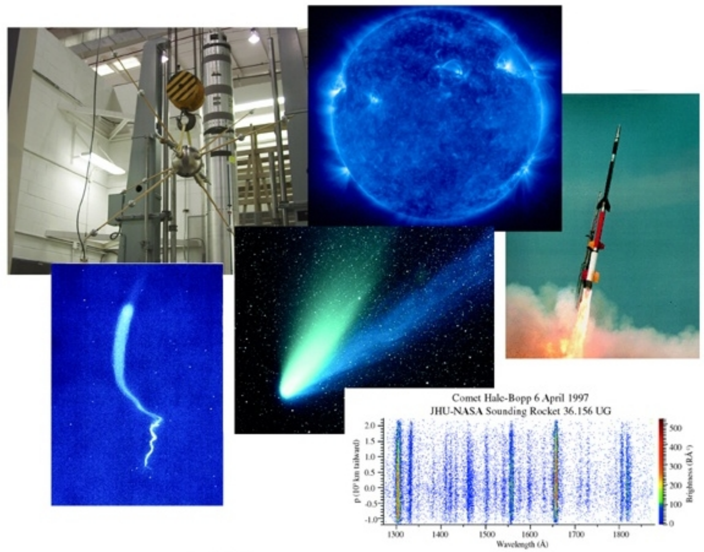
It *Is* Rocket Science…

Remarkable Discoveries from NASA's Sounding Rocket Program



Goddard Scientific Colloquium

Robert Pfaff
Sounding Rocket Project Scientist
NASA/Goddard Space Flight Center

November 1, 2013

Outline of Presentation

- General Features of NASA's Sounding Rocket Program
- Sounding Rocket Vehicles, Payload Notes, Launch Locations
- Science Discipline Requirements and Examples of Accomplishments
  - Astronomy / Planetary
  - Solar
  - Geophysics
  - Special Projects (e.g., Re-entry tests, Aerobraking, etc.)
- SR Technology Roadmap -- Future Prospects
- Summary

NASA Rocket Program -- General Remarks

- For over 5 decades, NASA’S Sounding Rocket Program has provided an essential ingredient of the agency’s exploration and science initiatives.

- Sounding Rocket Program rests solidly on 3 critical elements:
  -- Unique, cutting-edge science missions
  -- Platform for development and test of new technology
  -- Education and training of students, young researchers, and engineers

- Two important features of the program:
  -- Low Cost
  -- Rapid, quick response

NASA Rocket Program -- General Remarks (cont.)

Program serves numerous scientific disciplines:

-- Astronomy

-- Planetary

-- Solar

-- Geospace

(Magnetosphere/Ionosphere/Thermosphere/Mesosphere)

-- Microgravity

-- Special Projects

(e.g., Aero-braking and Re-entry Studies)

NASA Rocket Program -- General Remarks (cont.)

Success of NASA Sounding Rocket Program *implementation* rests on a strong three-way partnership:

Principal Investigator (and Science Team)

Sounding Rocket Program Office (Wallops)

NASA HQ

Plus

Industry -- Contractor Workforce at Wallops

is Indispensable Part of Program

NASA Rocket Program -- General Remarks (cont.)

- A very important aspect of the program is that **the P.I. is firmly in charge of the mission** -- from proposal to payload design to making the launch decision to the data analysis and publication of results.

  -- Very appealing aspect of SR program to scientists.

  -- P.I. must work within an agreed-upon science budget with no contingency.

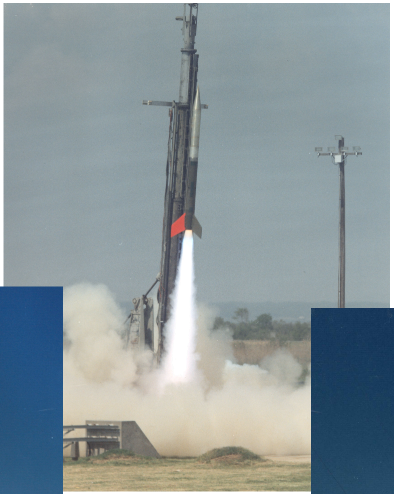
  -- Scope of project must stay within "envelope" outlined in proposal approved by both HQ and SRPO.

  -- Excellent, "real world" training for P.I., particularly with respect to managing a scientific investigation.

