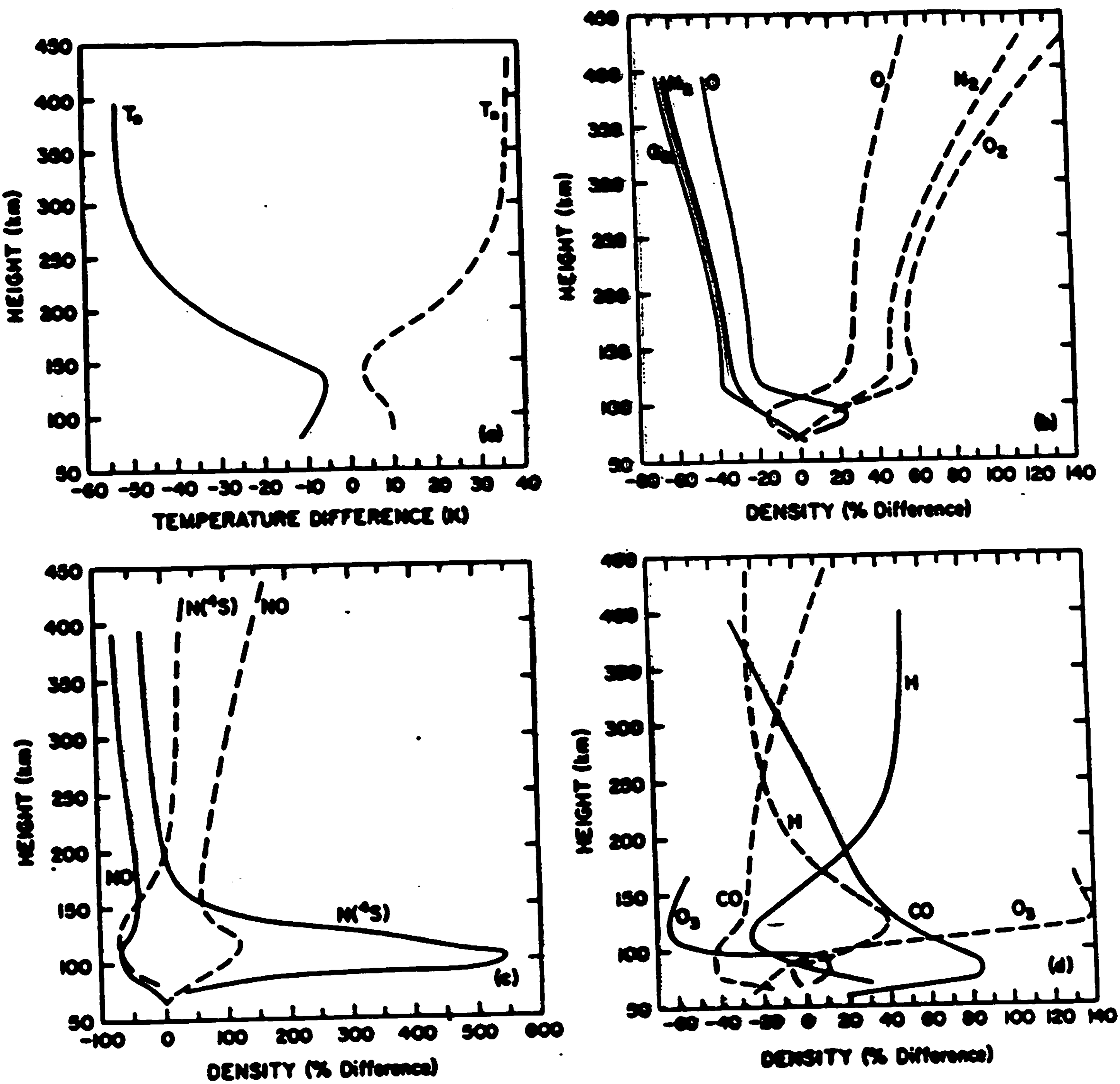
$$\boldsymbol{m} = [f_{N2},\ f_O,\ f_{O2},\ f_{10},\ f_{euv}]$$

