Chemical Release Applications, Observations and Modeling

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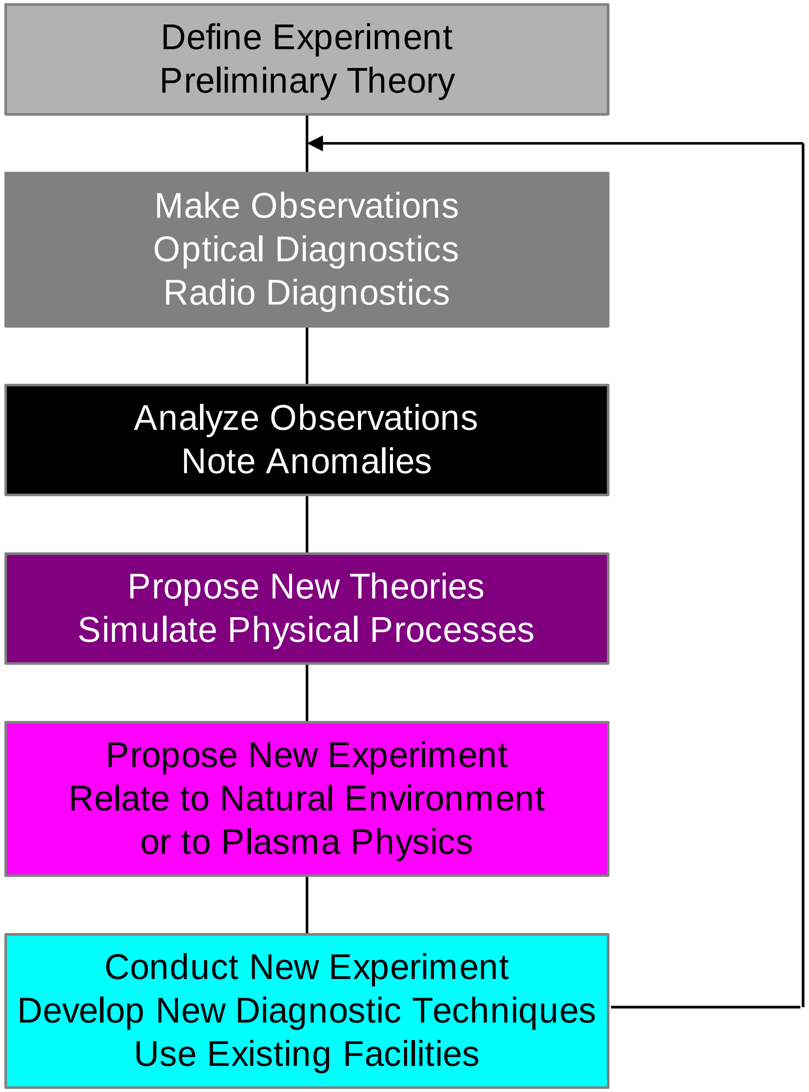
Atmospheric Chemical Releases

- History
  - Rockets
  - 50th Anniversary of the First Release 21 January 1955
  - "STARFISH" the Largest Release 9 July 1962
  - "Atlas V Skylab Launch" Largest Ionosphere Hole 14 May 1973
- Classification of Releases
- Chemical Release Diagnostics
- Ionization Enhancement Releases (Ba, Sm)
- Ionization Reduction Releases (SF_6, H_2O)
- Tracers (Na, TMA)
- Outstanding Mysteries of Chemical Releases
  - Mesospheric Wind Measurements
  - Artificial Aurora
  - Exhaust Plume Radar Scatter
- Future Experiments

Active Experiment Studies with Chemical Releases



Chemical Release Experiments in Space Plasmas

- Plasma and Neutral Vapor Injections
  - Creation of Density Enhancements
    - Critical Ionization Velocity (CIV) Phenomena
    - Photoionization
    - Dissociative Ionization
    - Impact Ionization
  - Plasma “Holes”
    - Charge Exchange + Election-Ion Recombination
    - Electron Attachment + Ion-Ion Neutralization
  - Tracing of Neutral Winds and Electric Fields
    - Neutral Trails
    - Ion Cloud Injections

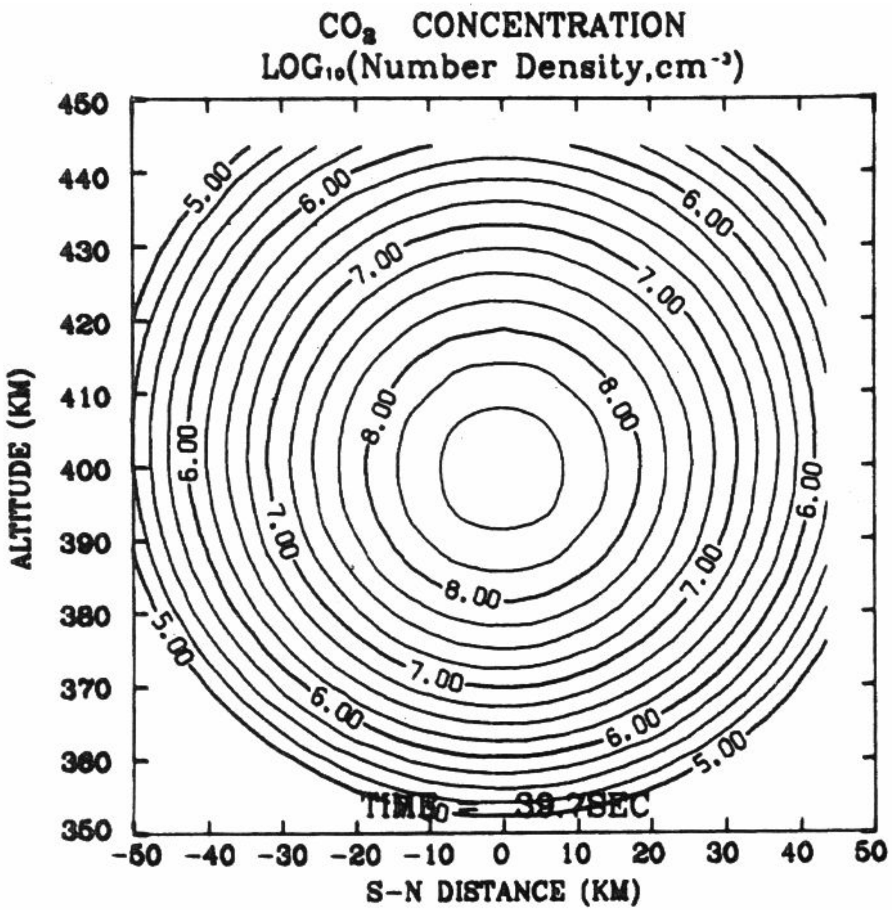
Diagnostic Techniques for Chemical Releases

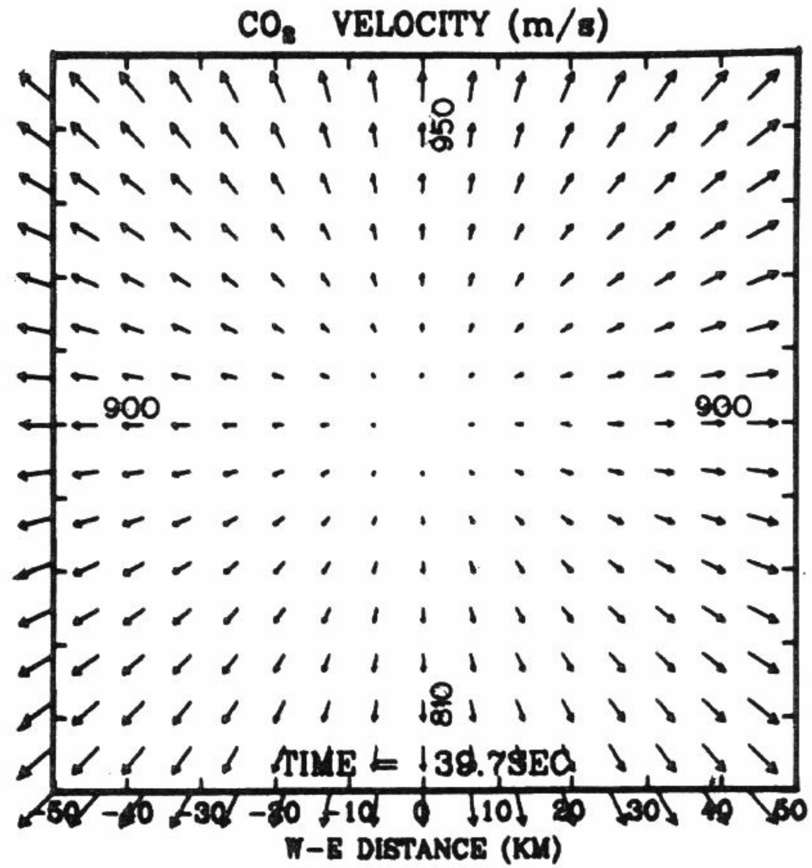
- Optical Emissions
  - Scattered Sunlight
  - Chemical Reactions: Chemiluminescence
    - Oxidation
    - Dissociative Recombination
    - Ion-Molecule Neutralization
- Radio Sensors
  - Radar
    - Incoherent Scatter
    - Coherent Scatter
  - Radio Propagation
    - Radio Beacon
      - Total Electron Content
      - Scintillations
    - Ionosonde Oblique Echoes
- In Situ Space Instrumentation
  - Electron and Ion Density
  - Plasma Temperatures

Chemical Release Modeling

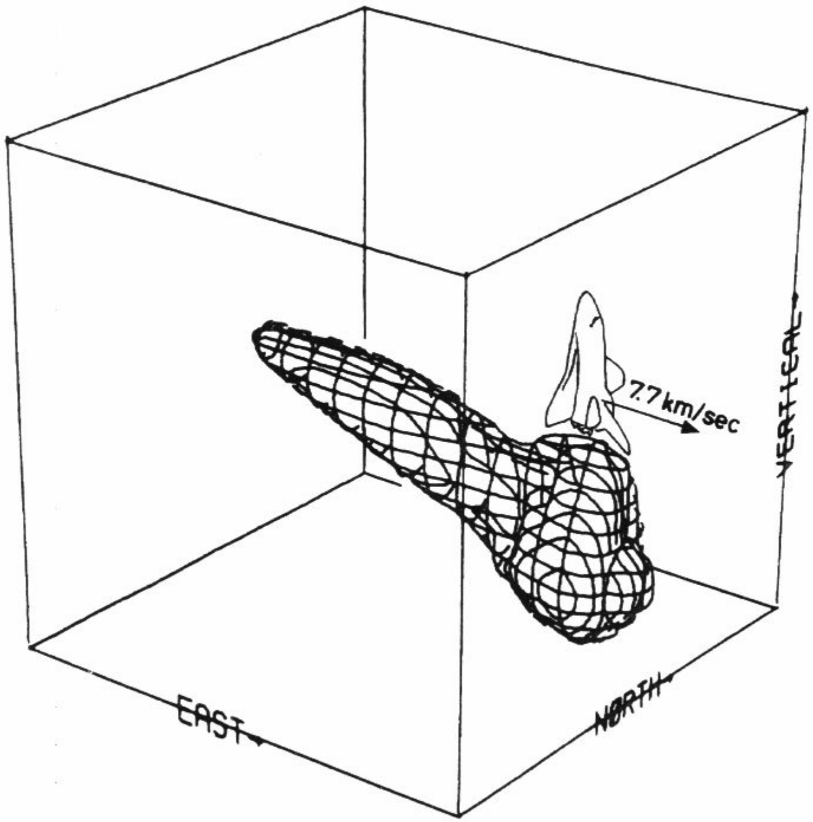
- Initial Velocity Distribution Function
  - Canonical Form
  - 1-D, 2-D, and 3-D Distributions
- Boltzmann Equation Solution
  - Spherical Expansion
  - Space Shuttle OMS Burn
- Monte Carlo Solutions
  - TRAMP and SOCTRATES Codes
  - Space Shuttel OMS Burn

Boltzmann Solution for Water Vapor Expansion

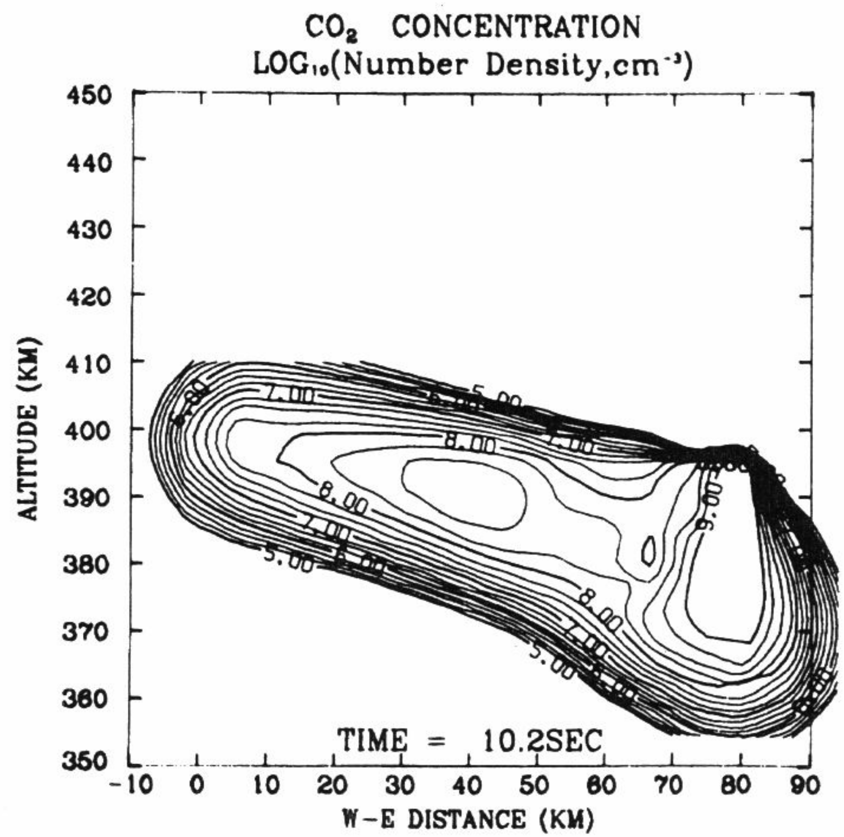




Boltzmann Solution for Shuttle Burn

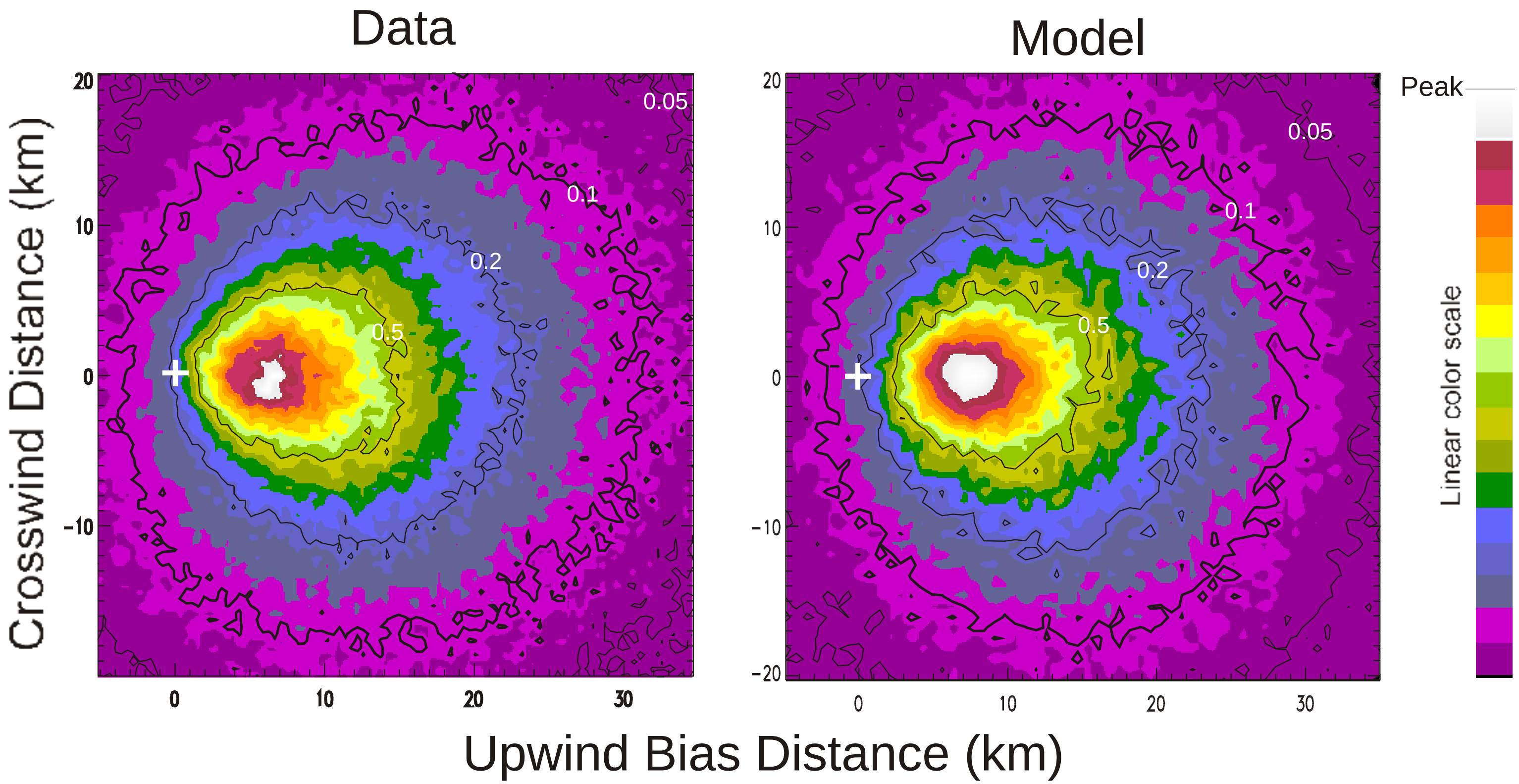


100.0 km CUBE CENTERED AT 400.0 km ALTITUDE
TIME AFTER RELEASE: 10.2 sec
CO_2 CONCENTRATION AT SURFACE: 4.9[7] cm^{-3}



Monte Carlo Plume Codes

- Transitional and Rarefied Axisymmetric Monte Carlo Plume (TRAMP)
- Spacecraft/Orbiter Contamination Representation Accounting for Transiently Emitted Species (SOCRATES)
- Example of TRAMP Results for Space Shuttle OMS Ram Burn (Dimpfl, Light and Bernstein, 2003)

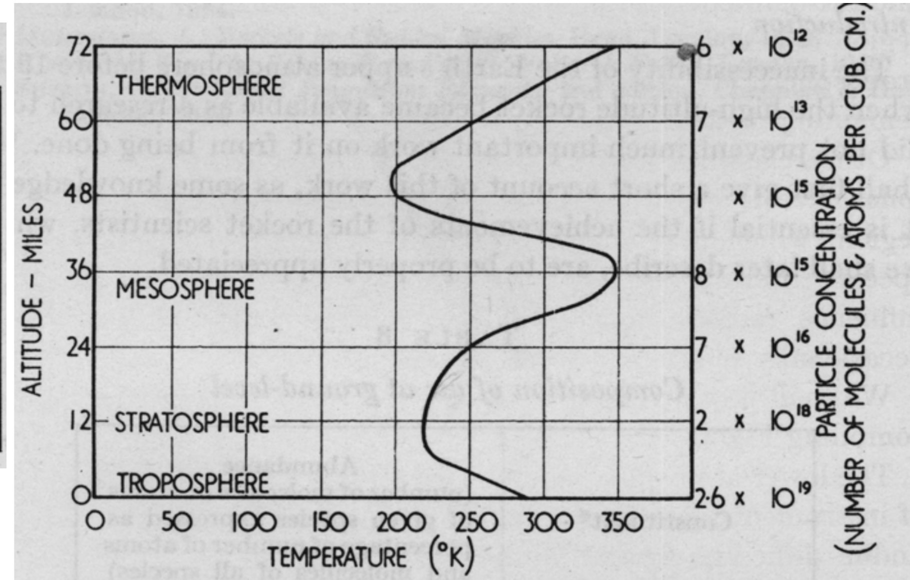


Chemicals Used in High Altitude Release Experiments

Purpose	Materials	Optical Emissions	Fastest Rate	Reaction
Plasma Clouds: Photo-ionization	Li, Na, Sr, Cs, Ba, Eu, U	553.5 nm (Ba) 455.4 nm (Ba^+)	0.05 s^{-1} (Ba) 0.005 s^{-1} (Eu) 0.00029 s^{-1} (Li)	Ba + hν ✹ Ba^+ + e^-
Plasma Clouds: Associative Ionization	Sm, La, Nd, Ti	Molecular Bands of SmO (656 to 570 nm)	2 x 10^{-11} (SmO)	Sm + O ✹ SmO^+ + e^- + 0.39 eV
Plasma Holes: Electron Attachment	SF_6, CF_3Br, $Ni(CO)_4$	777.4 nm (SF_6)	2.2 10^{-7} cm^3/s (SF_6)	SF_6 + e- ✹ SF_5^- + F - 0.25 eV SF_5^- + O^+ ✹ SF_5 + O* + 9.91 eV
Plasma Holes: Ion-Molecule Charge Exchange	H_2, H_20, CO_2	630 nm (CO_2)	3.2 10^{-9} cm^{-3} (H_20)	H_2O + O^+ ✹ H_2O^+ + O H_2O^+ + e^- ✹ OH* + H
Neutral Wind Tracer	Al, NO, Na, $Al(CH_3)_3$, $Fe(CO)_3$, $Ni(CO)_4$	Molecular Bands of AlO (484, 508, 465, 534 nm)	--	$Al(CH_3)_3$ + O ✹ AlO* + ...

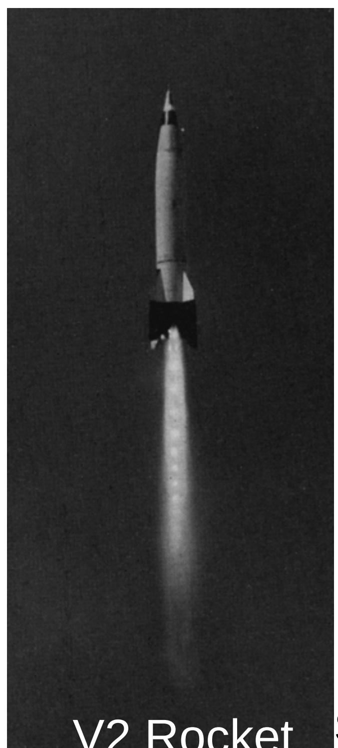
U.S. rocket firings prior to 1 July 1954

Vehicle	Date of first use	Number launched	Maximum altitude (miles)
WAC Corporal	26.9.45	10	44
V.2	16.4.46	67	132
Aerobee	24.11.47	141	89
V.2-WAC Corporal combination	13.5.48	8	242
Viking	3.5.49	11	158
Deacon-Skyhook (Rockoon*) .	21.8.52	29	65
		266	

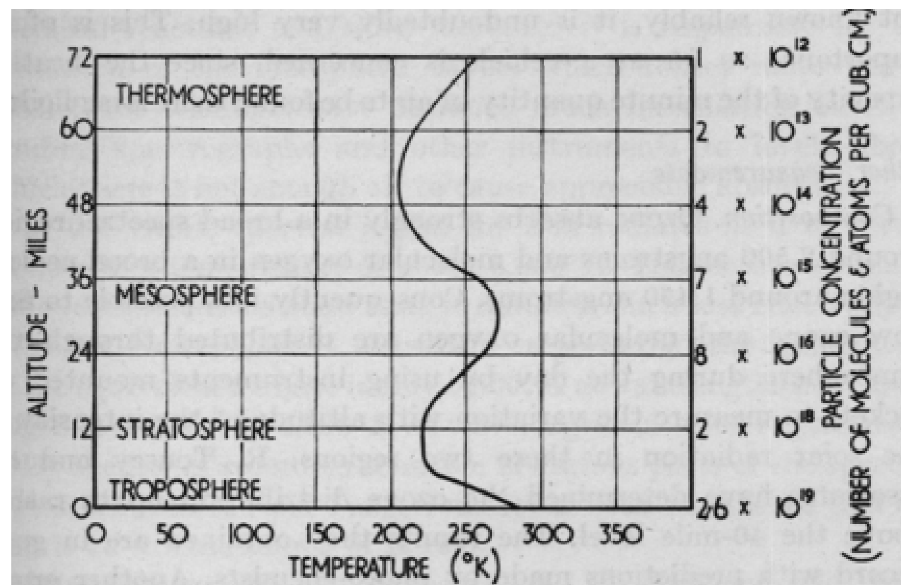


Proposed Structure of the Atmosphere
Before the Availability of Rocket Data

Rockets Data Impacts Atmospheric Research 1946 to Present



V2 Rocket



Structure of the Atmosphere Based on Rocket Data

Twilight Sodium Trail Yielding Neutral Wind Velocities in 1955

Emission from a Sodium Cloud Artificially Produced by Means of a Rocket

Howard D. Edwards, John F. Bedinger, and Edward R. Manring*

Geophysics Research Directorate, Air Force Cambridge Research Center,
Air Research and Development Command, L. G. Hanscom Field, Bedford, Mass.

and

C. D. Cooper

Department of Physics, University of Georgia, Athens, Ga.