Sounding Rocket Vehicles

Terrier Malemute

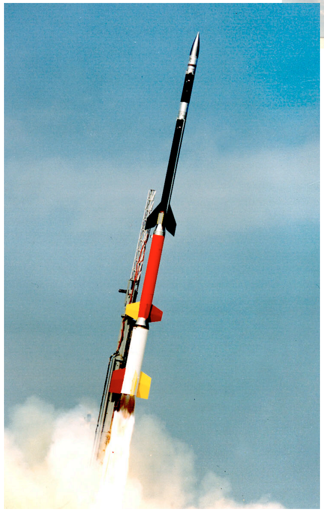
Nike Orion



Orion

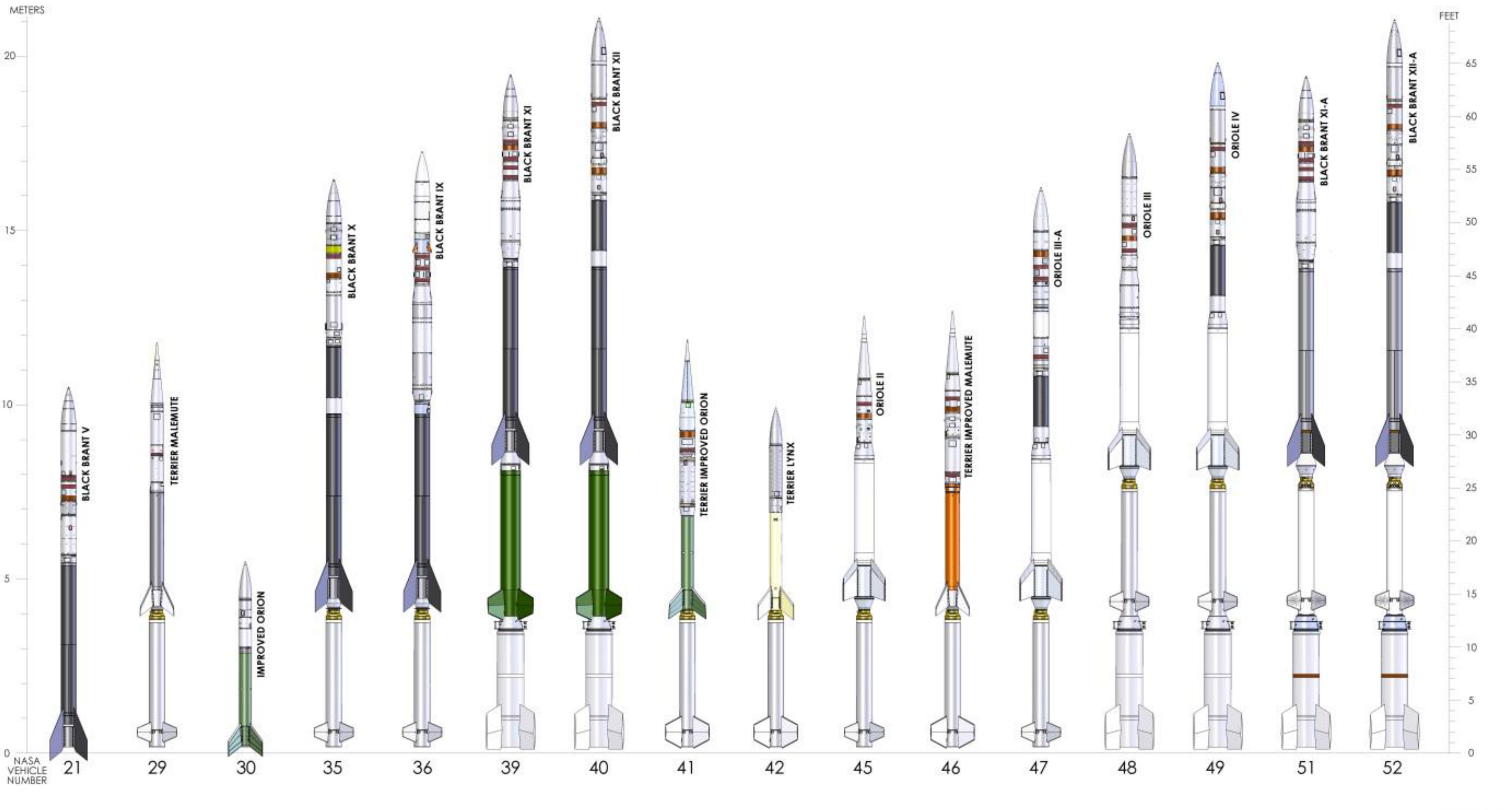
Terrier Orion

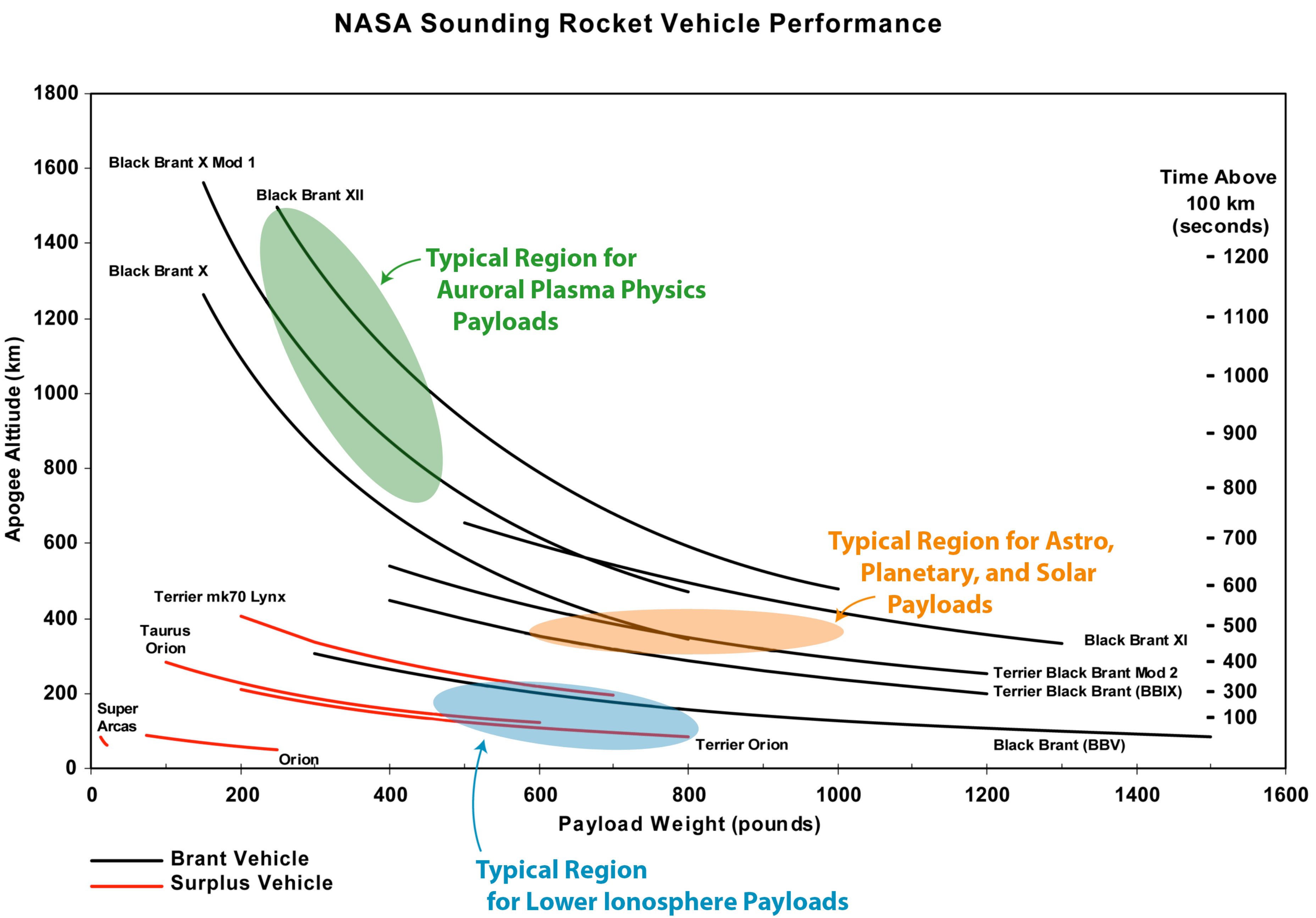
Black Brant IX



Black Brant XII

Current “Stable” of Sounding Rocket Motors at Wallops Flight Facility





NASA Sounding Rocket Vehicle Performance
Apogee Altitude (km)
1800
1600
1400
1200
1000
800
600
400
200
0
Payload Weight (pounds)
0
200
400
600
800
1000
1200
1400
1600
Time Above
100 km
(seconds)
1200
1100
1000
900
800
700
600
500
400
300
100
Black Brant X Mod 1
Black Brant XII
Black Brant X