CASE 2: *m represents individual densities:*

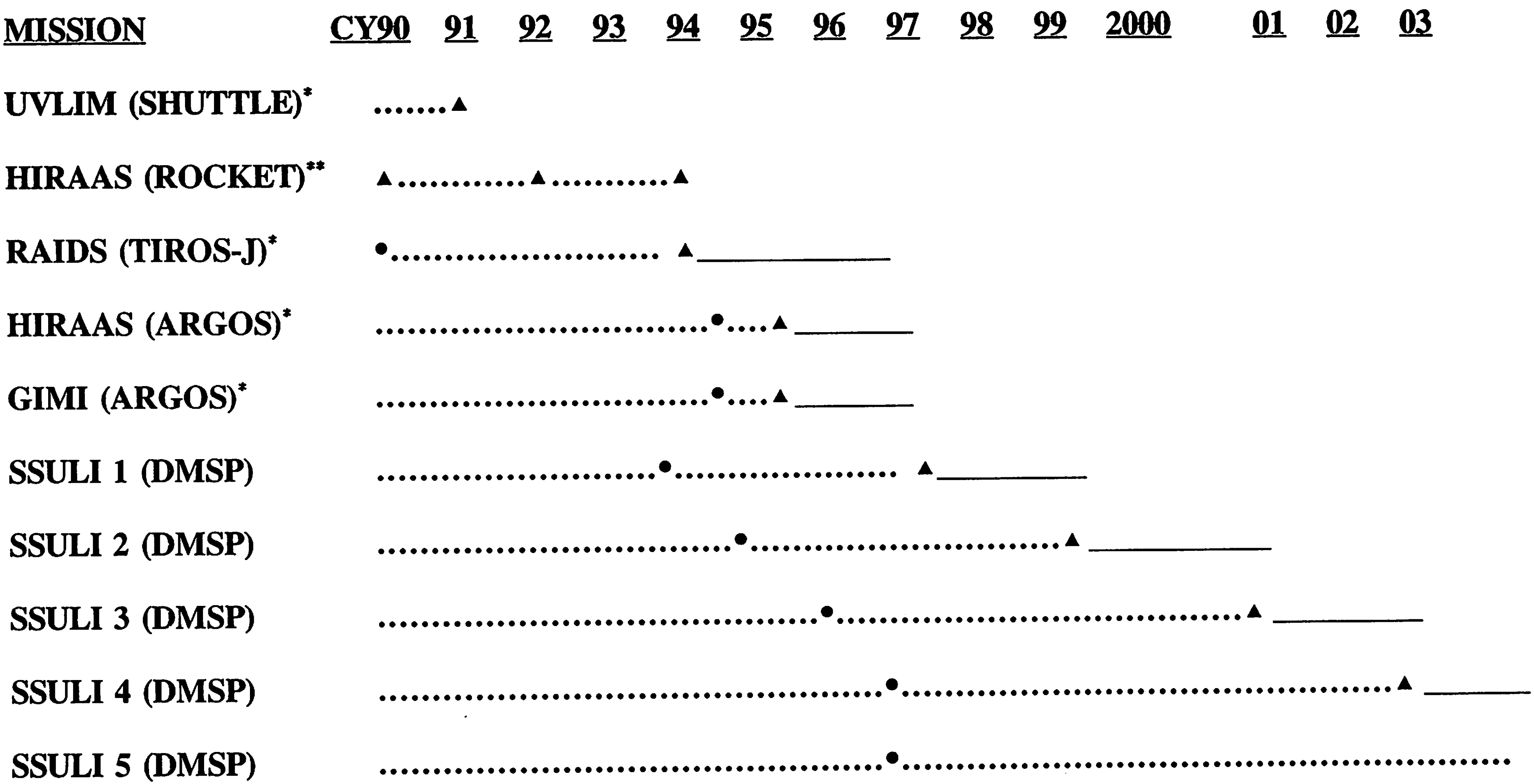
$$\boldsymbol{m} = [n_{N_2}(110),\ \ldots,\ n_{N_2}(500),\ n_O(110),\ \ldots,\ n_O(500),\ n_{O_2}(110),\ \ldots,\ n_{O_2}(500)]$$


dashed:INITIAL, solid:FINAL
SZA = 0
F10 = 70
OI 1356
N2 1383
ALTITUDE (KM)
COLUMN EMISSION RATE (R)
dashed:INITIAL, solid:FINAL
O2
N2
O
CONCENTRATION (CM−3)
1 σ UNCERTAINTY RANGE
O2
N2
O
T
x10⁶
ALTITUDE (KM)
CONCENTRATION (CM−3)
1 σ UNCERTAINTY RANGE
ALTITUDE (KM)
LOWER AND UPPER LIMITS (%)


MSM & CSM SOLUTIONS: F_{10} = 70
± 1 σ UNCERTAINTY RANGE
ALTITUDE (KM)
O_2
N_2
O
CONCENTRATION (CM^{-3})
LOWER AND UPPER LIMITS (%)


HEIGHT (km)
TEMPERATURE DIFFERENCE (K)
DENSITY (% Difference)
(a)
(b)
(c)
(d)
N(⁴S)
NO
CO
H
O₃
O
N₂
O₂

NRL UPPER ATMOSPHERE/IONOSPHERE MISSIONS



• DELIVERY
▲ LAUNCH
___ MISSION

12/2/92

* Space Test Program (STP)
** NASA

SUMMARY

- *UV remote sensing has evolved sufficiently that accurate, routine observations of the upper atmosphere (and ionosphere) are possible on a global scale*

- *Non-linear inversion methods show great promise for retrieval of concentrations from airglow observations*

- *Validation is underway with various data sets*

- *DoD missions should provide continuous observations over 1-2 solar cycles, beginning next year with RAIDS*