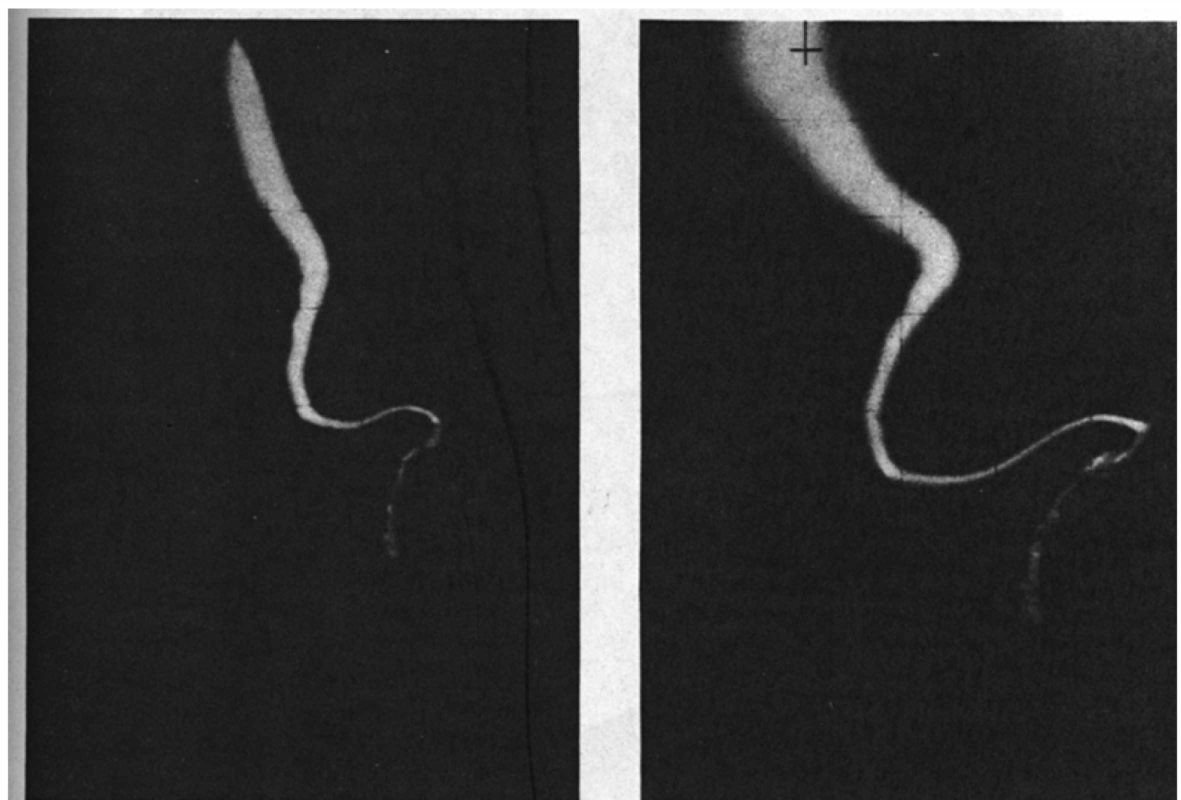
Abstract—Following Bates's suggestion, three kilograms of metallic sodium vapour were ejected into the atmosphere from 50 to 113 km by means of two Aerobee rockets. The rockets were launched at the beginning of evening twilight on 21 January and 12 October 1955.

Enhanced sodium emission at 5890 Å was definitely observed visually, photometrically and spectrographically from 85 km to 113 km during twilight. No sharp time discontinuities in intensity were observed when the region was enclosed by the earth's optical shadow. No increase in emission was observed during the night.

Possible explanations are given for the lack of emission below 85 km.

Spreading of the sodium cloud indicated winds at the 85-km level to be 180 m.p.h. from the north-west and 100 m.p.h. from the south-east at the 110-km level.

Images at One Minute Separation

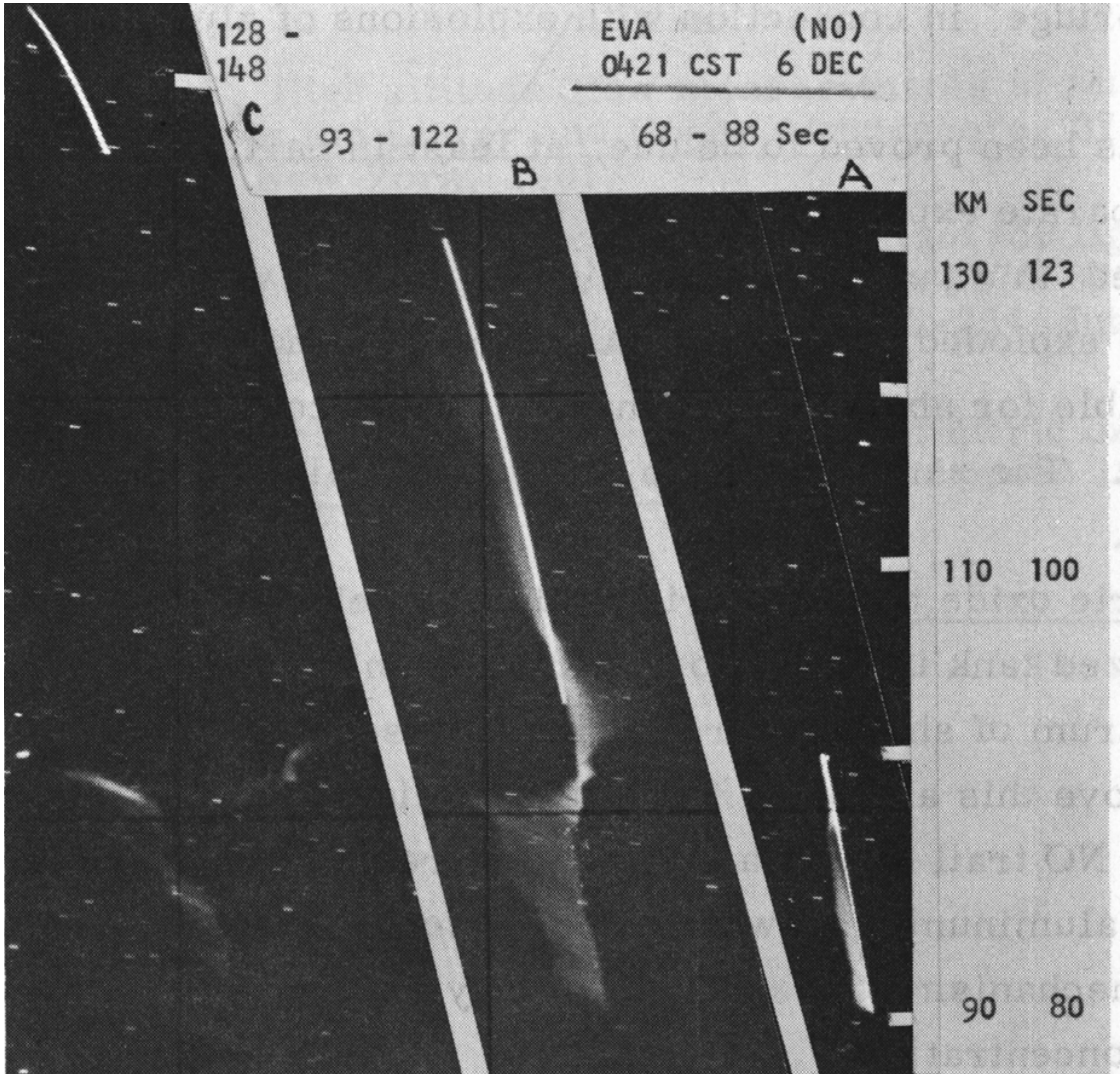


Derived Shear:

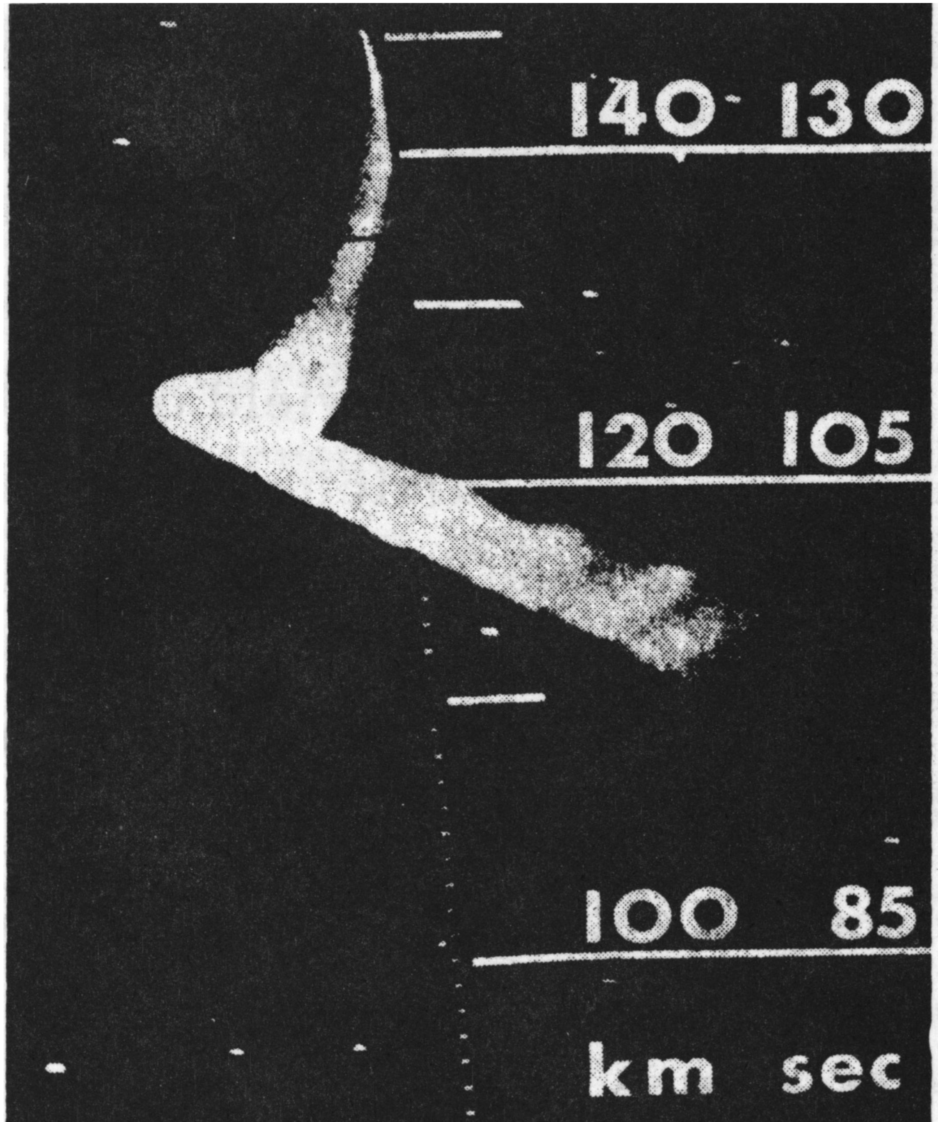
80.5 m/s NW at 85 km

44.7 m/s SE at 110 km

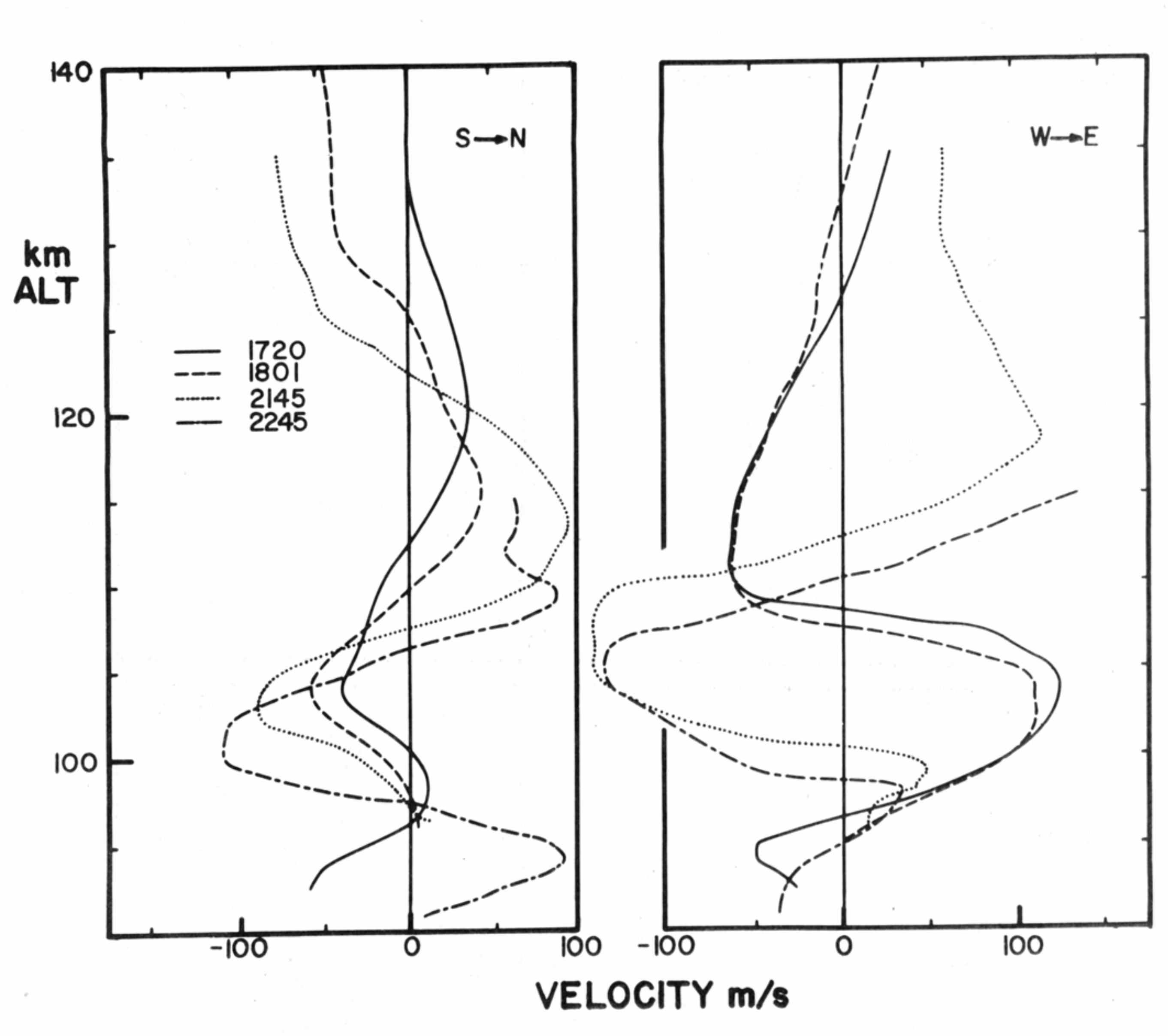
Nitric Oxide (NO) Trail, 6 December 1962



Aluminum Trail, 3 Dec 1962



TMA Derived Wind Vectors, 3 December 1962



Tri-Methyl Aluminum (TMA) Trail

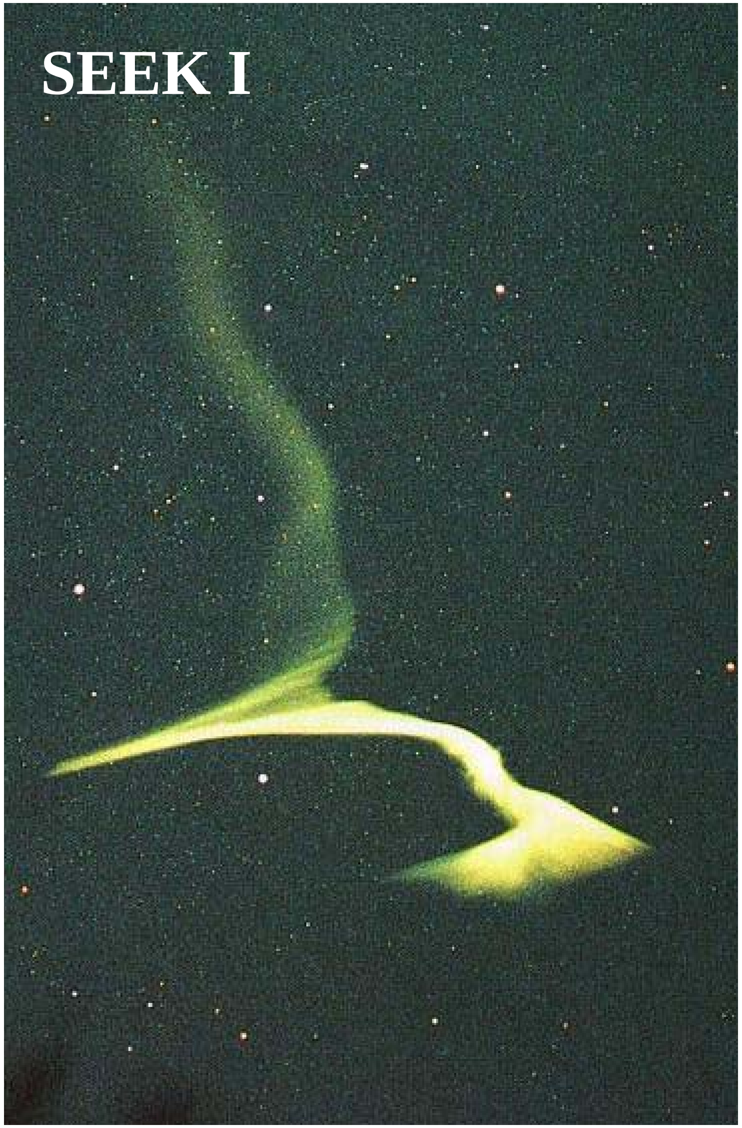
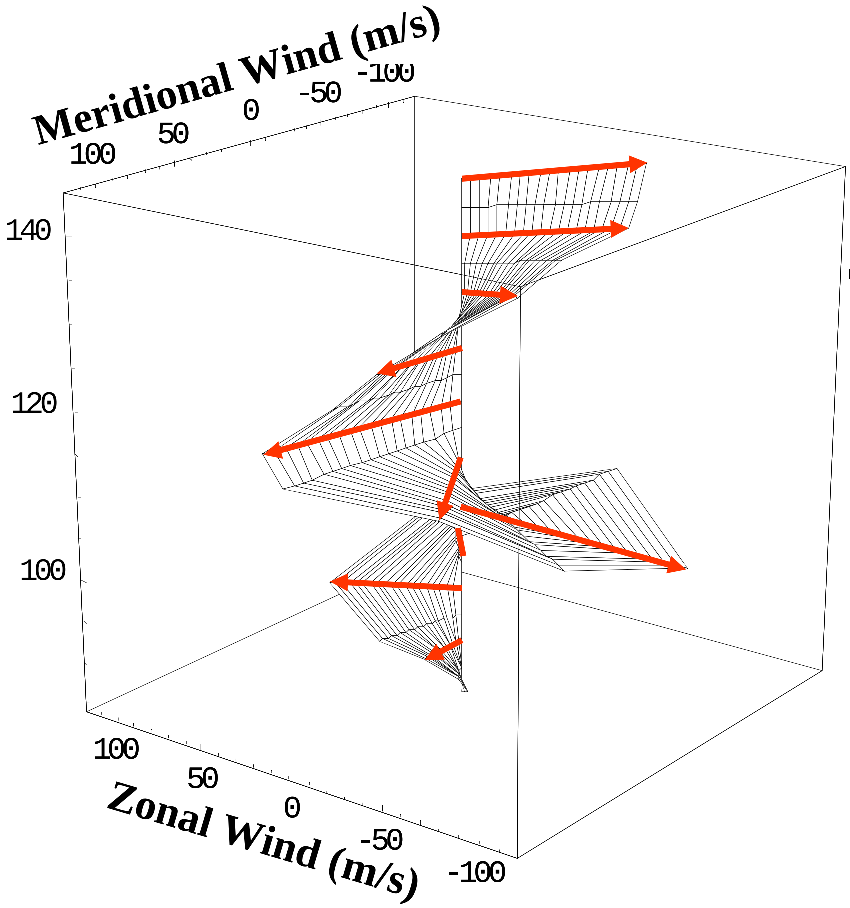
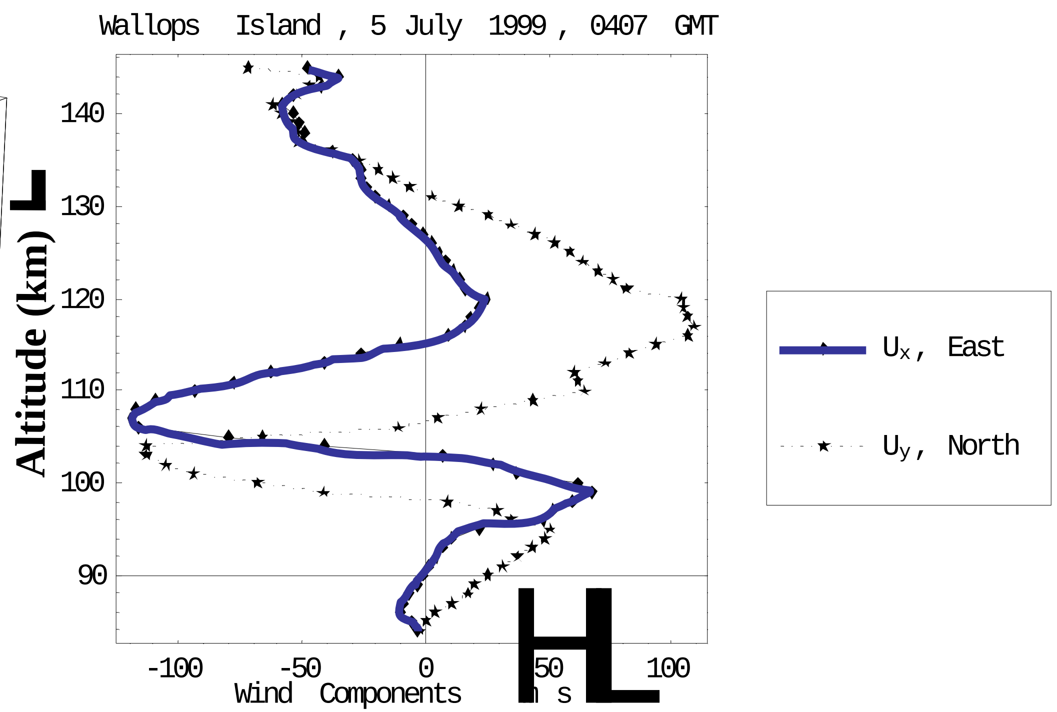