Typical Region for
Auroral Plasma Physics
Payloads
Typical Region for Astro,
Planetary, and Solar
Payloads
Terrier mk70 Lynx
Taurus
Orion
Super
Arcas
Orion
Terrier Orion
Black Brant XI
Terrier Black Brant Mod 2
Terrier Black Brant (BBIX)
Black Brant (BBV)
Brant Vehicle
Surplus Vehicle
Typical Region
for Lower Ionosphere Payloads

Wallops Flight Facility -- Basic Payload Design and Sub-systems

Mechanical
- Nosecones
- Diameters range from 4 to 22 inches
- Deployments
- Sub-payloads

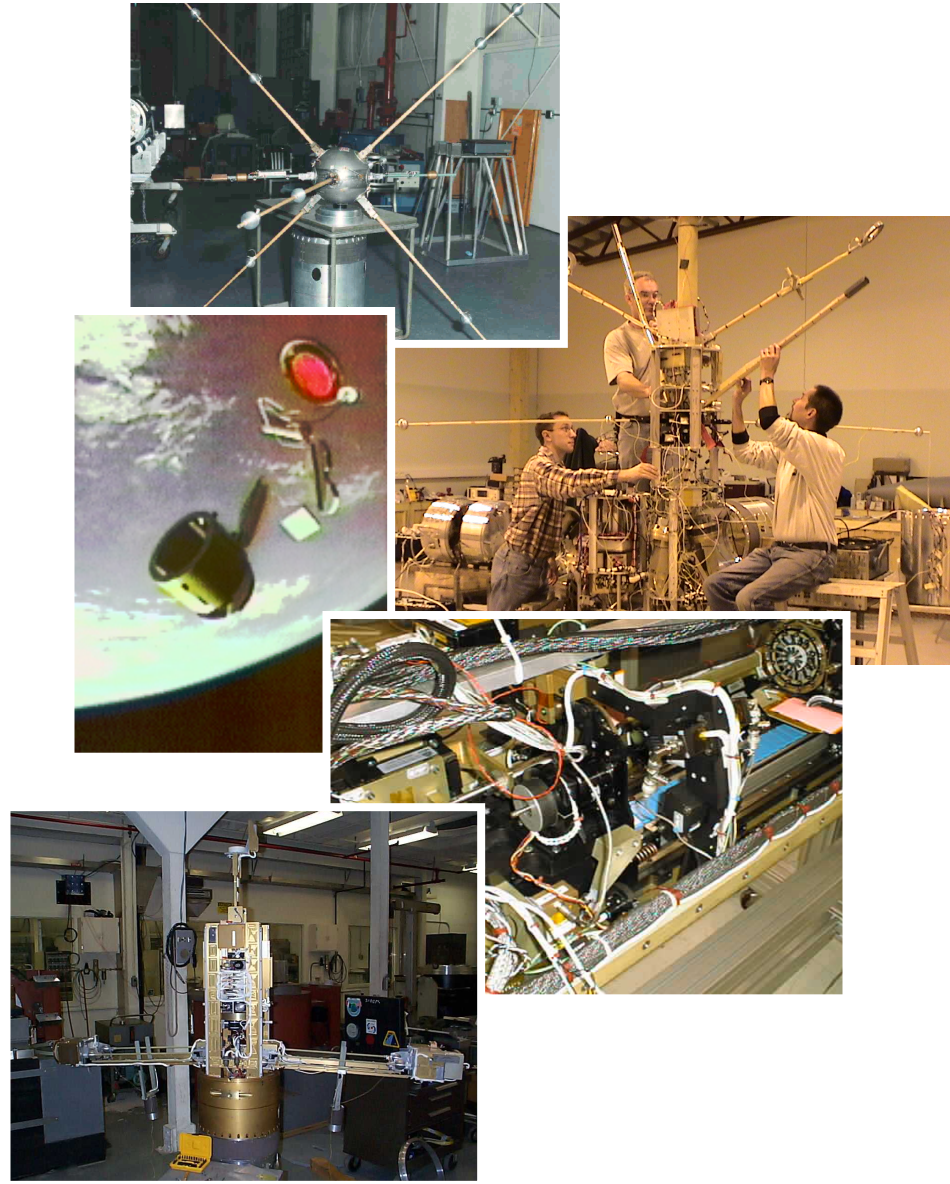
Power
- +28 V, ±18 V, + 9 V typical
- 10-100 Watts typical (from batteries)

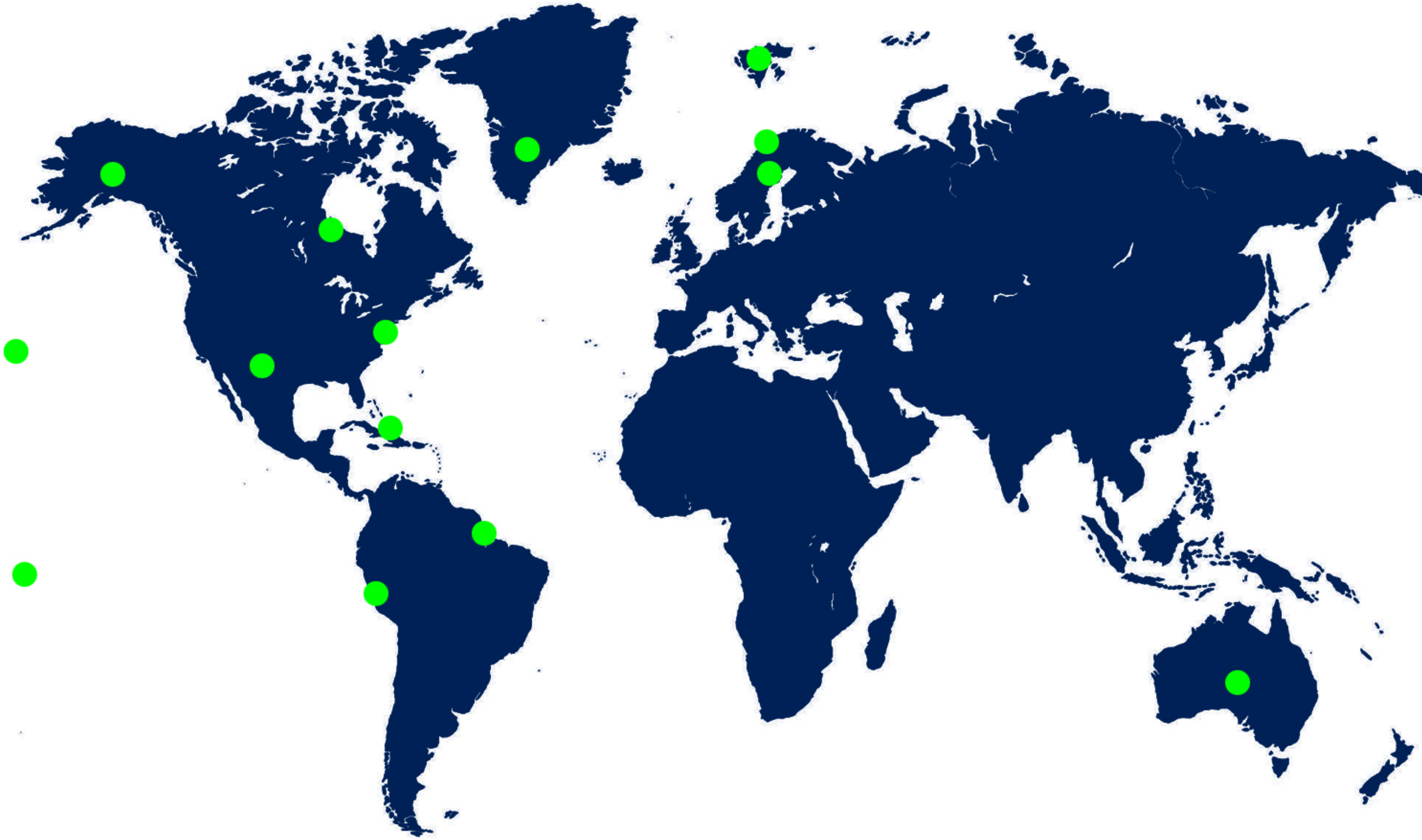
Telemetry, Timers, Commands
- Multiple links up to 10 Mbps typical
- Serial, parallel, analog data accepted
- GSP provides trajectory
- Uplink command for events, joy-stick control
- Timing typically with < 0.1 sec accuracy

Attitude Control and Knowledge
- Coarse pointing along or perp to B or V
- Fine pointing to ~0.1 arcsec

Recovery sub-systems
- Land, Water, Air

Trajectory and Performance Analysis





Sounding Rocket Launch Sites Used by NASA in last 30 years

Sounding Rocket Launch Sites Used by NASA in last 30 years

- US Fixed
  - Wallops Flight Facility
  - White Sands Missile Range
  - Poker Flat Research Range
- Foreign Fixed
  - Sweden
  - Norway (Andoya & Svalbard)
- Mobile
  - Australia
  - Brazil
  - Puerto Rico
  - Greenland
  - Peru
  - Kwajalein



Sounding Rocket Mission Categories

- Astronomy -- Planetary -- Solar

  Telescopes

- Geospace (Upper Atmosphere/Ionosphere/Magnetosphere)

  In-situ measurements, chemical releases

- Special Projects (e.g., Aero-braking, re-entry simulation)

Sounding Rocket Mission Categories

Disciplines: UV Astronomy, X-Ray, Planetary, Solar

Use Remote sensing → Telescopes

Main requirements:

1. Observing platform above earth's atmosphere (>100 km) to avoid attenuation effects
2. Fine pointing of payloads (sub-arc second usually required)

Features:

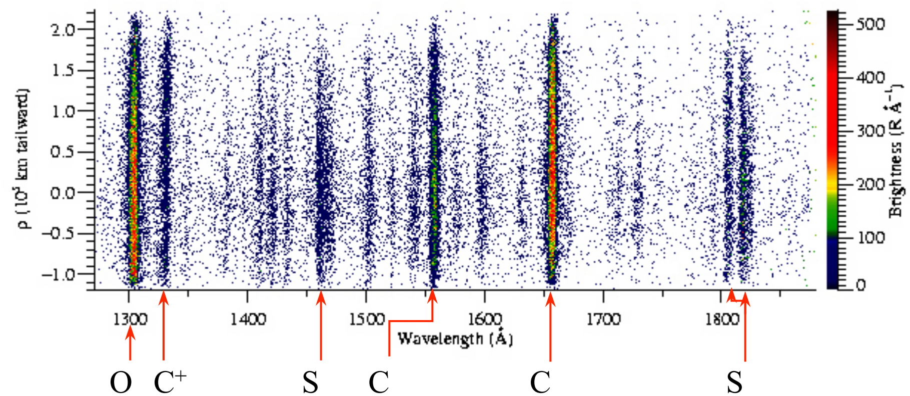
1. Payload recovery/re-flights are routine (launches typically at White Sands)
2. Real-time, joy stick uplink command positioning available
3. Southern Hemisphere launch location (Australia) used on campaign basis
4. Ability to observe sources close to the sun (e.g., comets, Mercury, Venus)

Strongest Ever Carbon Monoxide Production Discovered in Coma of Comet Hale-Bopp

Image of Comet Hale-Bopp, courtesy W. Johnasson.