Image Courtesy M.F. Larsen, Clemson

Neutral Wind Profile Derived from TMA Trails

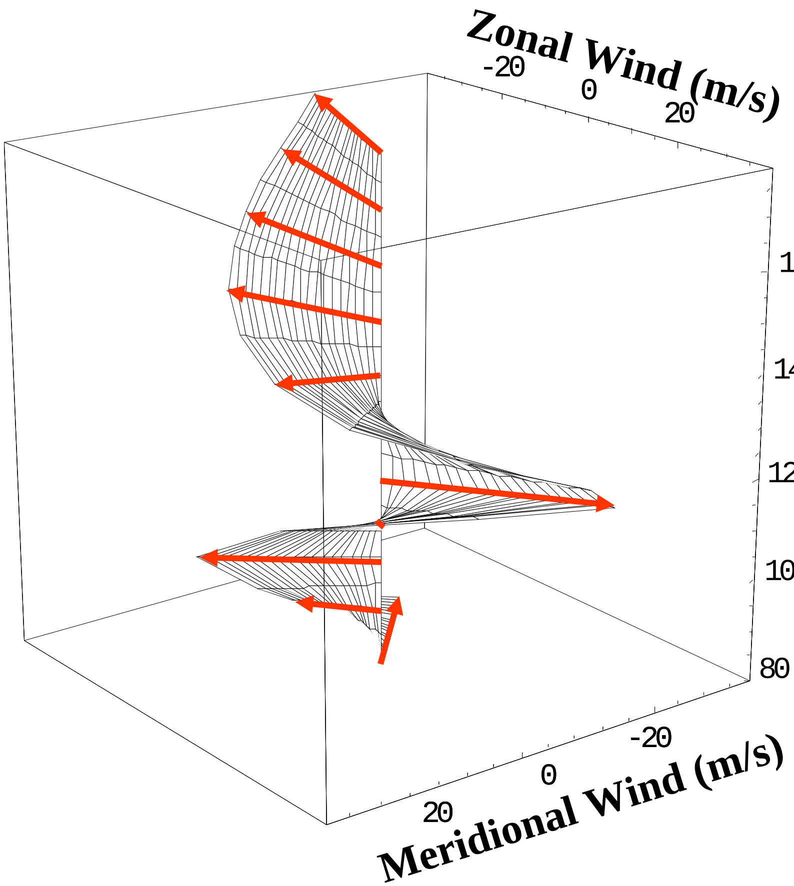


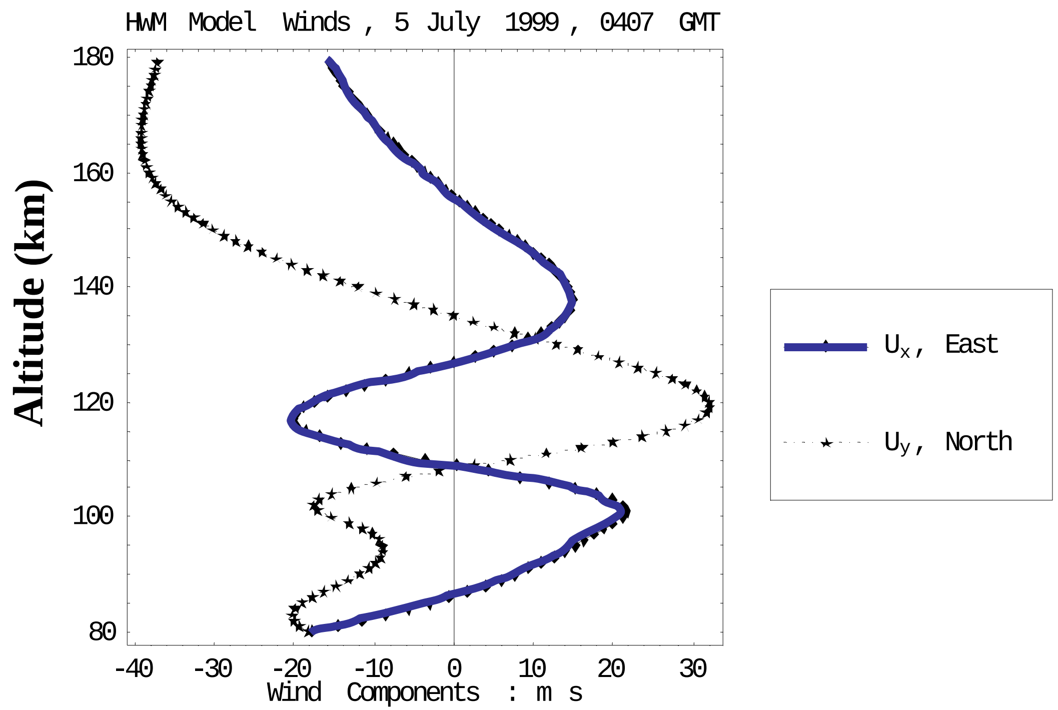


At 105 km, β = 0.86, U_0 = 120 m/s, d = 2 km

Data Courtesy M.F. Larsen, Clemson

Neutral Wind Profile Modeled by HWM93

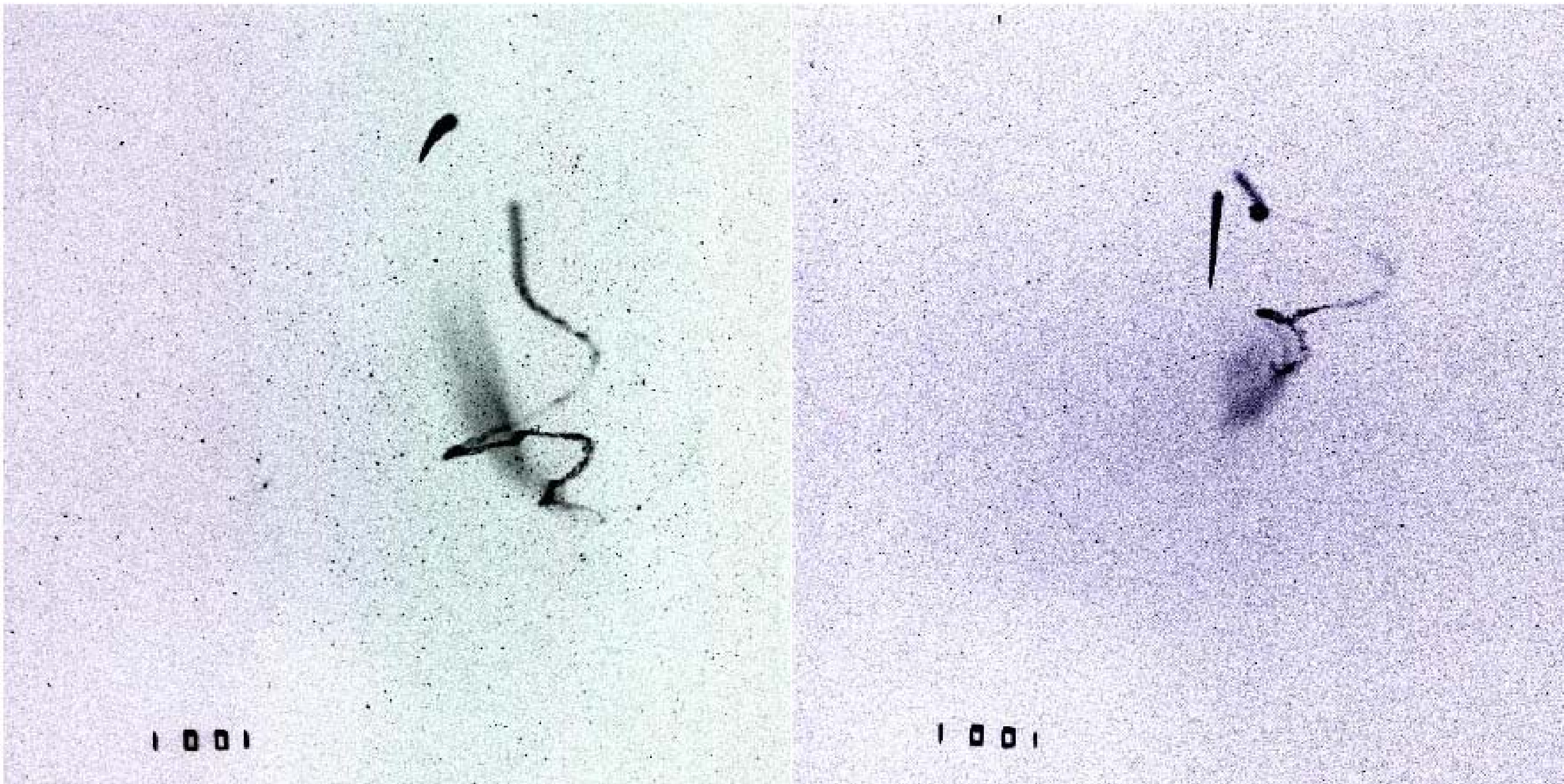




At 109 km, β = 0.05, U_0 = 37 m/s, d = 6.2 km

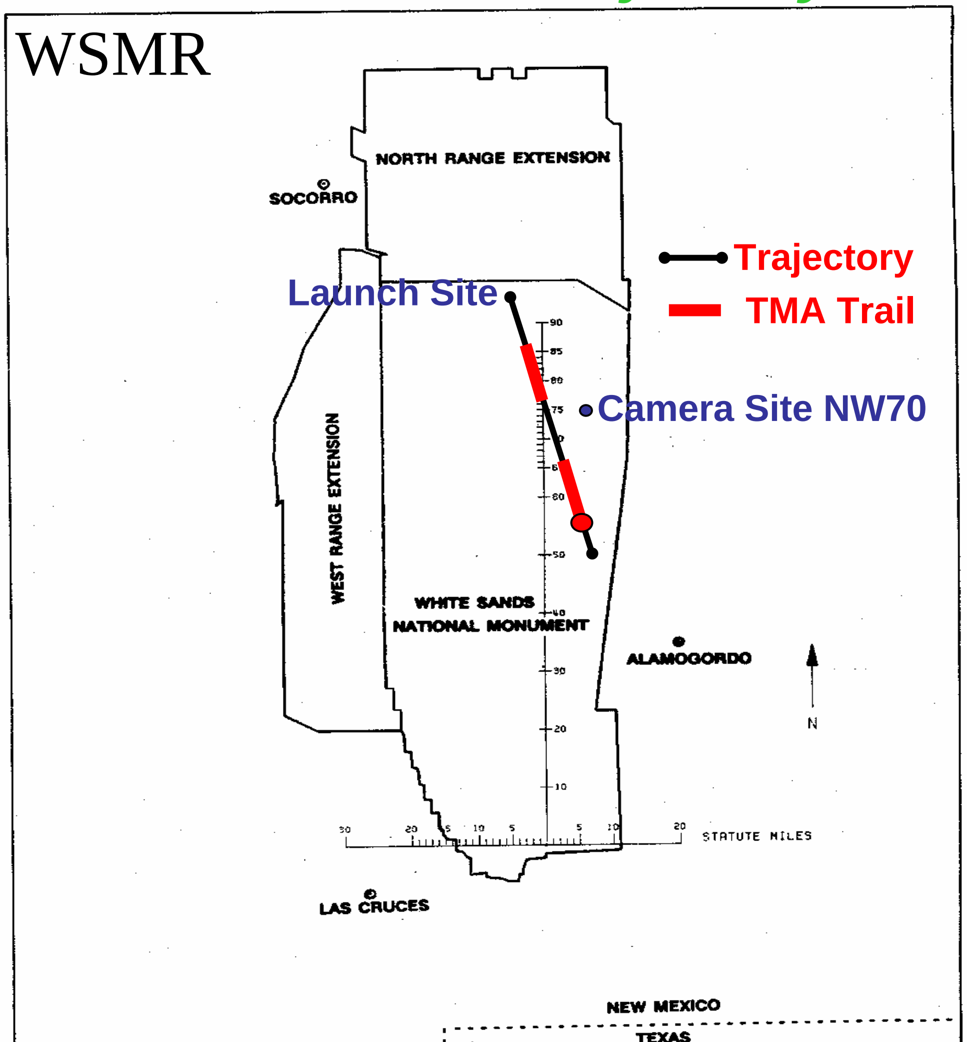
Simulation Data Courtesy Doug Drob, NRL

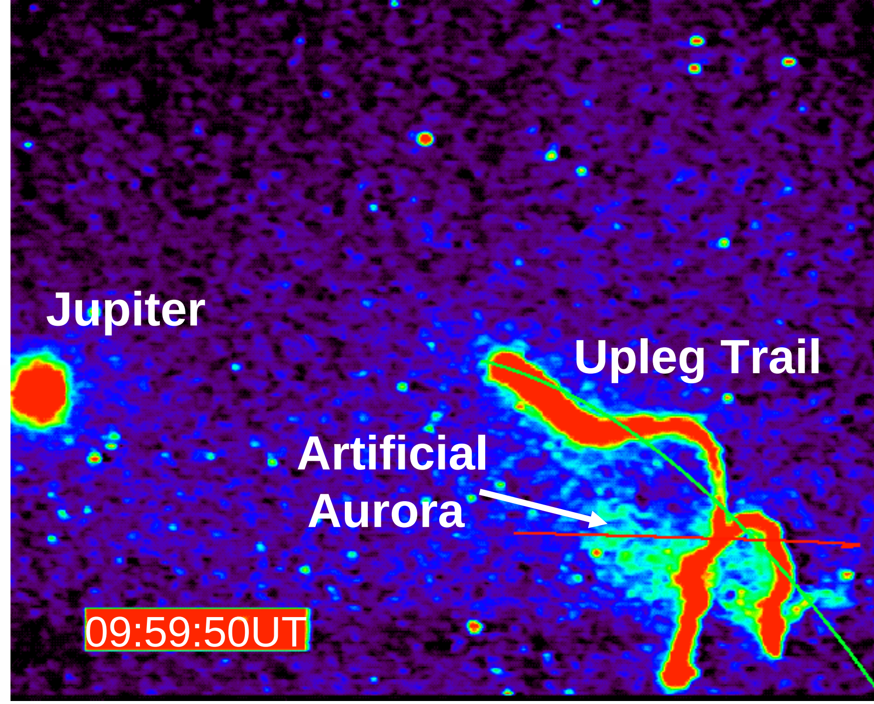
Artificial Aurora from Sunspot and Starfire Sites in New Mexico, 26 October 2000, 1001 UT
Courtesy L.J. Gelinas and M.F. Larsen

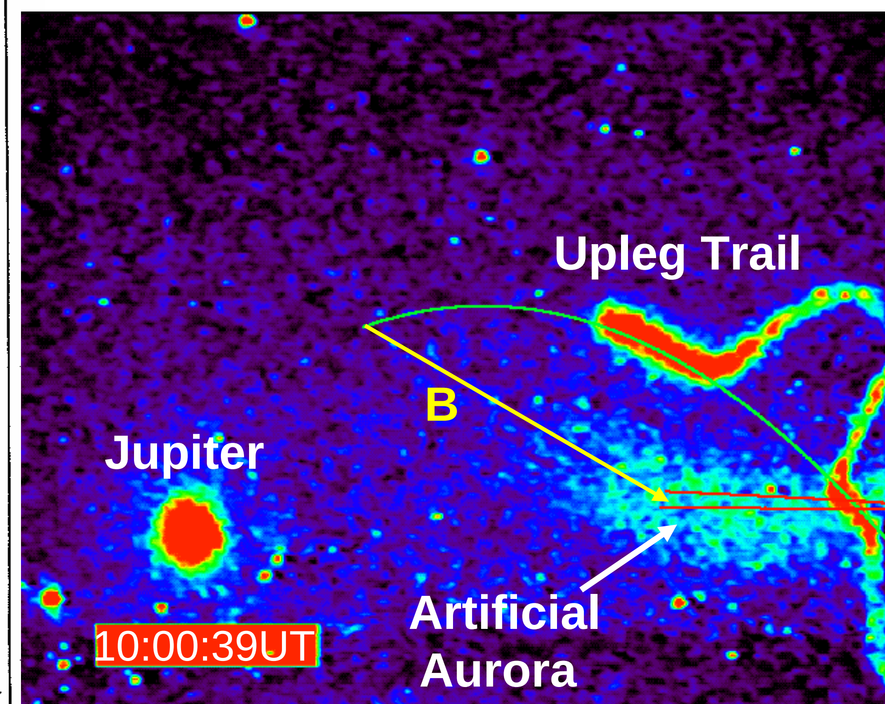


Artificial Aurora

White Sands Missile Range and TOMEX Trajectory

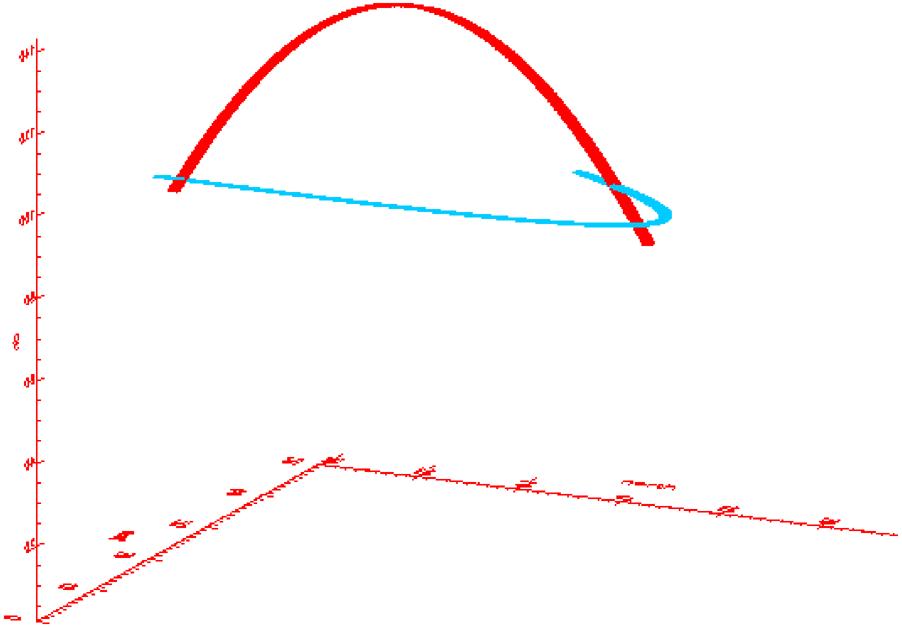






Images

Magnetic Field Projection of Trail



Cause of Artificial Aurora Unknown

Energetic Particles: Electrons or Ion

Chemistry: TMA + Kerosene + Atomic Oxygen

AC and DC Electric Fields: Parallel and Perpendicular

Starfish Nuclear Detonation

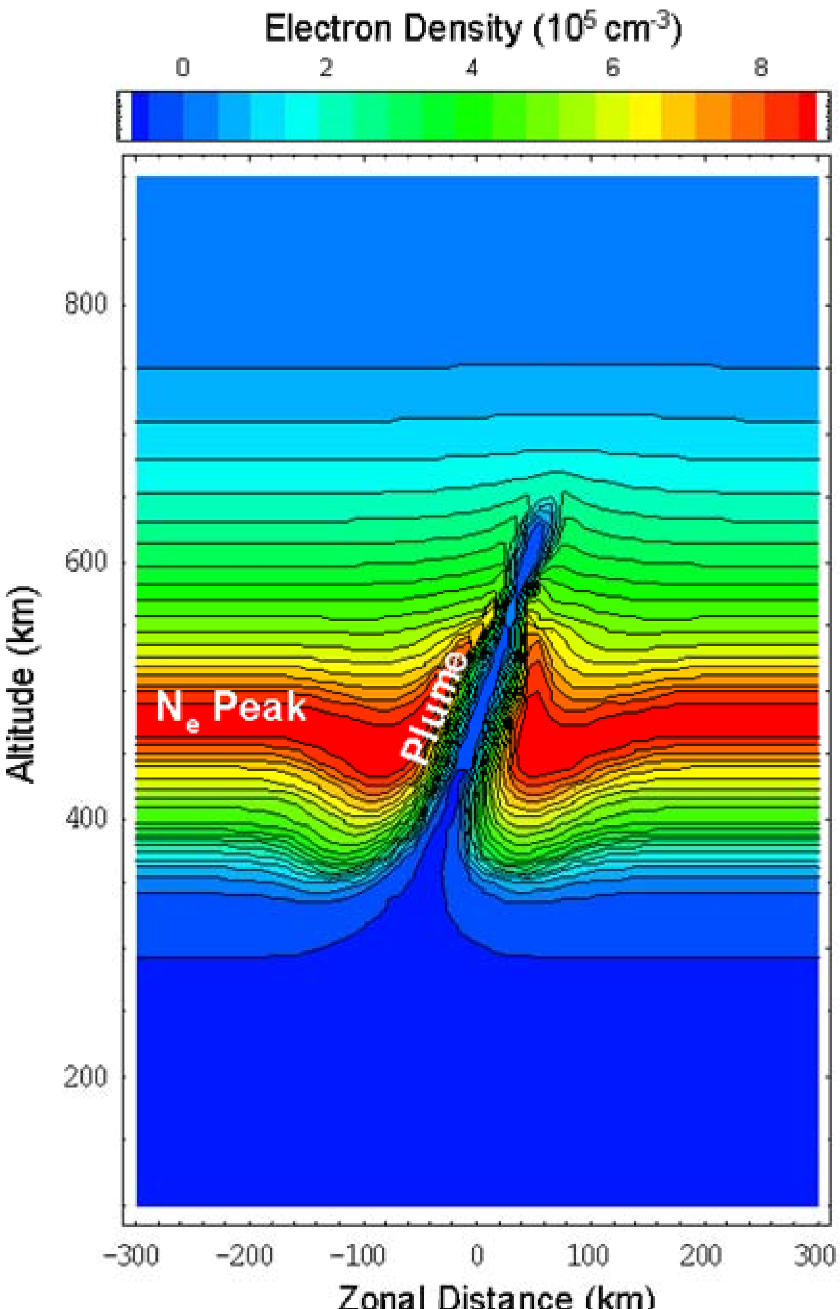
Name:	Starfish
Date:	9 July 1962
Time:	9:00 GMT
Location:	Johnston Island
Altitude:	399 km
Yield:	1450 kt

Spruce

Ave Fria Dos

Avefria Dos- This release was at Tonopah, Nevada in May 1978 (Pongrantz et al.) at an altitude of about 190 km. The view is from Hot Creek Valley, Nevada about three minutes after the release. This was a 1.45 kg shaped charged barium release fired across the magnetic field. The barium cloud had an initial radius of about 1 km. The "cats paw" part of the figure is looking up the magnetic field line, and the longer part of the cloud is not up the field line.

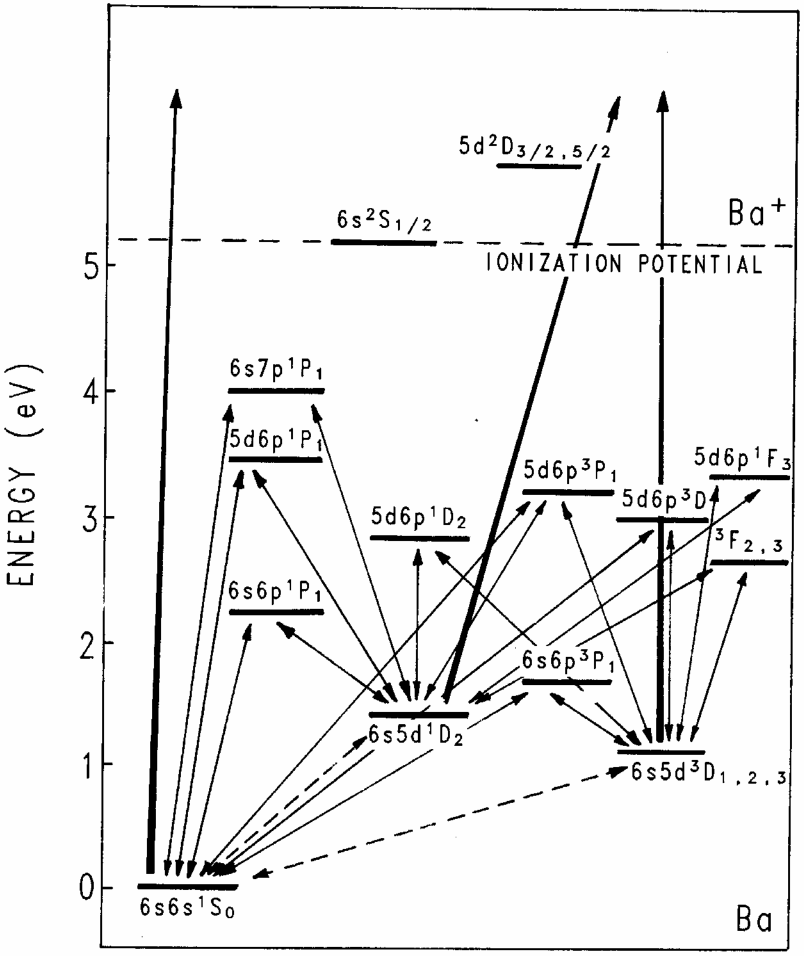
Barium Cloud Irregularities are Surrogates for Equatorial Bubbles



BIME II
13 September 1082
21:00:UT
Natal, Brazil
AMFO Detonation at 280 km
Paul A. Bernhardt
LANL/NRL

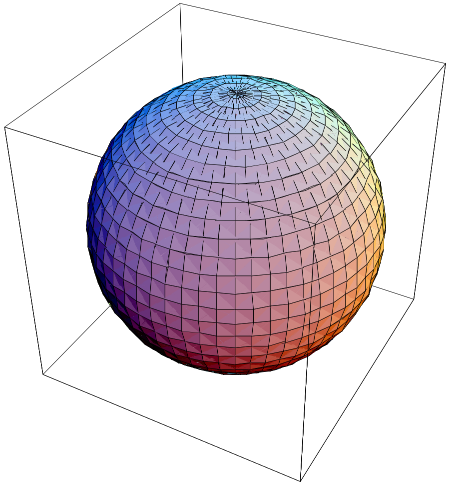
Barium Term Diagram

- 30 Second Ionization Time
- Colors: Green Neutral and Violet Ion Emissions
- Two Photon Ionization
  1. Metastable State Population
  2. Ionization From Metastable State

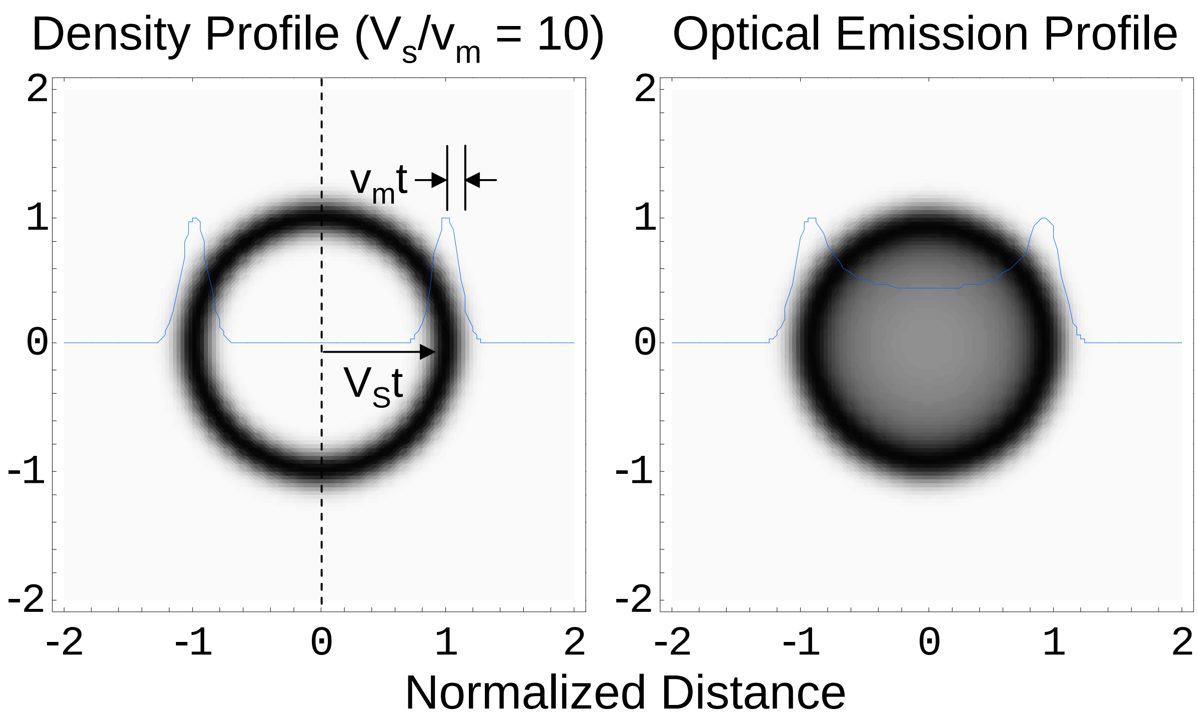


Space Shuttle Observations of a Barium Cloud During STS-50, 2 July 1992, El Coqui Rocket Campaign, Puerto Rico

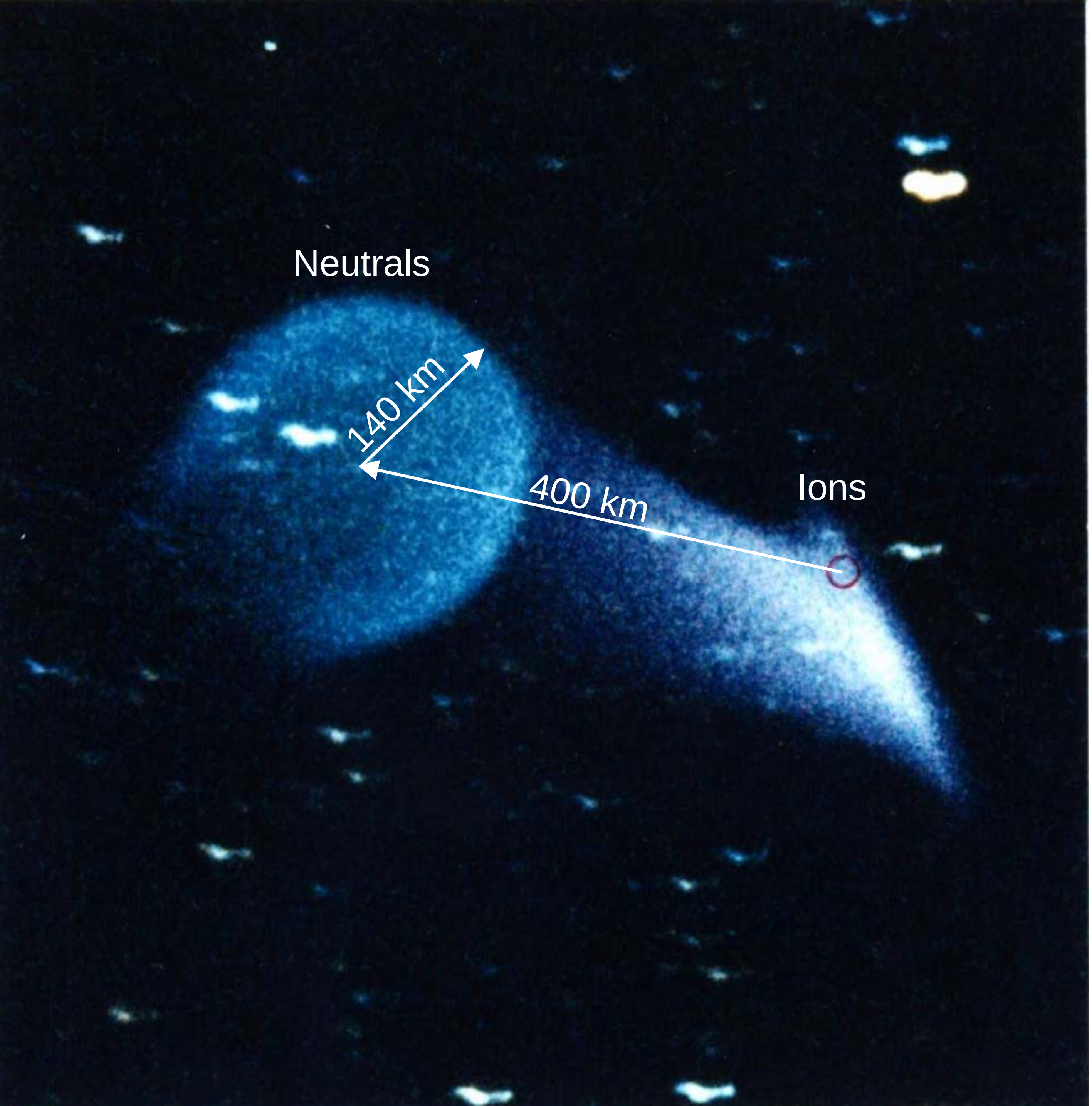
Density Shells and Optical Observations



- Three-Dimensional Shell Expansions into a Vacuum



  – Characteristics
    - Circular Optical Projection from all Directions
    - Self-Similar Expansion
    - Barium Thermite Parameters: $V_s \cong 1.38$ km/s, $v_m \cong 0.26$ km/s
    - Lithium Thermite Parameters: $V_s \cong 3.67$ km/s, $v_m \cong 1.30$ km/s