Comet Hale-Bopp -- 6 April 1997

JHU-NASA Sounding Rocket 36.156 UG

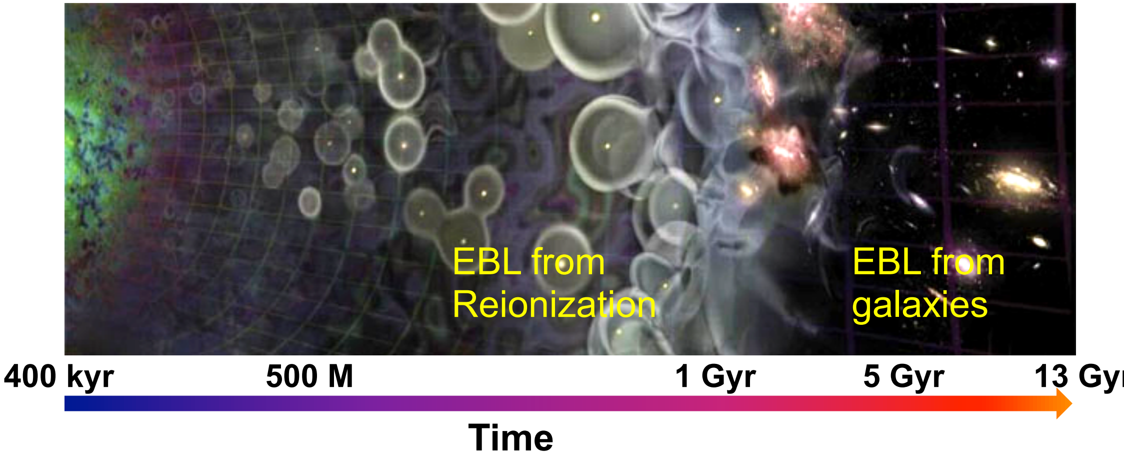


- **Remaining emissions are bands of the carbon monoxide Fourth Positive system.**

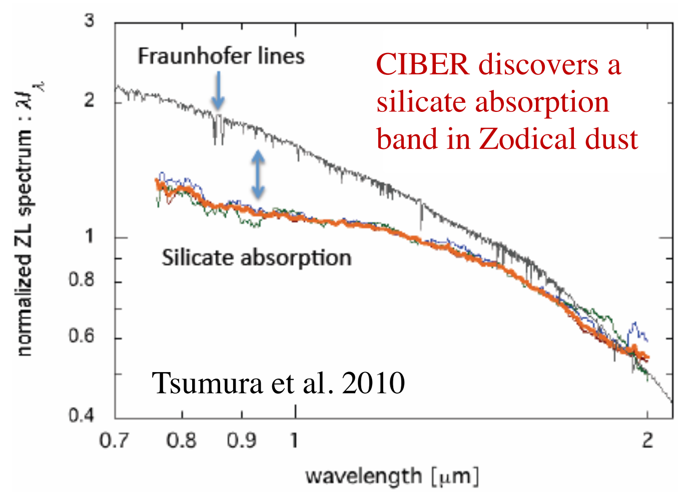
- Carbon abundances may simply result from photodissociation of CO.
- Observations gathered very close to perihelion; Comet was very active.

[Data: P. Feldman, Johns Hopkins Univ.; See also J. McPhate, *Ap. J.*, *521*, 920, 1999.]

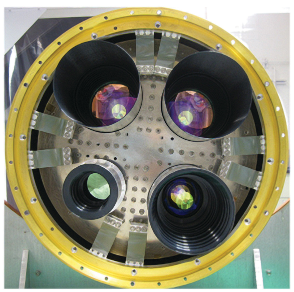
Searching for Signatures of First Light in the Extragalactic Background

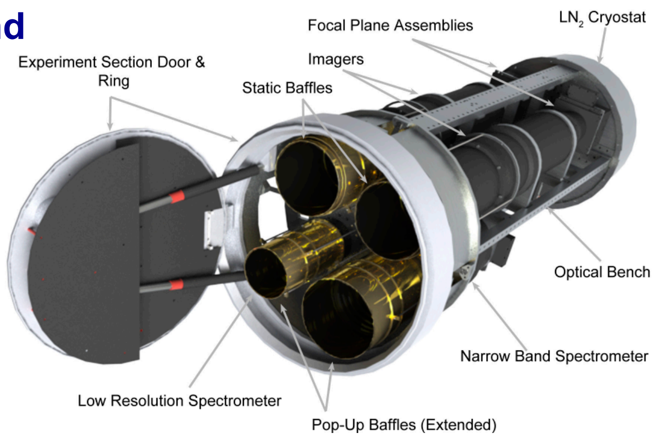


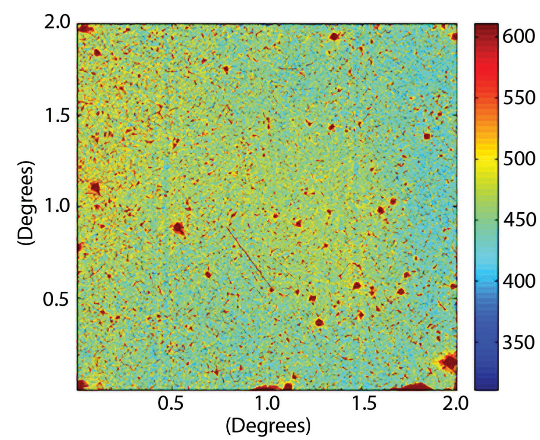
Low-Resolution Spectrometer Measures EBL at 0.8 – 2.1 μm by absolute photometry



Cosmic Infrared Background Experiment (CIBER)







EBL fluctuations first reported in the near-IR from Spitzer Telescope

CIBER's dual wide-field imagers provide spectrum at shorter wavelengths than Spitzer as well as the band-to-band correlation