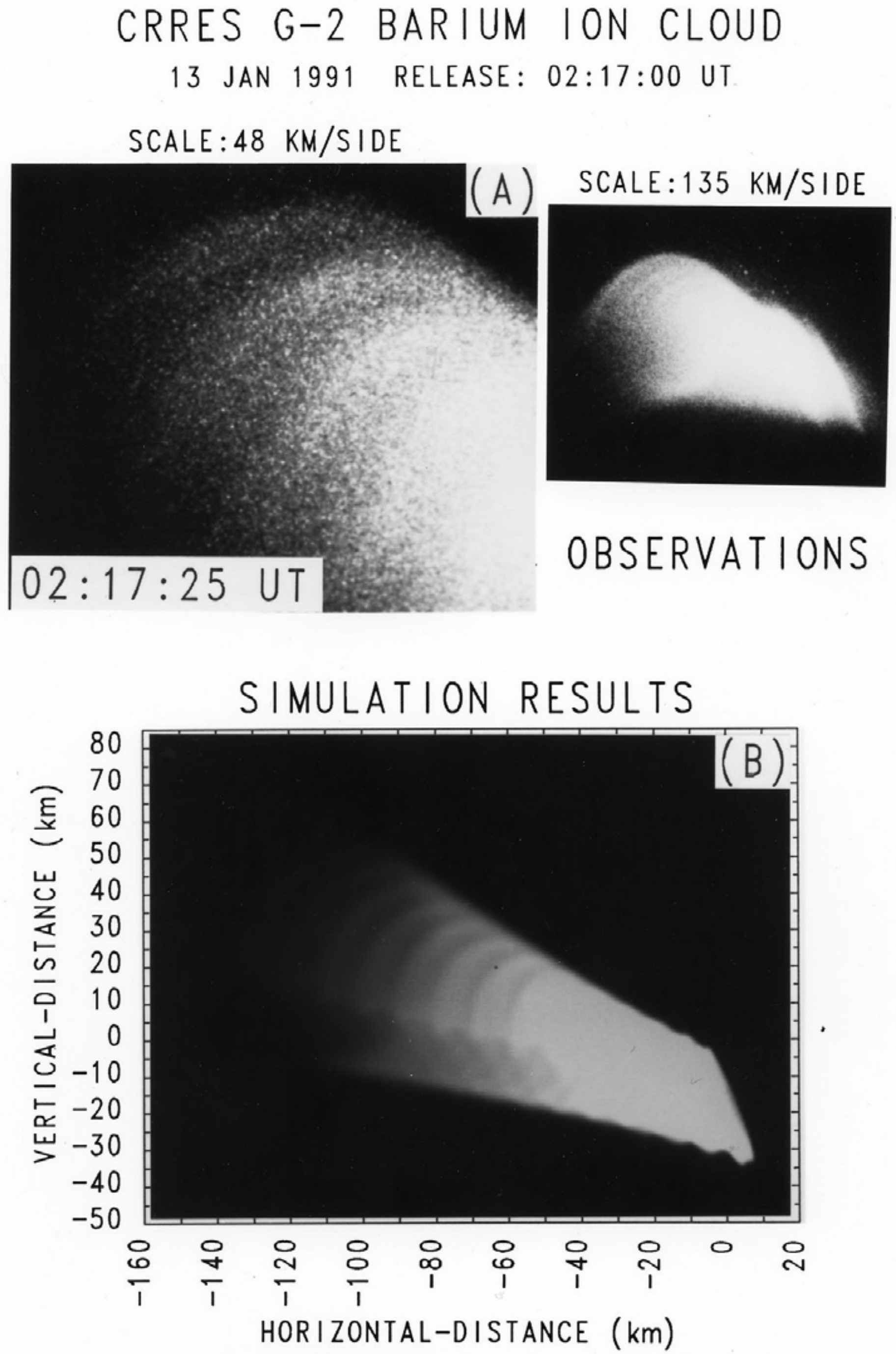
CRRES G-2 Barium Release

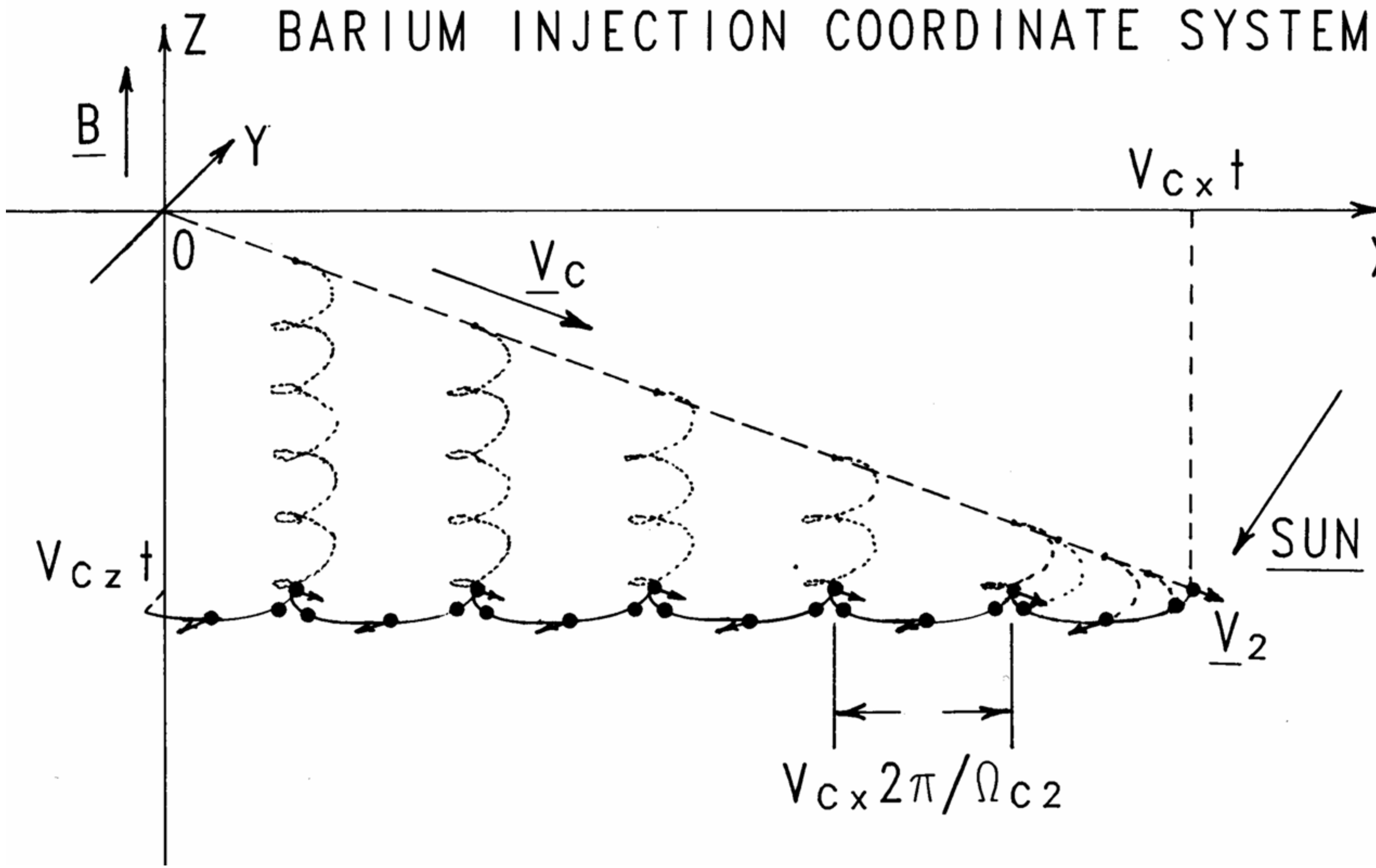
13 January 1991

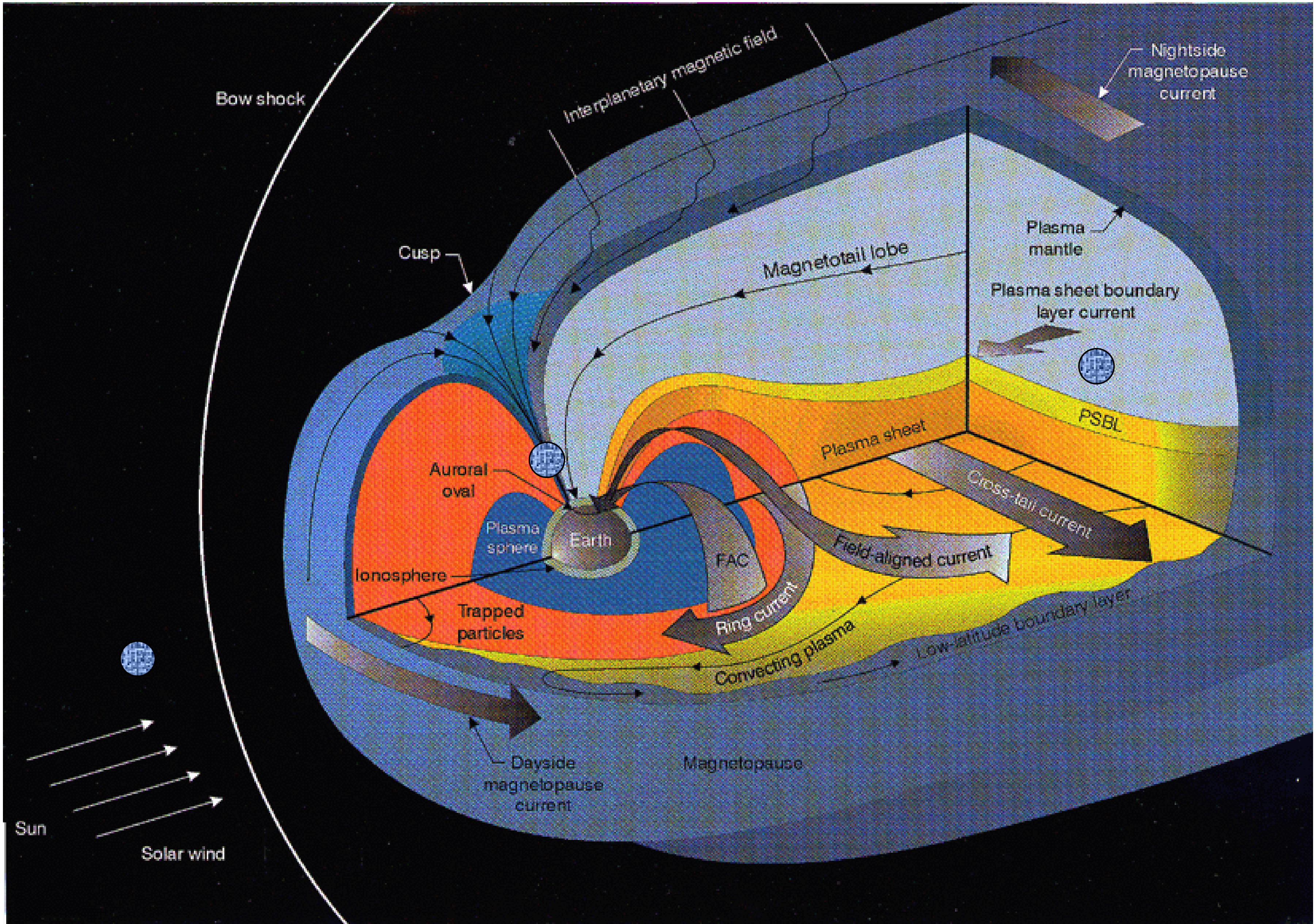
Release 02:17:00 UT

Image 02:18:24 UT

Observation and Simulation of Cycloid Bunching in the CRRES G-2 Barium Ion Cloud

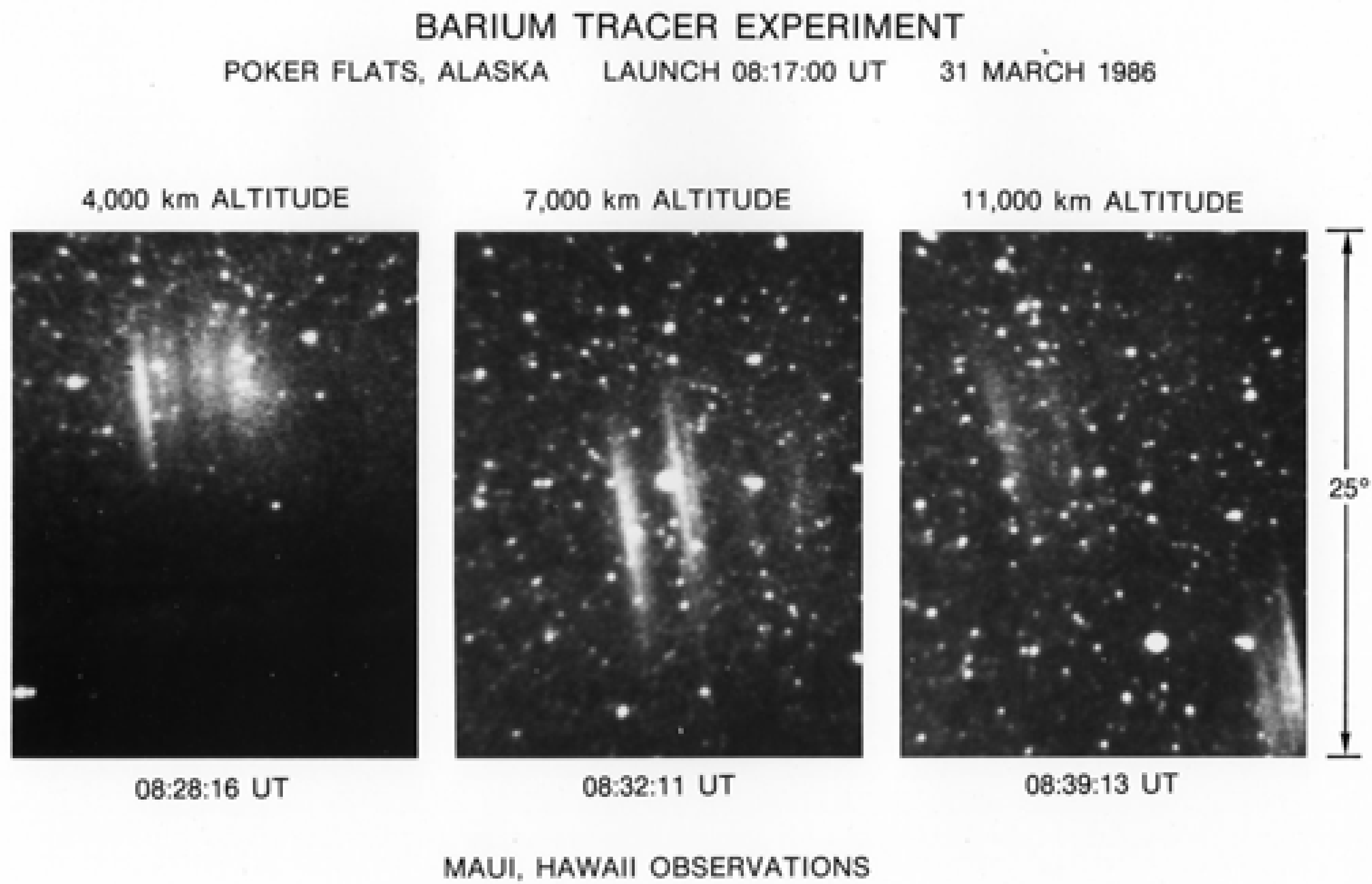



BARIUM INJECTION COORDINATE SYSTEM
Z
B
Y
0
X
Vc
Vcx t
Vcz t
SUN
V2
Vcx 2π/Ωc2

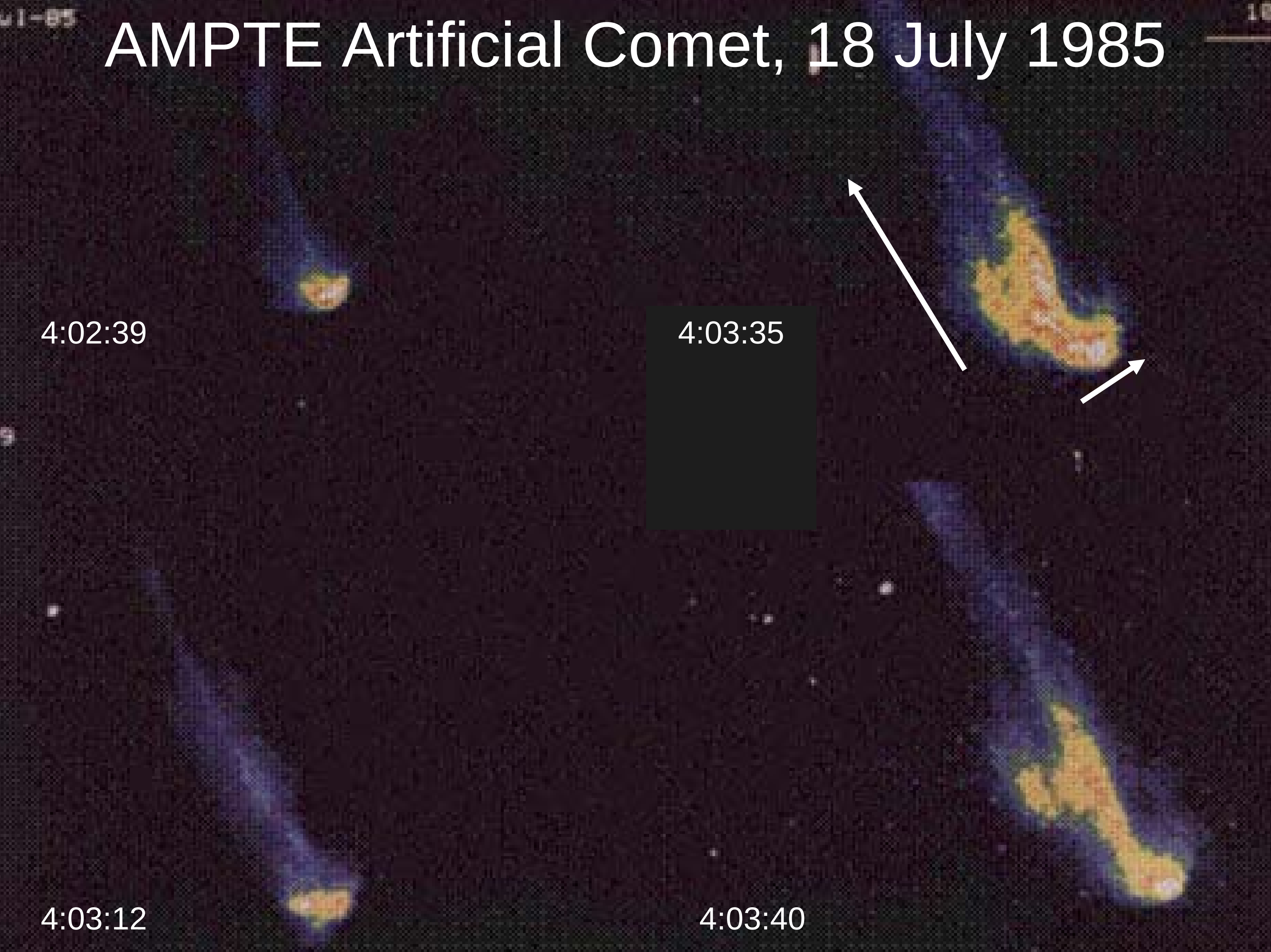


Bow shock
Interplanetary magnetic field
Nightside magnetopause current
Cusp
Magnetotail lobe
Plasma mantle
Plasma sheet boundary layer current
PSBL
Plasma sheet
Auroral oval
Plasma sphere
Earth
Ionosphere
Cross-tail current
Field-aligned current
FAC
Ring current
Trapped particles
Convecting plasma
Low-latitude boundary layer
Dayside magnetopause current
Magnetopause
Sun
Solar wind

Parallel Electric Field Sensing Using Barium Ion Tracers



AMPTE Artificial Comet, 18 July 1985



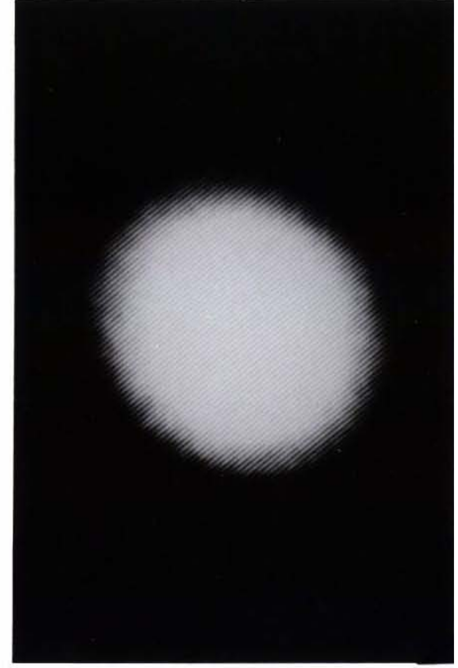
AMPTE Barium Release in the Magnetotail

Diagmagnetic Cavity Formation

12 March 1985


9:21:25


9:22:05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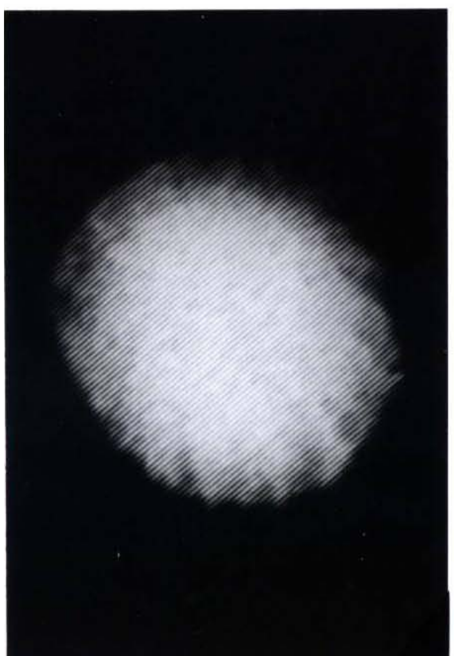
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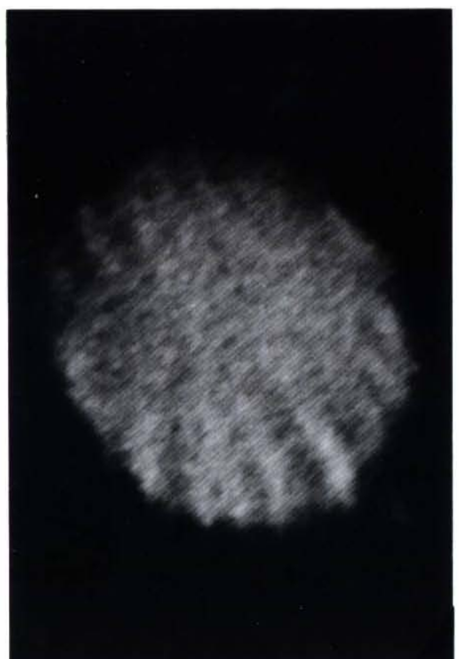

9:24:01

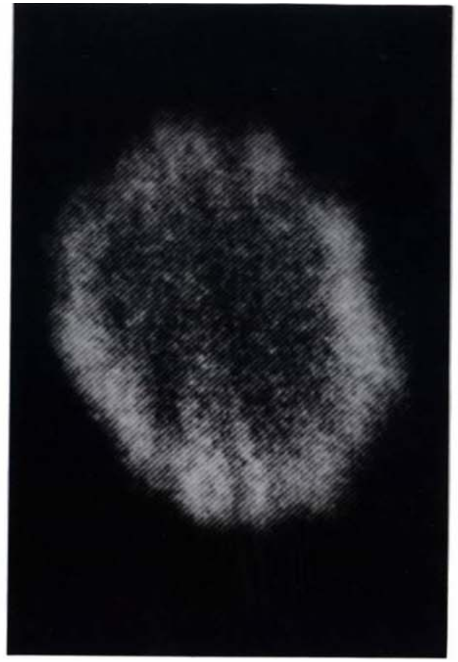

9:24:39

Maximum Radius = 210 km

Ambient Magnetic Field = 8 nT

7.5 x 10^{24} Barium Atoms Released

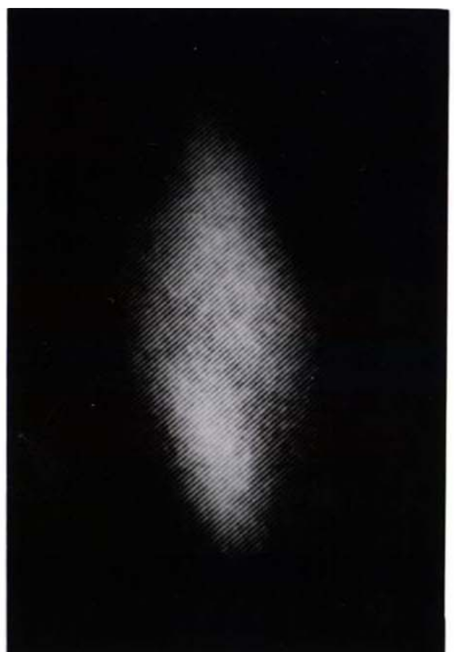
9:21:25



9:22:05

9:22:44

9:23:22



9:24:01

9:24:39

AMPTE Barium Release in the Magnetotail

Diagmagnetic Cavity Collapse

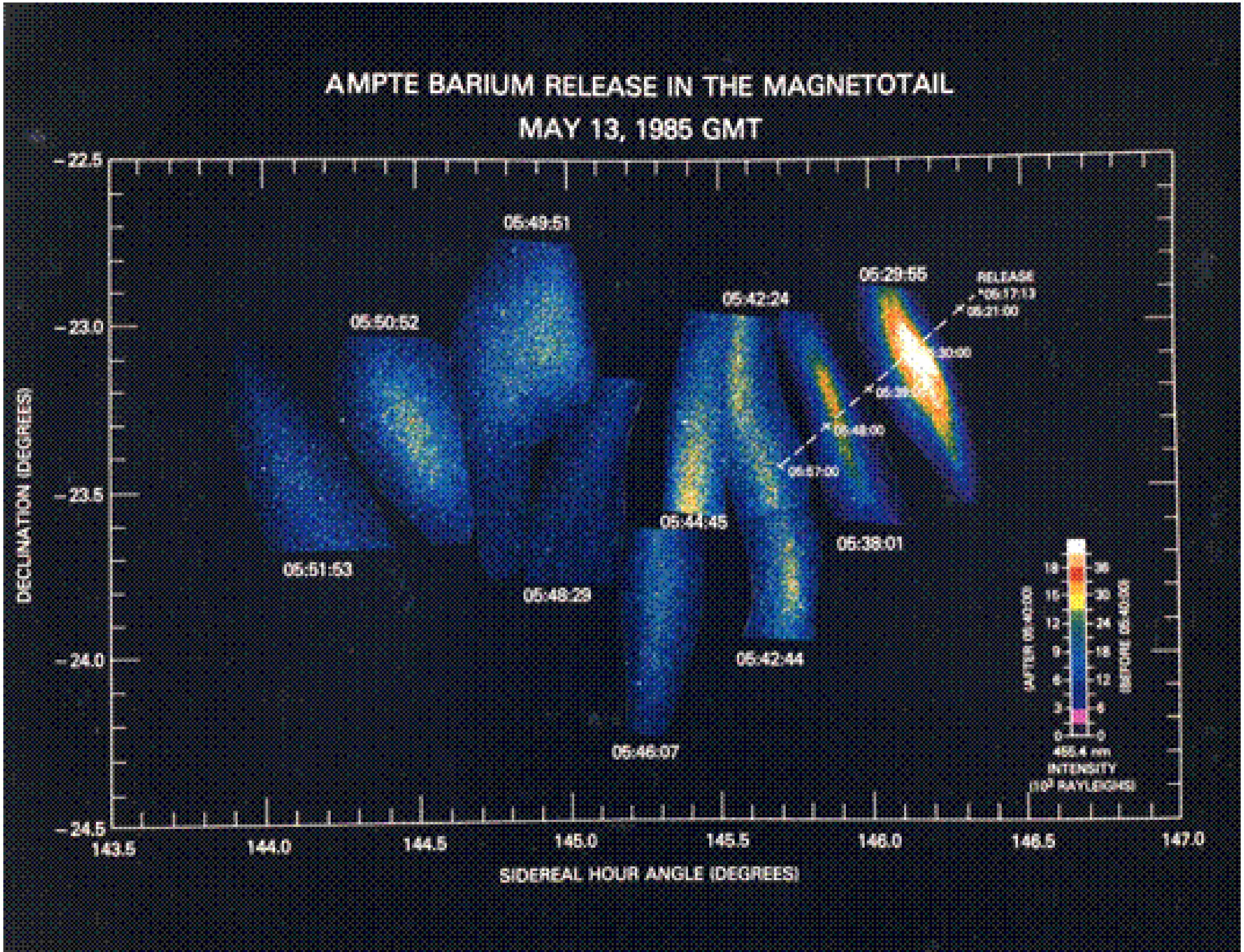
12 March 1985

Maximum Radius = 210 km

Ambient Magnetic Field = 8 nT

7.5×10^{24} Barium Atoms Released

Down Tail Motion of the AMPTE Barium Ion Cloud



CRRES G-7 Lithium Release

13 January 1991 07:00 UT

33000 km Altitude

Release + 24 Seconds

110 km Radius

Release + 24 Seconds

420 km Radius

Release + 24 Seconds

1270 km Radius

Generation of Electron and Ion Clouds by Samarium Metal Release

COPE II September 1998

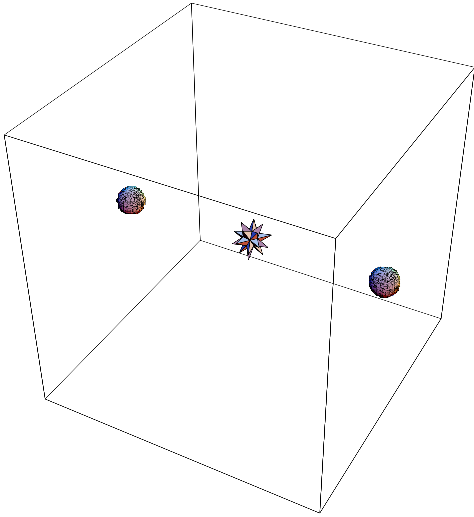
$Sm + O \rightarrow SmO^+ + e^- + 0.39\ eV$

8 x 40 km Cloud

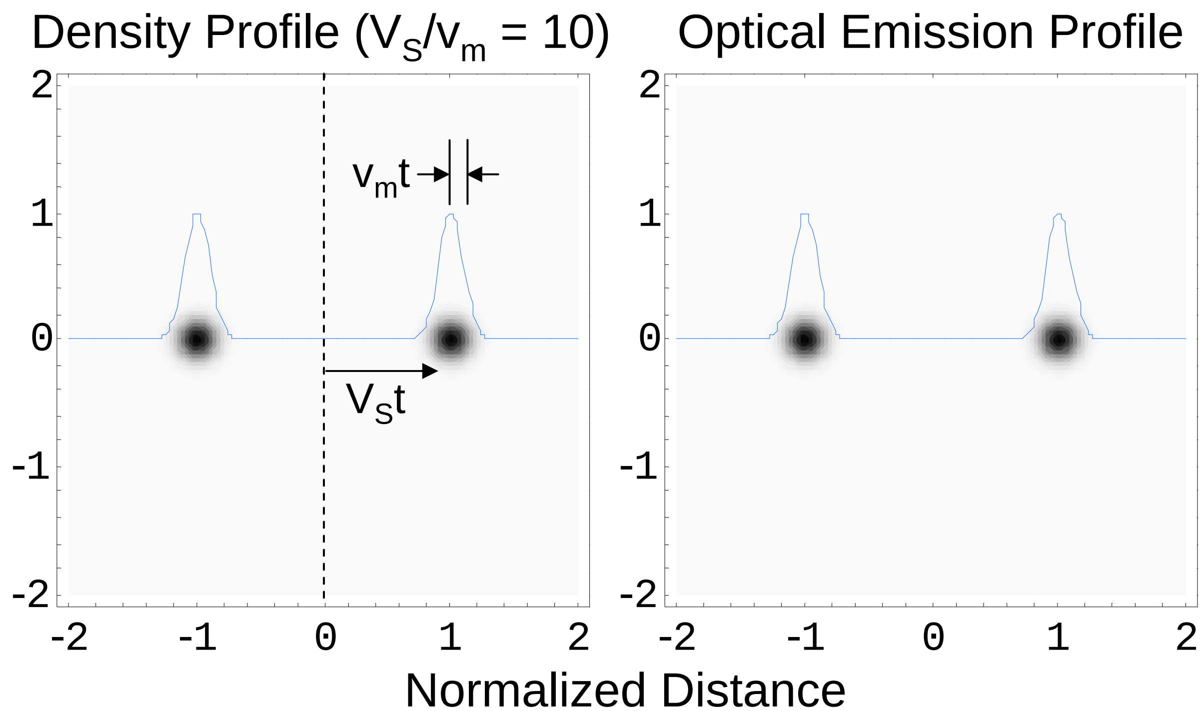
$Ne \rightarrow 10^9\ cm^{-3}$

Follow On Experiment by AFRL in Planning Phase

Density Shells and Optical Observations

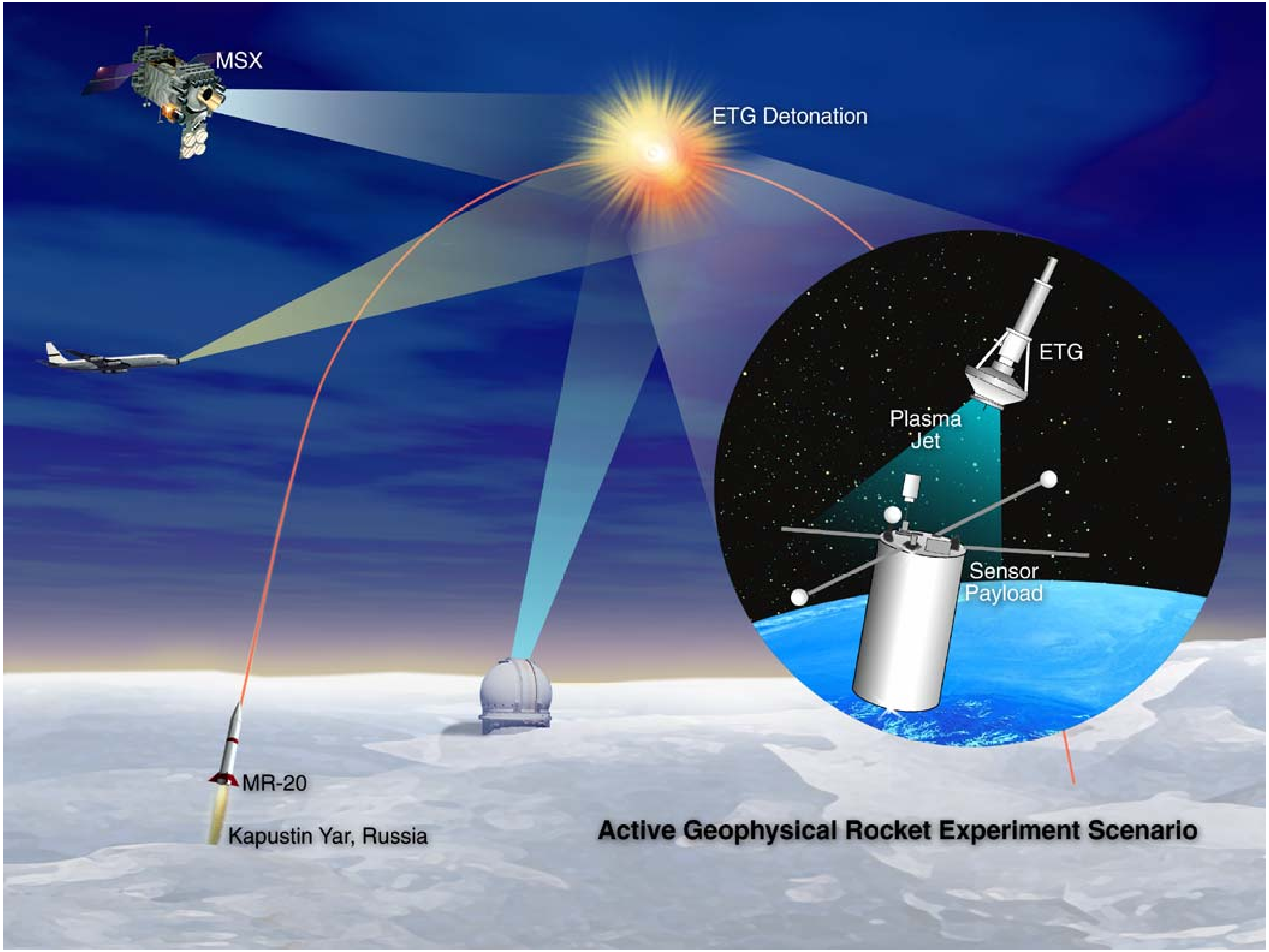


- One-Dimensional Jet Releases in a Vacuum

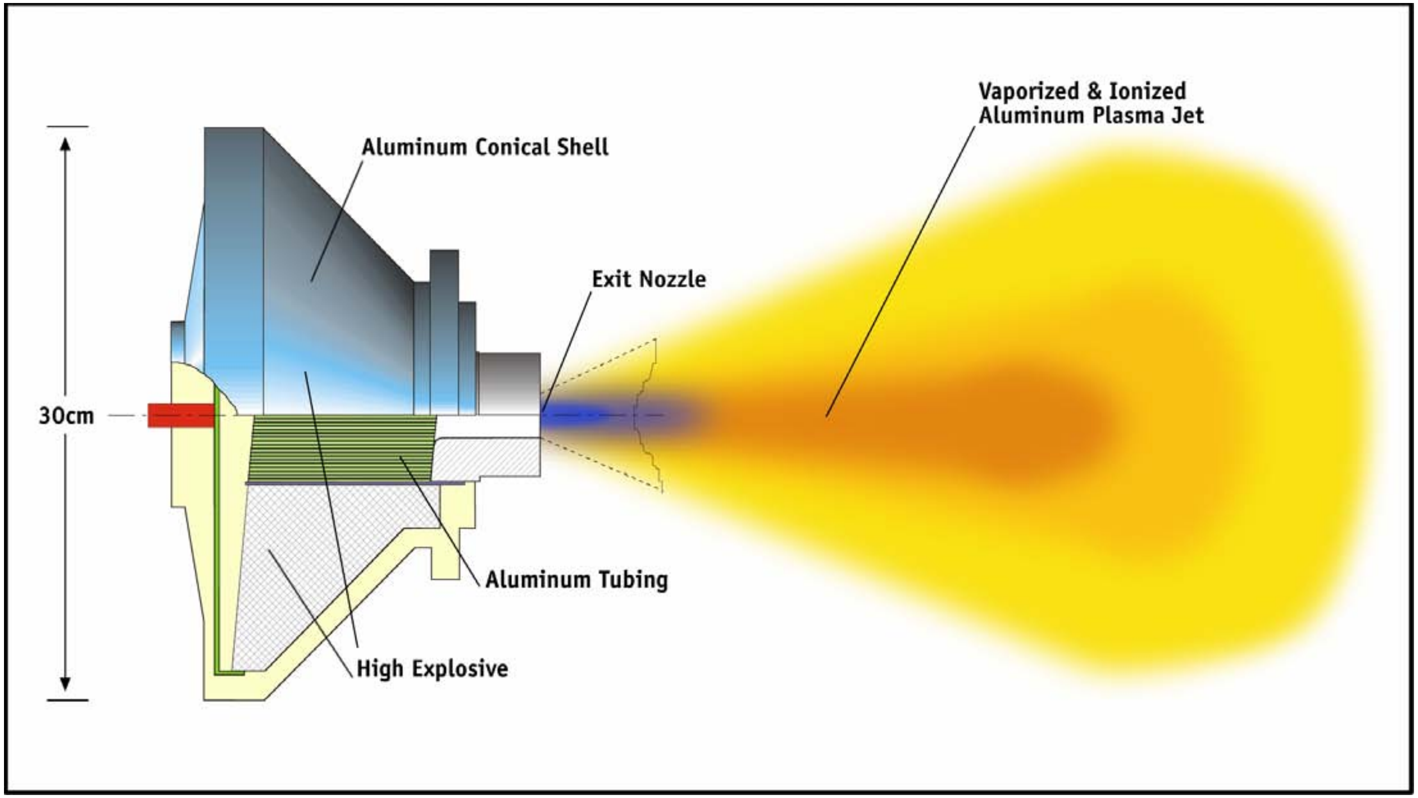


– Characteristics
  - Directed Injection of Expanding Ball
  - Aluminum ETG Parameters: $V_s \cong 20$ km/s, $v_m \cong 8$ km/s

Fluxus 1&2 Experiment Scenario



Explosive Type Generator (ETG)

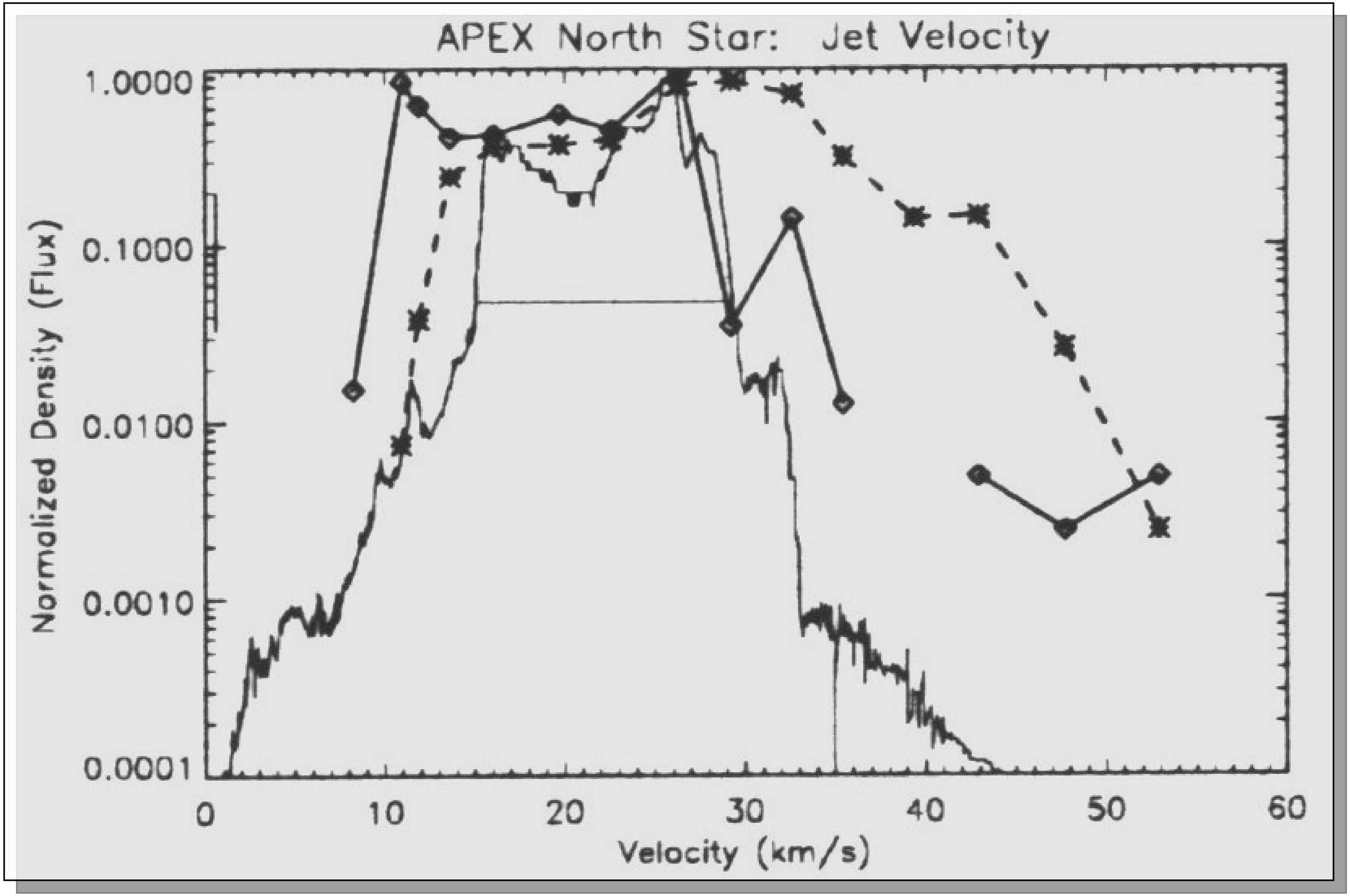


ETG Specifications:

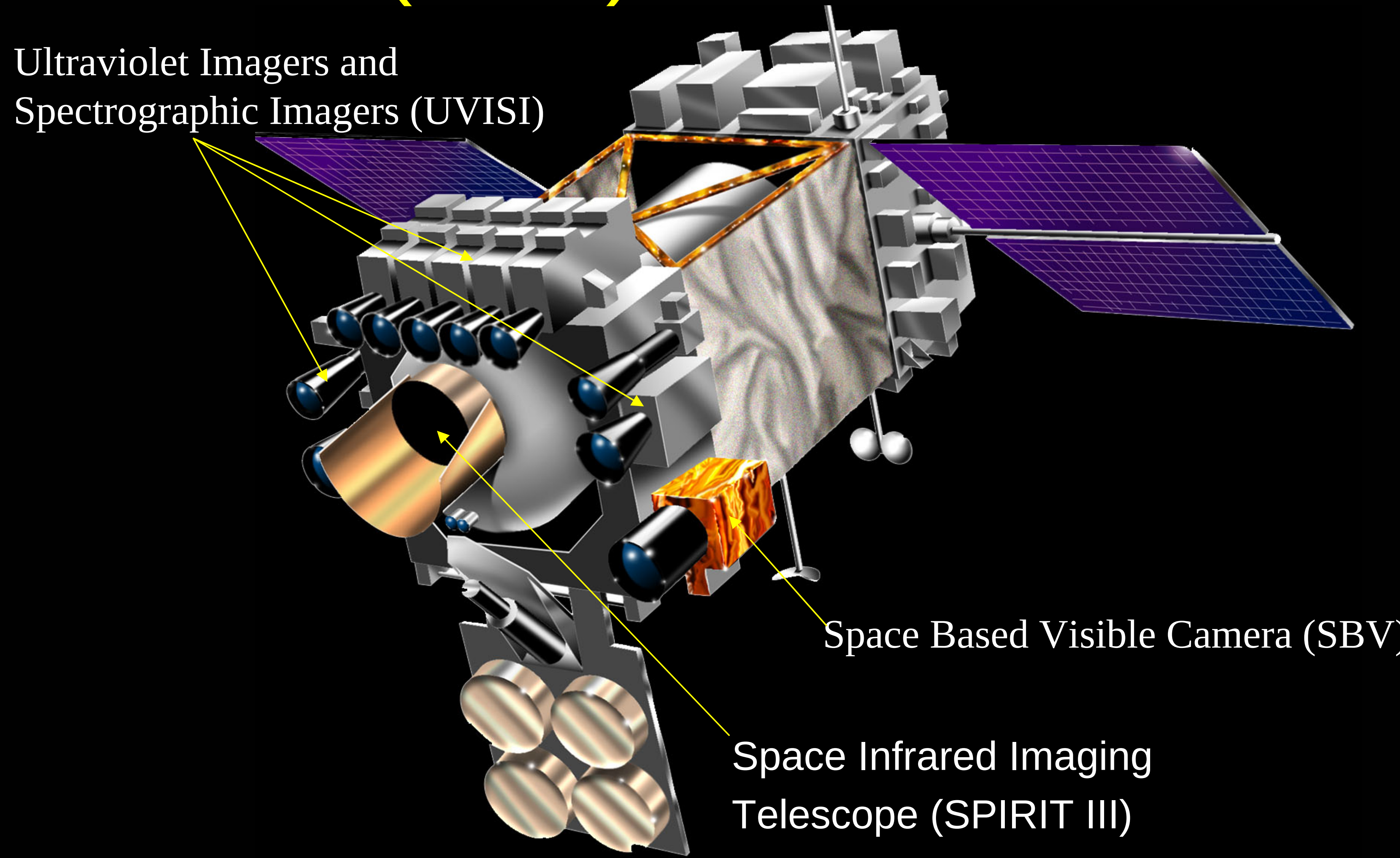
High Explosives:
- Weight: 9.7 kg
- Energy: 40 MJ
- Type: 35% TNT
  65% RDX

Plasma Jet
- Material: Aluminum
- Mass: 40 g
- Energy: 6 MJ
- Velocity: 20 km/s

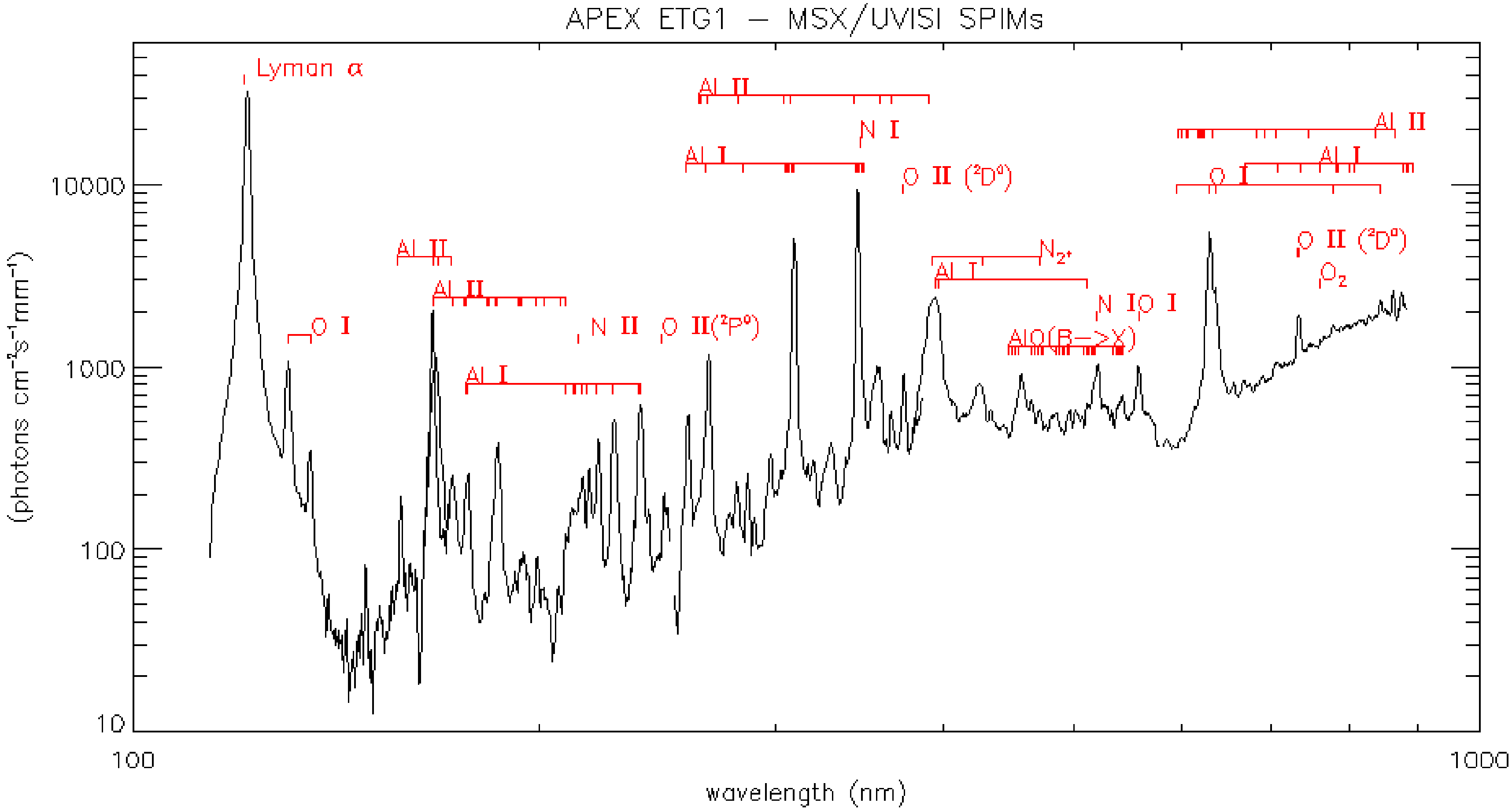
Plasma Jet Velocity Distribution



Midcourse Space Experiment (MSX) Satellite



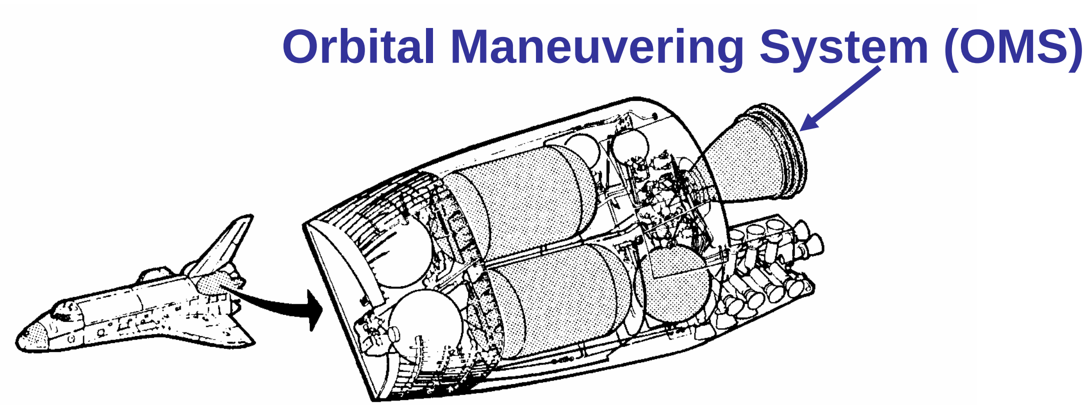
MSX UVISI Spectral Observations APEX ETG-1



Integration Time: 0.5 sec

Range to Plasma Jet: 2800 km, Field of View: 0.1 x 1.0º

Space Shuttle OMS Engine Exhaust Parameters

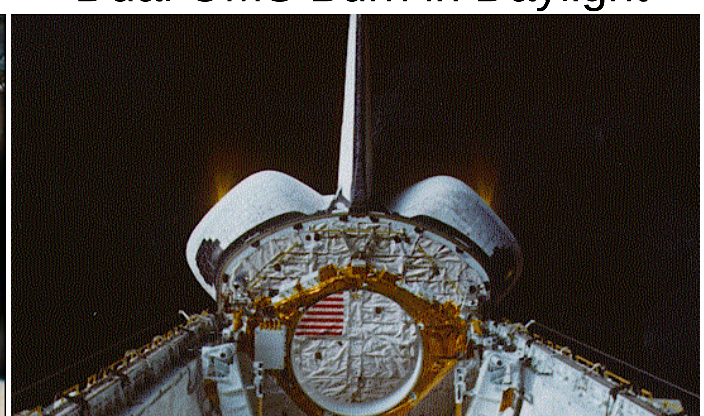


Flow Rate: 5.0 x 10^{26} Molecules per Engine

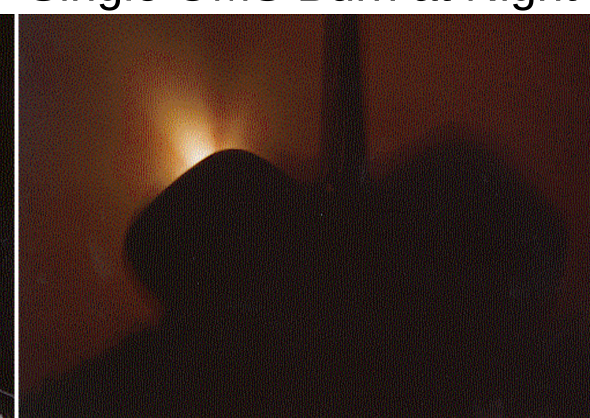
Exhaust Species	Mole Fraction
CO	0.050
CO_2	0.122
H_2	0.241
H_2O	0.274
N_2	0.313