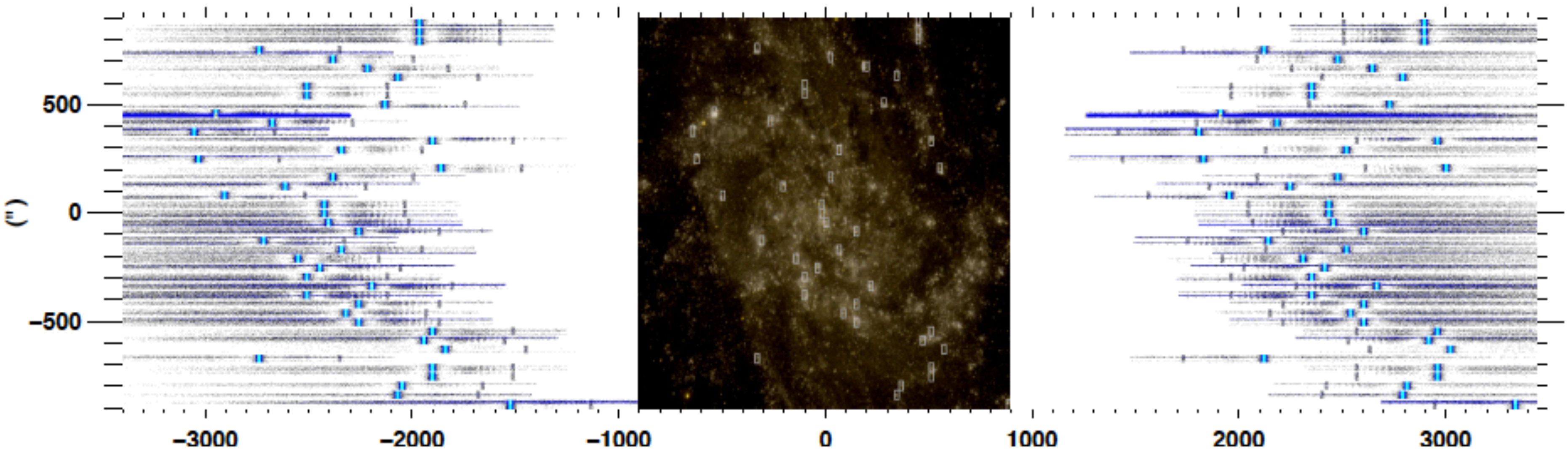
Raw data (right) show 2 deg wide FOV. Units: surface brightness intensity

P.I. Is Jamie Bock, Cal Tech

Off Rowland Circle Imaging Spectrograph (FORTIS)

Science: Multi-object UV spectroscopy of star forming regions in merging galaxies, comets.

FORTIS Simulations

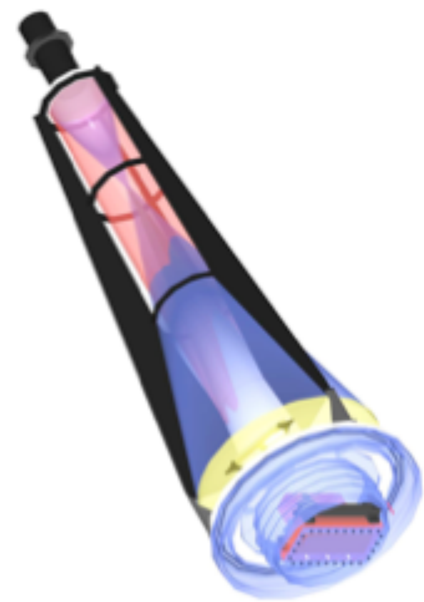


FORTIS:

-- Explores escaping UV radiation using a new type of spectro/telescope

-- Uses prototype of micro shutter array (MSA) which GSFC developed for JWST

-- Can acquire spectra from 43 targets simultaneously within 0.5^{o} angular region



First launched in May, 2013 to explore Lyα escape from star-forming galaxies

Next launch: Nov. 19 to Comet ISON. FORTIS's wide FOV and multi-object far-UV spectroscopic capability is deal for investigating volatile emissions from a comet

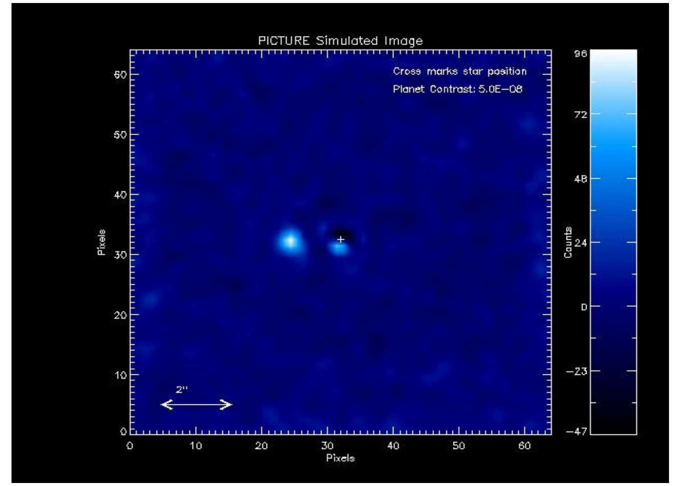
P.I. Is Steve McCandliss, JHU

Planet Imaging Concept Testbed Using a Rocket Experiment (PICTURE)

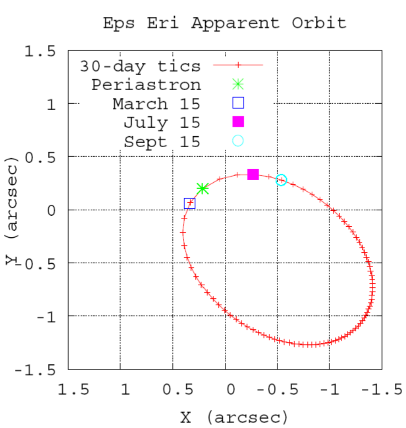
Goal 1: Directly image an extrasolar planet/debris disk around epsilon eridani in visible light

Goal 2: Demonstrate nulling interferometer technology for future NASA missions

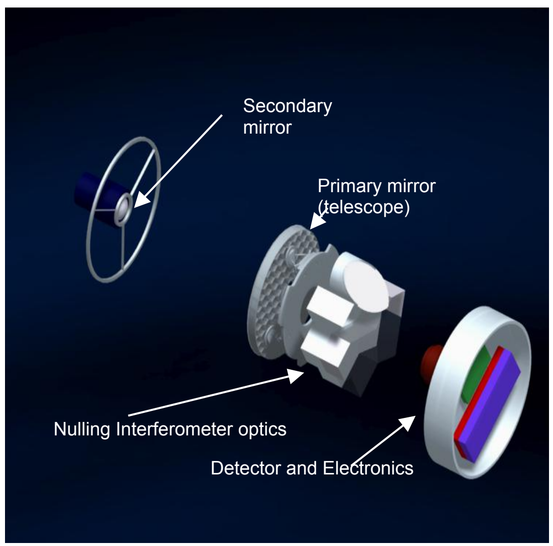
First launch experienced payload telemetry error;
→ Payload recovered and returned to P.I. for follow-up



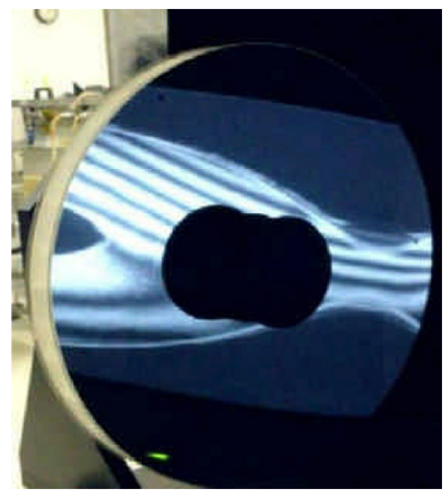
Expected Image



Accurate pointing (< 0.1 deg) needed.