Nonuniform Dual OMS Burn

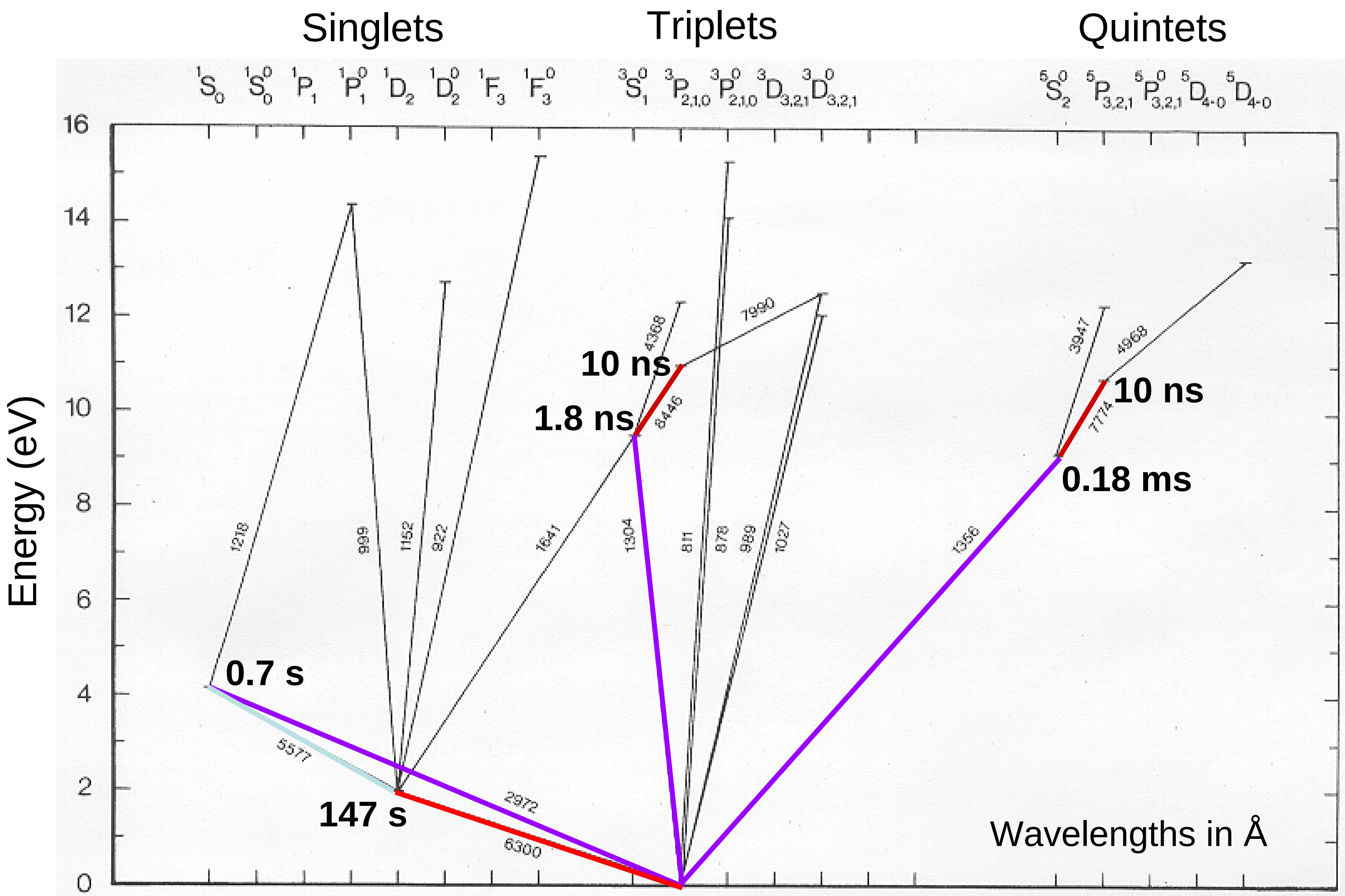
Symmetrical Dual OMS Burn in Daylight



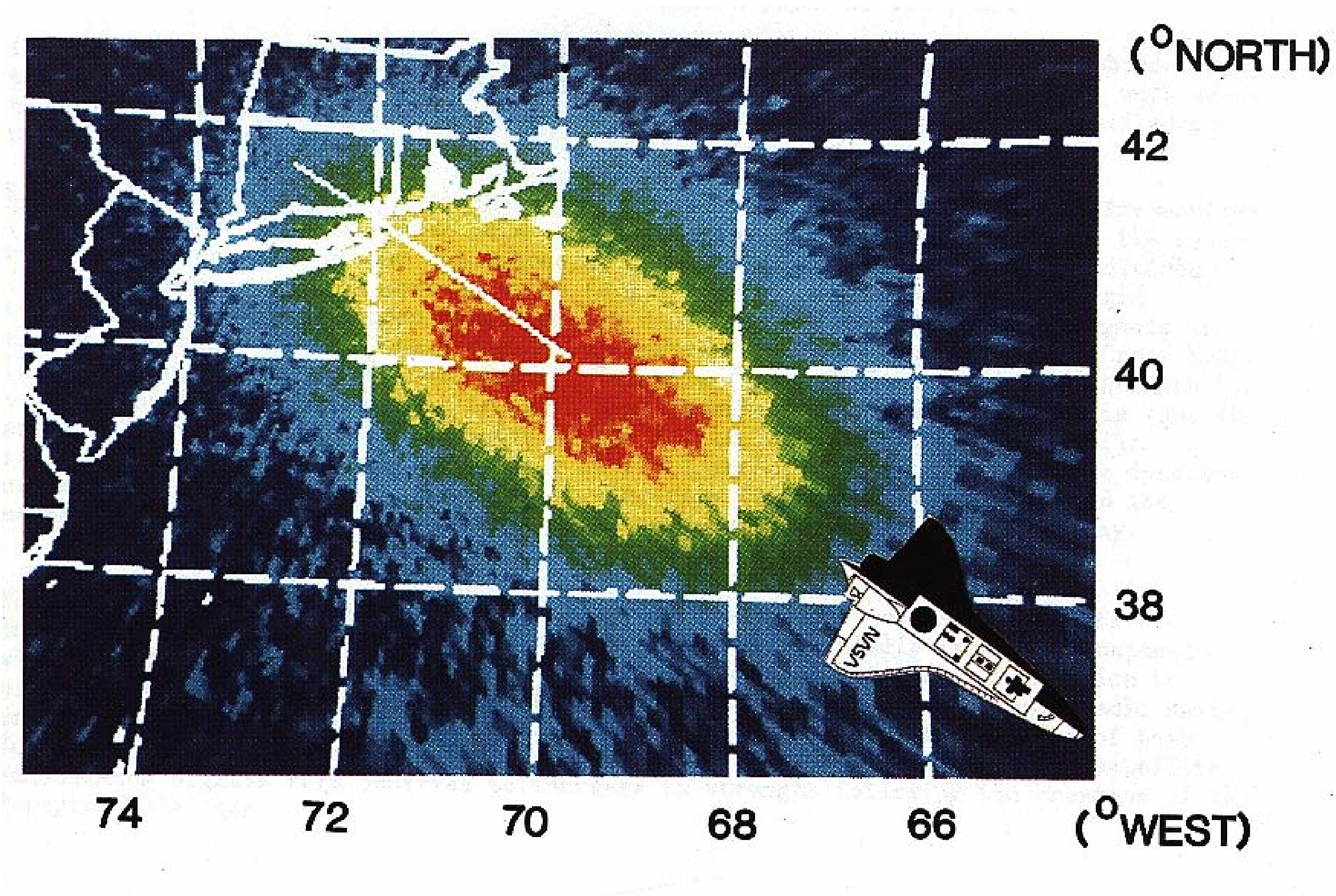
Single OMS Burn at Night



Transitions for Atomic Oxygen



Spacelab 2 Burn Over Millstone Hill, MA
630 nm Emission, 29 July, 1985



Atlas-F Launch, 23 June 1981 10:50:00 UT

Red-Line Emissions From Reactions Between the Ionosphere and the Rocket Exhaust

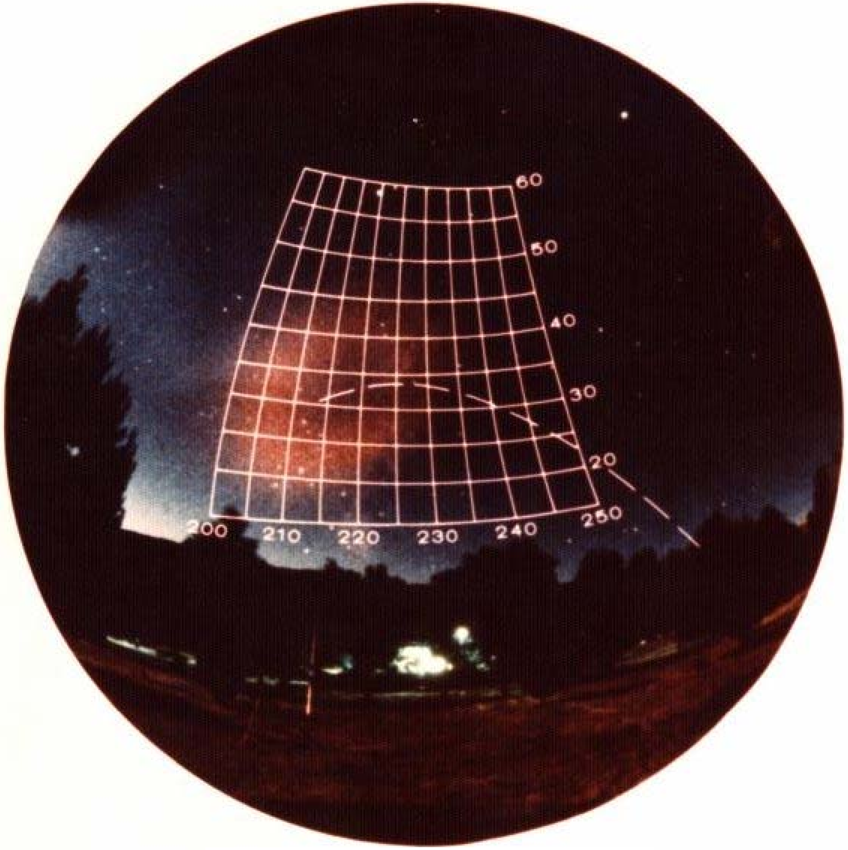
10:54:45 UT

10:56:24 UT

Atlas-F Launch, 23 June 1981 10:50:00 UT

Red-Line Emissions From Reactions Between the Ionosphere and the Rocket Exhaust

10:54:45 UT



10:56:24 UT

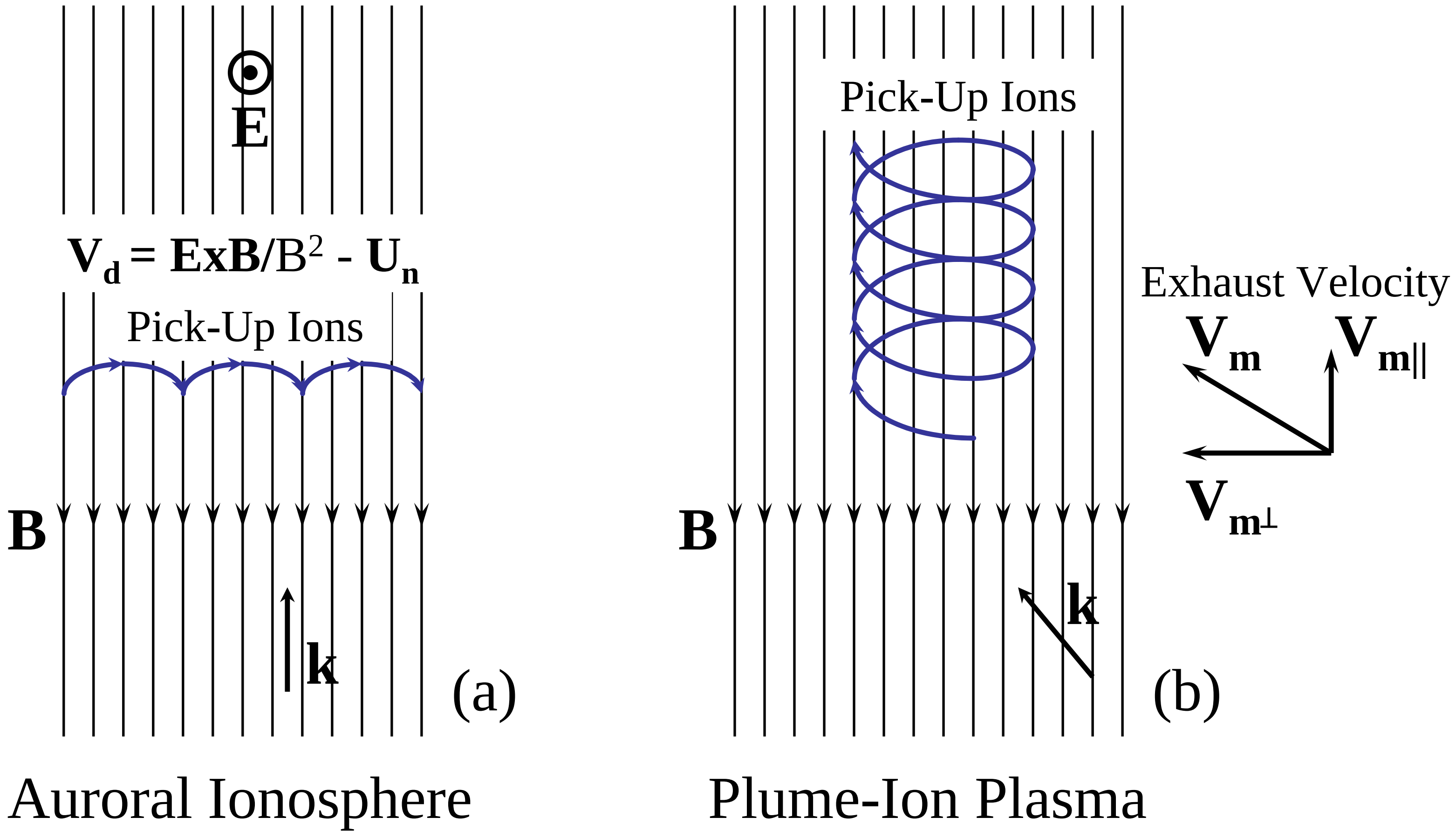
Atlas-F Launch, 23 June 1981 10:50:00 UT

Red-Line Emissions From Reactions Between the Ionosphere and the Rocket Exhaust

11:01:17 UT

10:04:35 UT

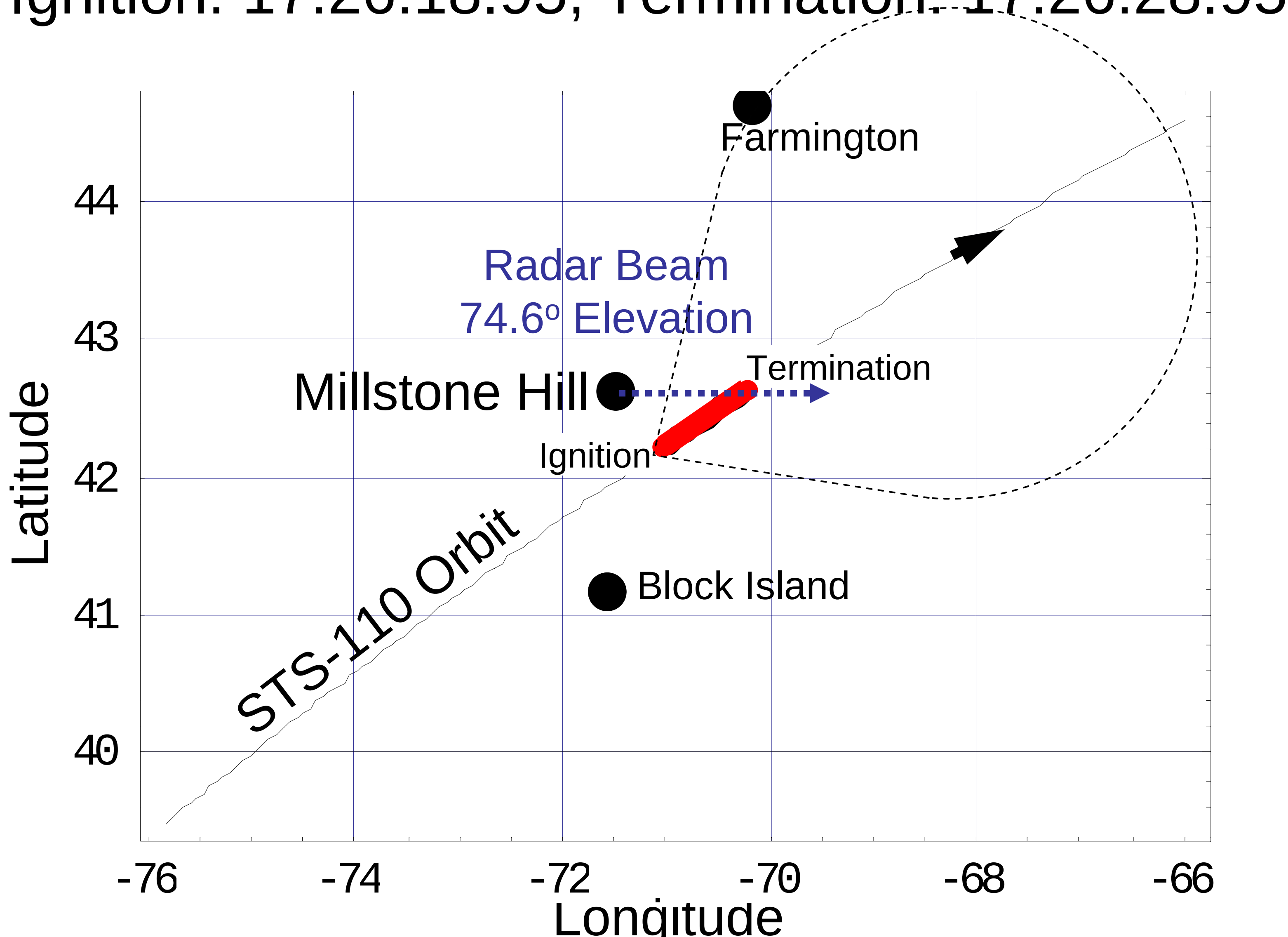
Ion Ring Distributions from Auroral Convection and Exhaust Injection



STS-110 Burn Location

18 April 2002 GMT

Ignition: 17:26:18.95, Termination: 17:26:28.95

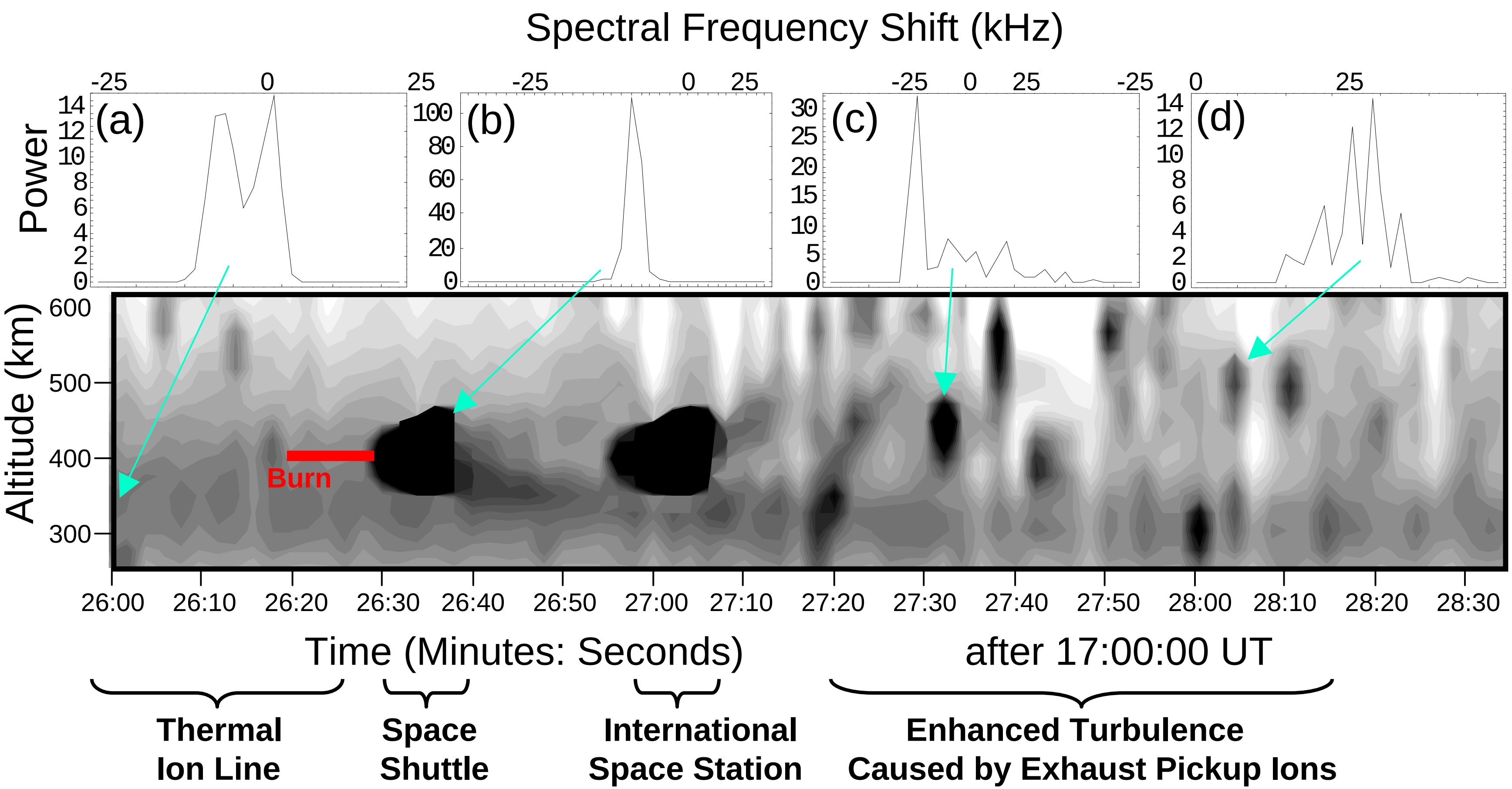


SIMPLEX IV Radar Backscatter

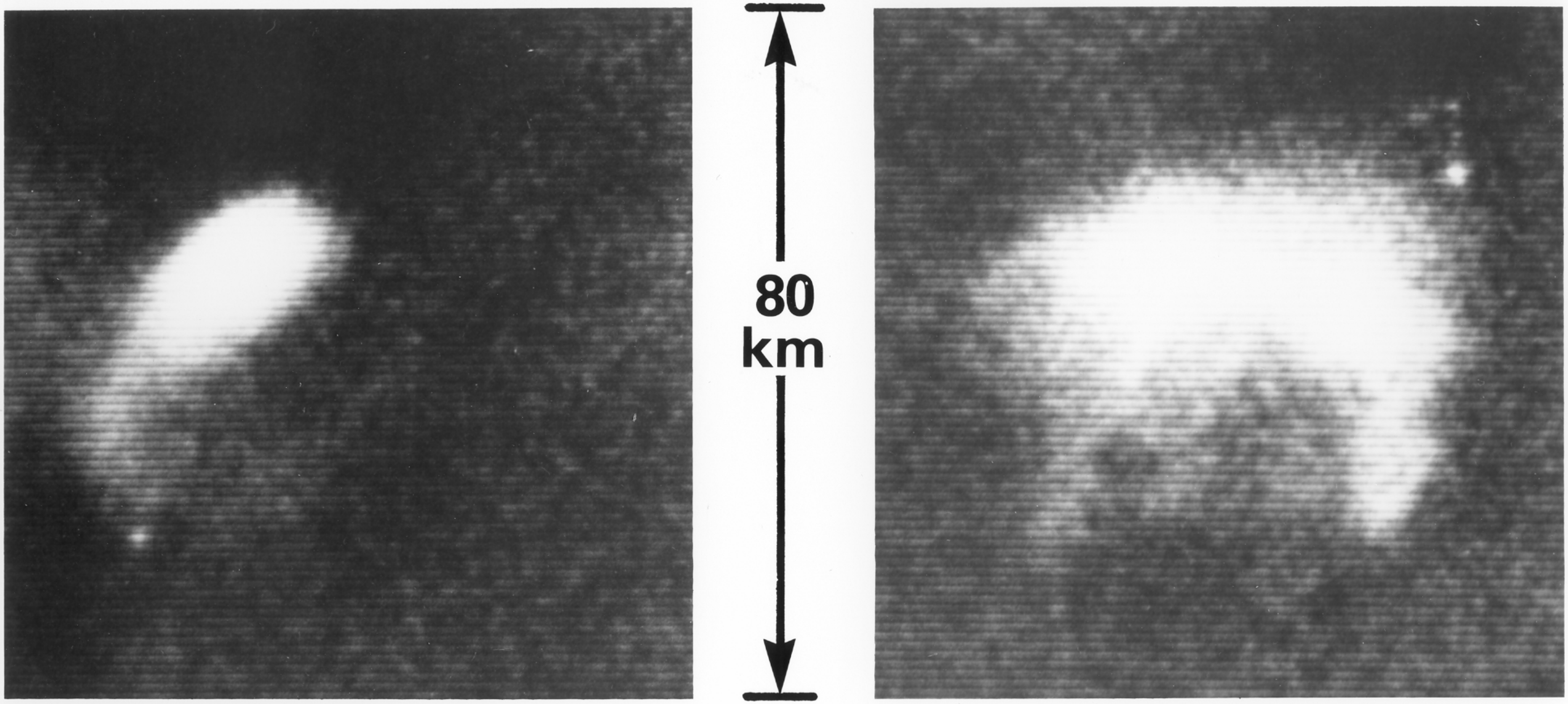
Millstone Hill Radar, 18 April 2002

Burn Time 17:26:19 – 17:26:29 UT

2 Second and 24 km Resolution



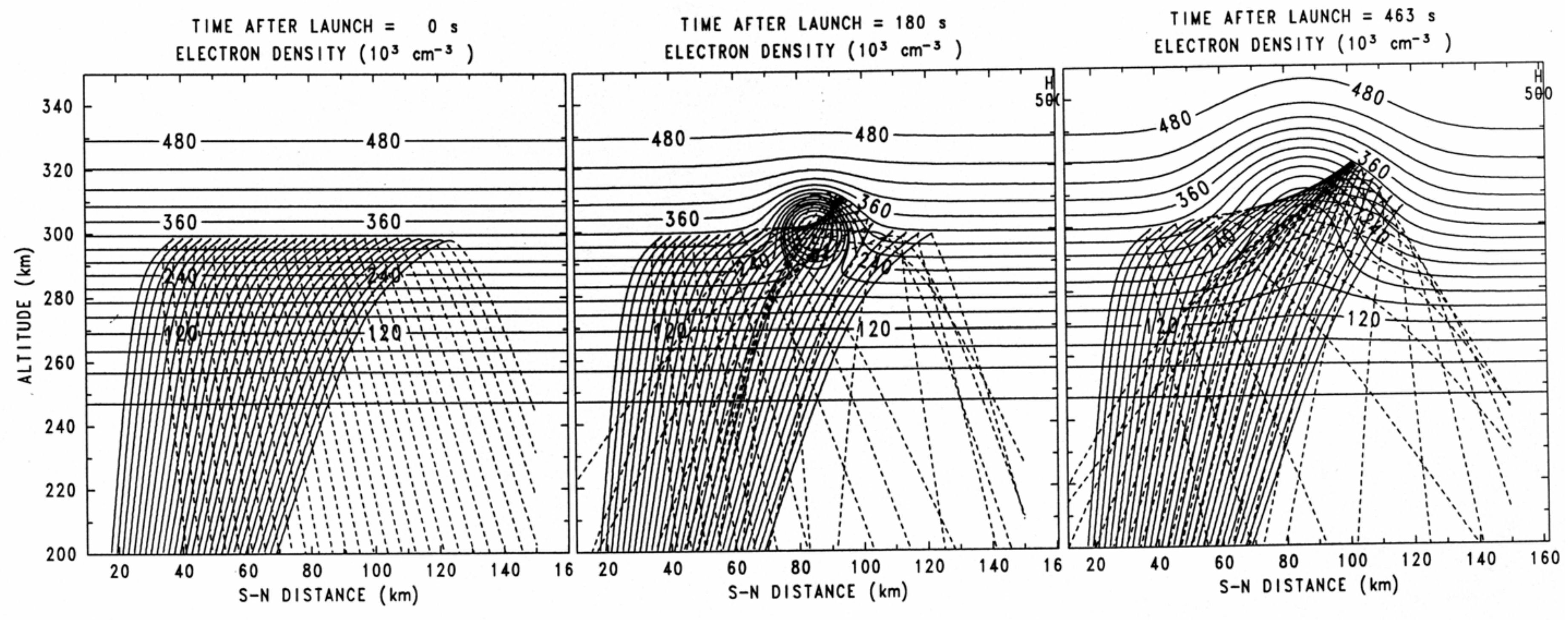
SPINEX-2 28 APRIL 1986



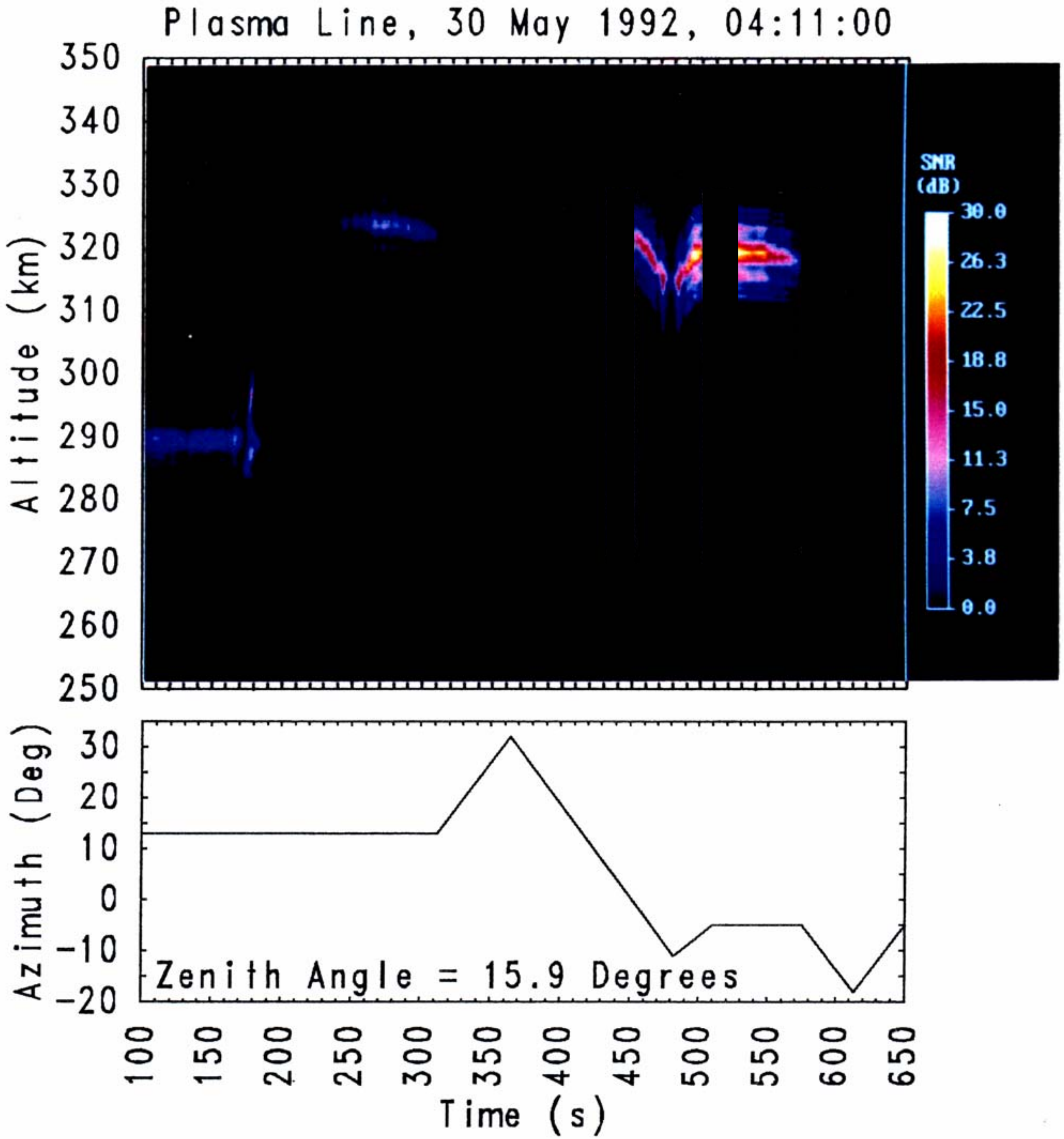
02:01:03 UT   02:01:40 UT

777.4 nm AIRGLOW EMISSIONS FROM A 40 kg RELEASE OF SF_6 AT 252 km ALTITUDE

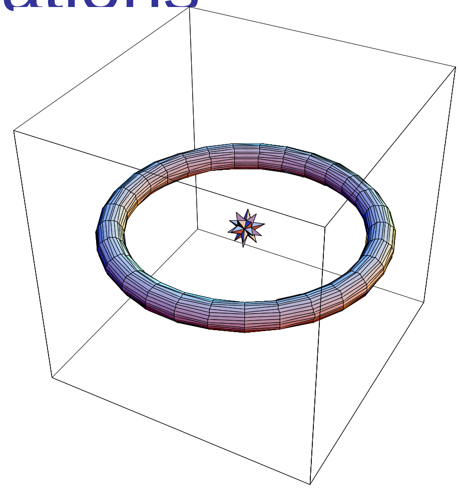
5.8 MHz Radio Wave Focusing by an Artificial Hole



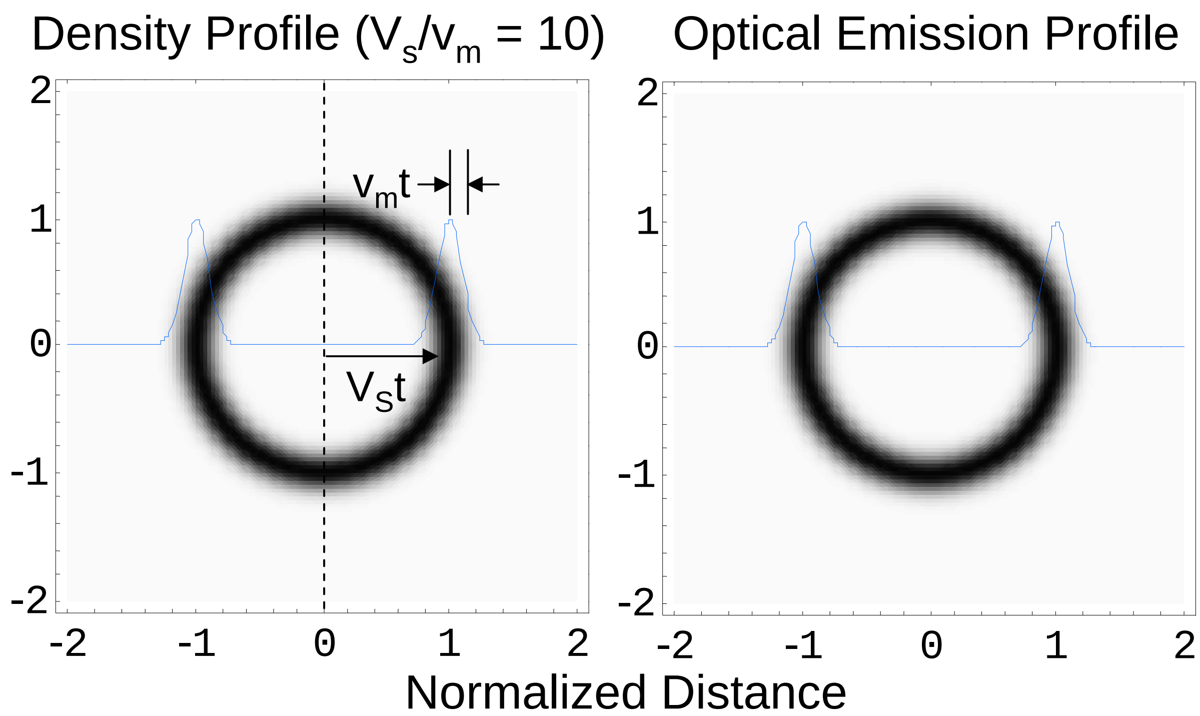
The Ionospheric Focused Heating Experiment During the El Coqui, CRRES Rocket Campaign



Density Shells and Optical Observations

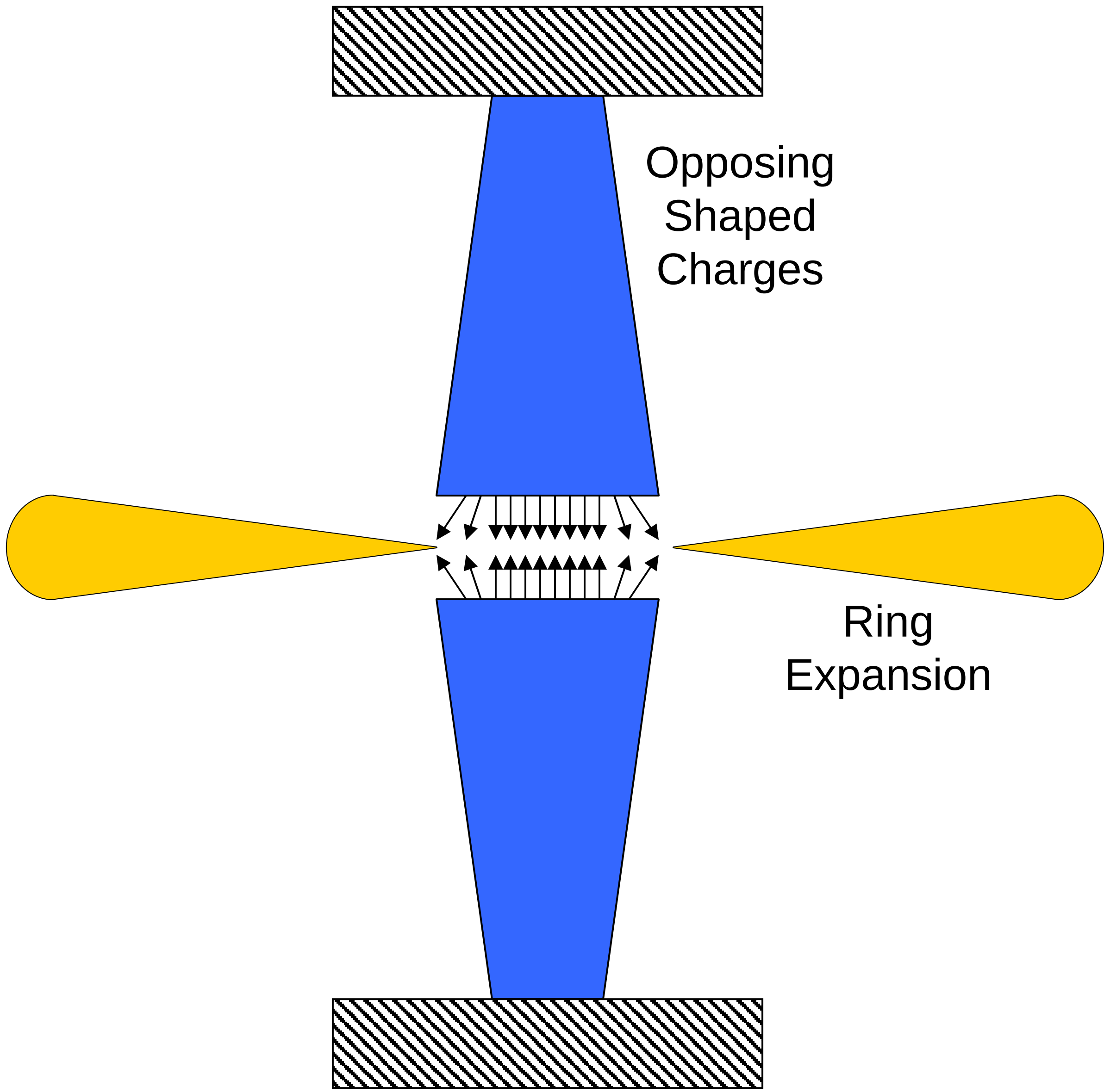


- Two-Dimensional Ring Expansions into a Vacuum



- Characteristics
  - Circular or Eliptical Optical Projection Depending on Viewing Direction
  - Self-Similar Expansion
  - No Optical Data Available

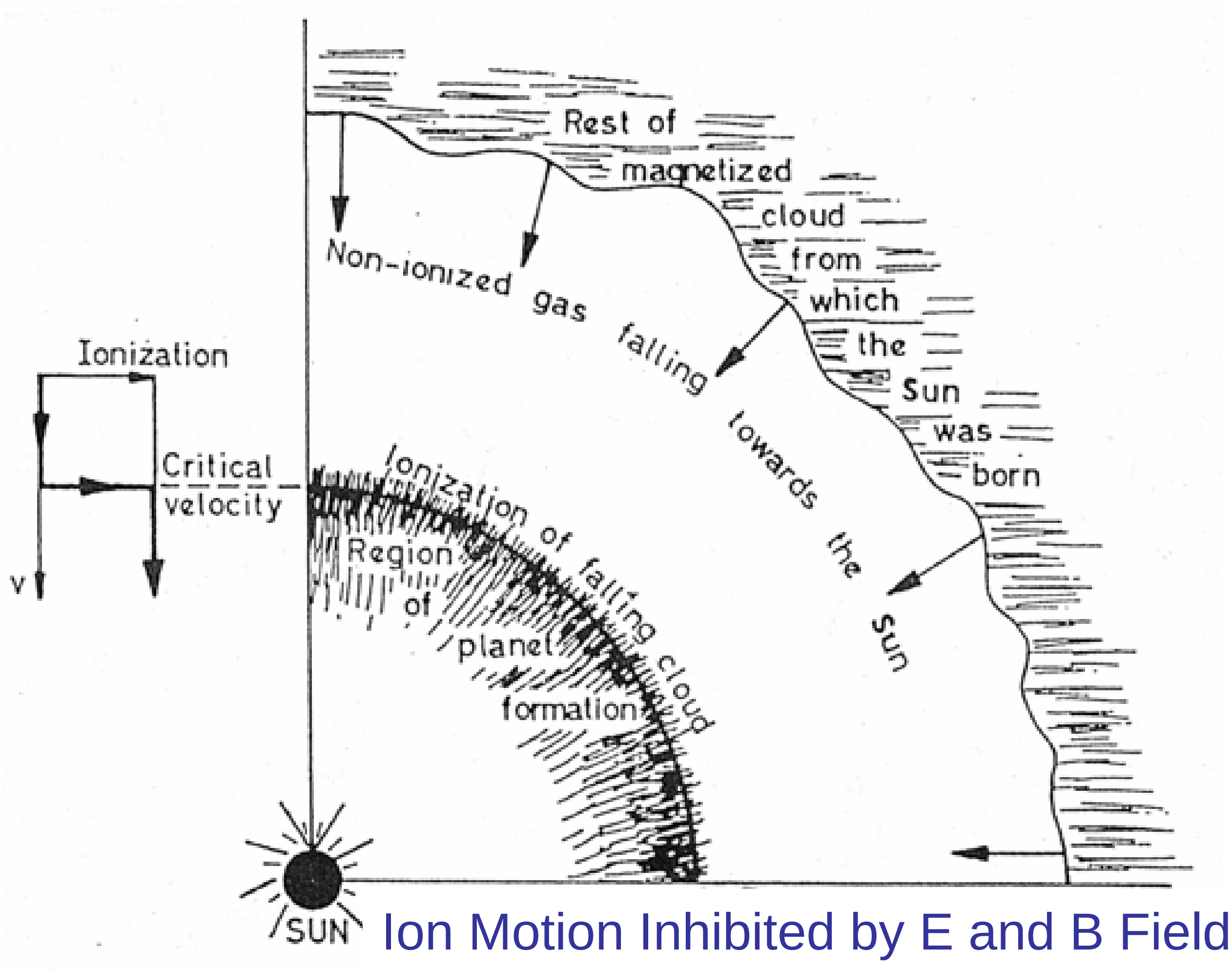
Ring Generator From LANL



Origin of Planetary System (Alfven, 1960)

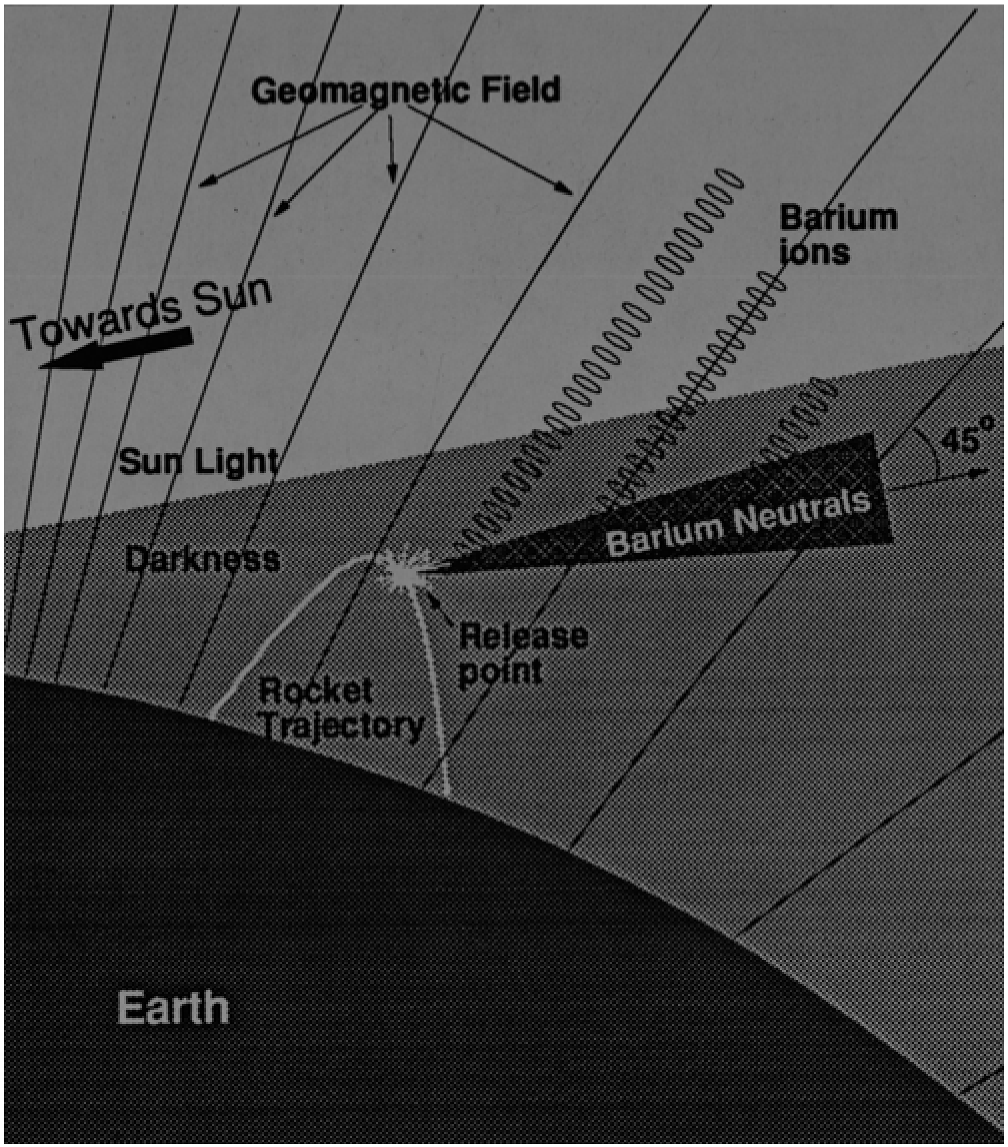
Critical Velocity Transition:

Kinetic Energy > Ionization Potential

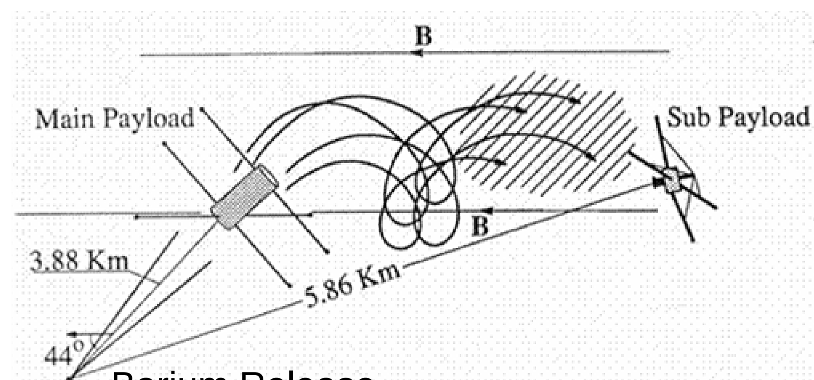


Ion Motion Inhibited by E and B Fields

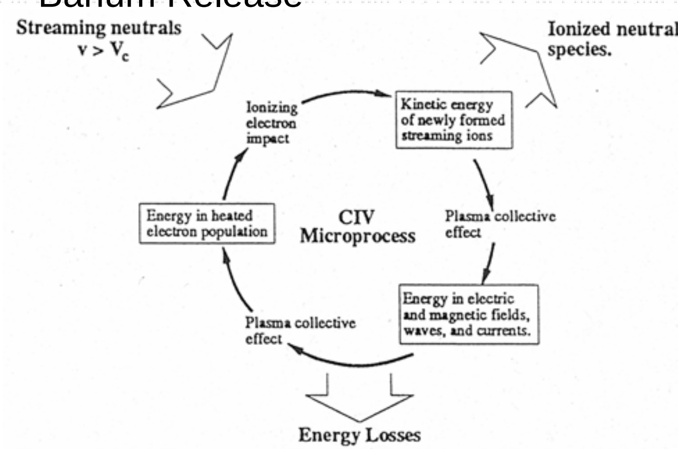
Critical Ionization Velocity Experiments



Experiment	Year	Plasma Density	$\vec{B}_o$ Angle	Type	Prompt Ionization Total	Prompt Ionization CIV
Chachalaca[†]	1972	?	10 – 15°	30° Cone	≈5%	≈5%
Buaro[†*]	1976	1×10^6	90°	30° Cone	-	0%
Porcupine[†]	1979	6×10^5	28°	Cone	6-7%	16-18%
Bubble Machine II[†*]	1982	?	-	Radial	0%	0%
Star of Lima[†]	1983	2×10^4	90°	Cone	0.05%	0%
Star of Condor[‡]	1983	2×10^4	-	Radial	0.004%	0.0017%
George Orwell[†]	1984	?	-	Radial	0%	0%
SR90[‡*]	1986	1.5×10^4	48°	Cone	0.34%	0.17%
CRIT I[†]	1986	3.4×10^4	47°	Cone	0.02%	0.01%
CRIT II[†]	1989	5.4×10^5	57°	Cone	4%	1.67%



Barium Release



Critical Ionization Velocity (CIV) Experiments

Experiment	Year	Plasma Density	B_0 Angle	Type	Prompt Ionization Total	CIV
Chachalaca (Ba)	1972	?	10-15°	30° Cone	~ 5% (Ba)	~ 5% (Ba)
Buaro (Ba- Solar UV)	1976	1×10^6	90°	30° Cone	--	~ 0% (Ba)
Porcupine (Ba)	1979	6×10^5	28°	Cone	6-7%	16-18%
Bubble Mathcine II (Ba- Solar UV)	1982	?	--	Radial	0%	0%
Star of Lima (Ba)	1983	2 x 104	90°	Cone	0.05%	0%
Star of Condor (Sr)	1983	2 x 104	--	Radial	0.004%	0.0017%
George Orwell (Sr)	1984	?	--	Radial	0%	0%
SR90 (Sr)	1986	1.5×10^4	48°	Cone	0.34%	0.17%
CRIT I (Ba)	1986	3.4×10^4	47°	Cone	0.02%	0.01%
CRIT II (Ba)	1989	5.4×10^5	57°	Cone	0.02%	0.01%
CRRES G-13 (Ba, Sr)	1990	?	80°	Cone	0.15% (Ba) 0.02% (Sr)	0.15% (Ba) 0.02% (Sr)
CRRES G-14 (Ba, Sr)	1990	?	77°	Cone	0.40% (Ba) 0.27% (Ca)	0.40% (Ba) 0.27% (Sr)

Conclusions and Future Experiments

- Chemical Release Mysteries
  - Measured Mesospheric Winds are Factors of 3 Lower than HWM Model Winds
  - Rapid Diffusion Rates in Lower Thermosphere
  - Artificial Aurora Below TMA Trails
  - Sources of Radar Scatter Spectra 100's of km from Space Shuttle OMS Plume
- Future Experiments
  - NASA/Clemson TMA Releases During EQUIS II at Kwajalein
  - AFRL Samarium Releases in the Kwajalein ALTAIR Radar
  - NRL Space Shuttle Burns Over Millstone Hill, Arecibo, Jicamarca, Kwajalein
  - NRL Artificial Dusty Plasma Experiment