Experiment concept

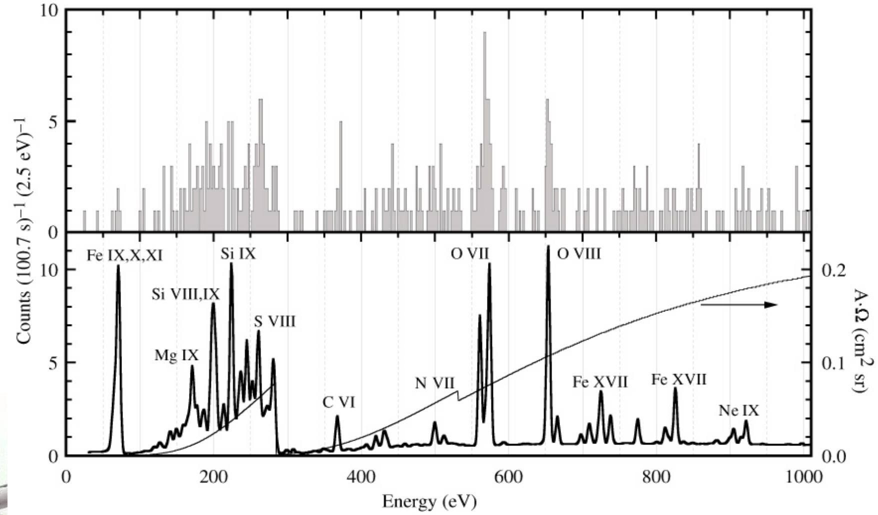


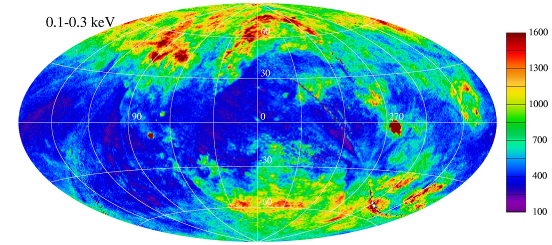
Lightweight primary mirror;
0.5m dia, 4.5 kg

Carbon fiber telescope structure

S. Chakrabarti, Boston University, P.I

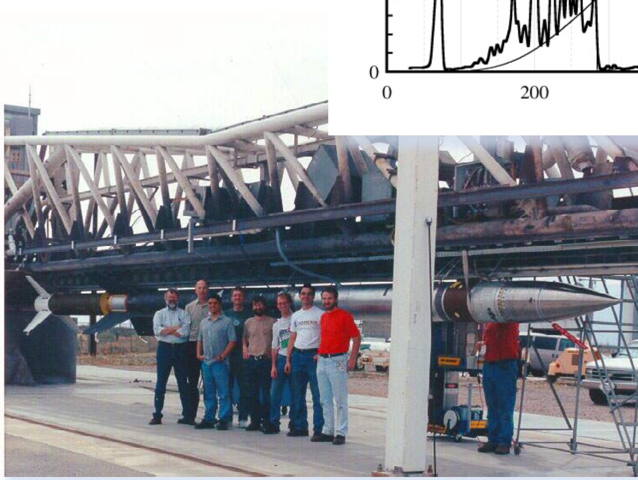
New X-Ray Detector Developed on Sounding Rockets





ROSAT Image

McCammon et al., ApJ 2002,
Crowder et al., ApJ 2012



Scientists at the launch pad

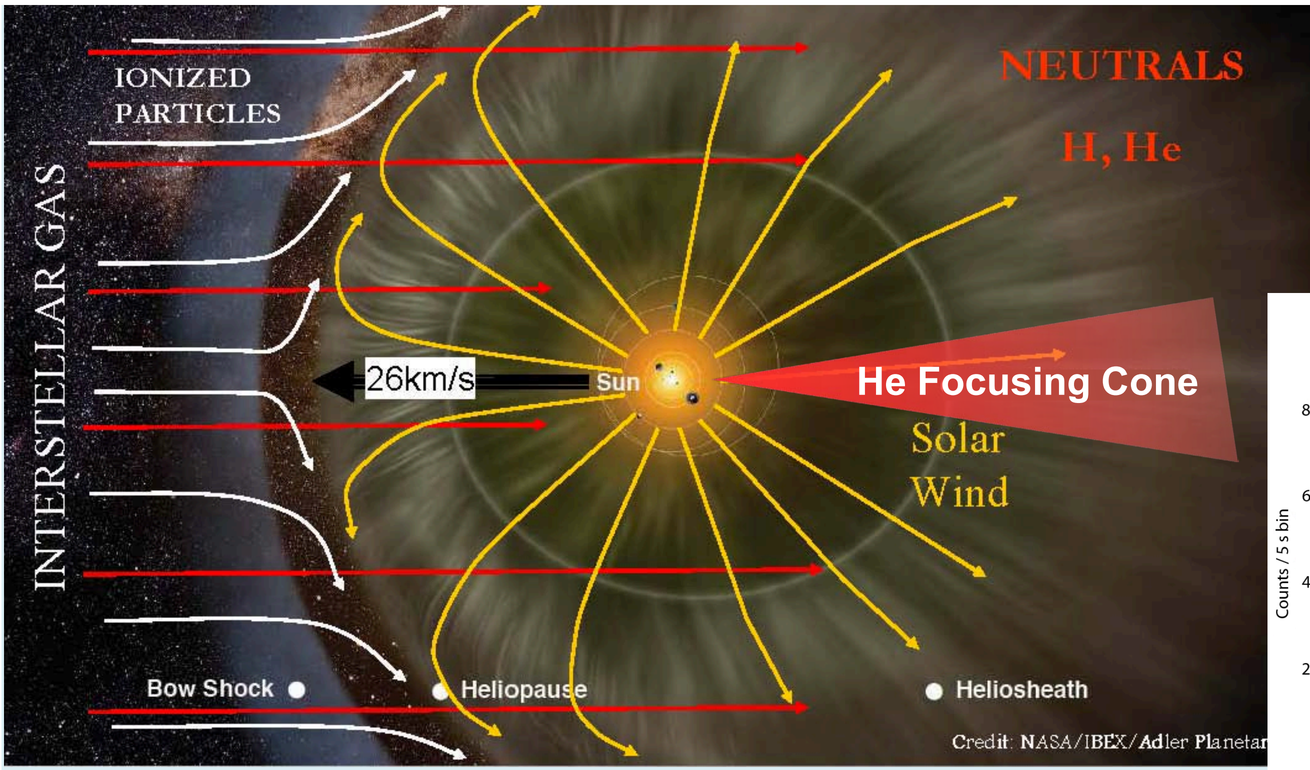
Graduate student checks instrument

- 1st Detection of diffuse emission in 172 Å Fe lines
- Observations demonstrate soft X-ray background is a superposition of local charge exchange and more distant thermal plasmas
- Similar detector to be deployed on Astro-H and Athena-plus

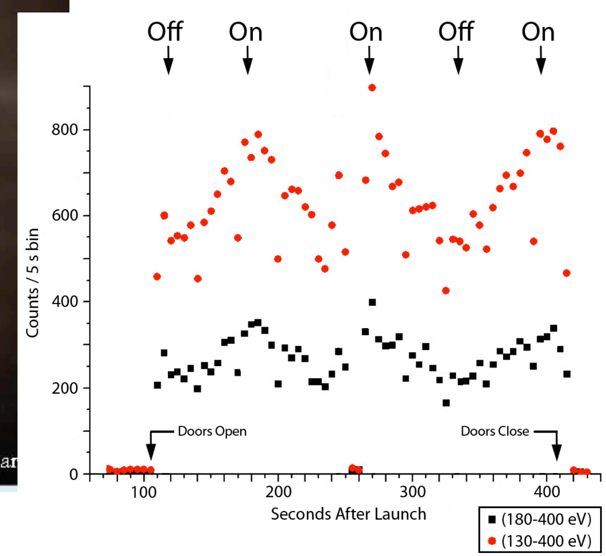
Data and photos: D. McCammon, Univ. of Wisc.

Diffuse X-rays of the Local Galaxy -- Use Signature of Solar Wind Helium Focusing Cone to Study Hot Bubble

- 2 large-area proportional counters (~1,000 cm^2) for geometrical measurement of the Local Diffuse X-ray Background → Rocket provides Collecting Area x FOV product that far exceeds satellite X-Ray telescopes such as XMM.
- Measures excess SWCX X-ray emission by scanning ON and OFF the He focusing Cone



He cone inferred from IBEX observations



100's eV Count Rate *vs*. Flight Time

Massimiliano, Univ. of Florida, is PI, GSFC provided detector

Solar Instruments on Rockets Provided Major Advances for Solar Satellite Missions

Sounding Rockets have Enabled Normal Incidence, Multi-Layer Optics, EUV, UV Spectroscopy to be Developed → Revolutionized Solar Observations

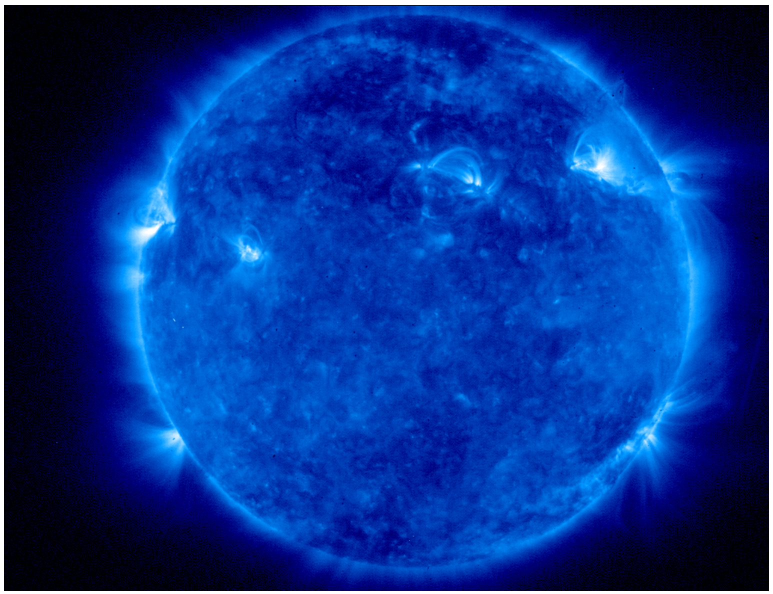


Image from Moses, NRL

Rocket (Black) → Satellite (Red)

Bruner, Walker, Golub, Moses: EUV Multilayer Normal Incidence Optics for High Resolution

SOHO EIT, TRACE, STEREO EUVI, SDO AIA

Davis, Moses: Soft Xray Grazing Incidence and CCD detectors

Yohkoh, Hinode X-ray telescopes

Neupert, Davila: EUV Spectroscopy

SOHO CDS, Hinode EIS

Brueckner, Bruner, Korendyke: VUV Spectroscopy

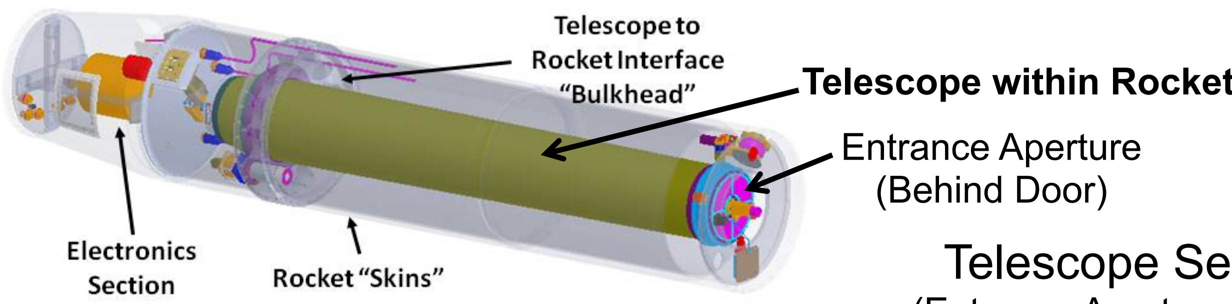
SOHO SUMER, TRACE

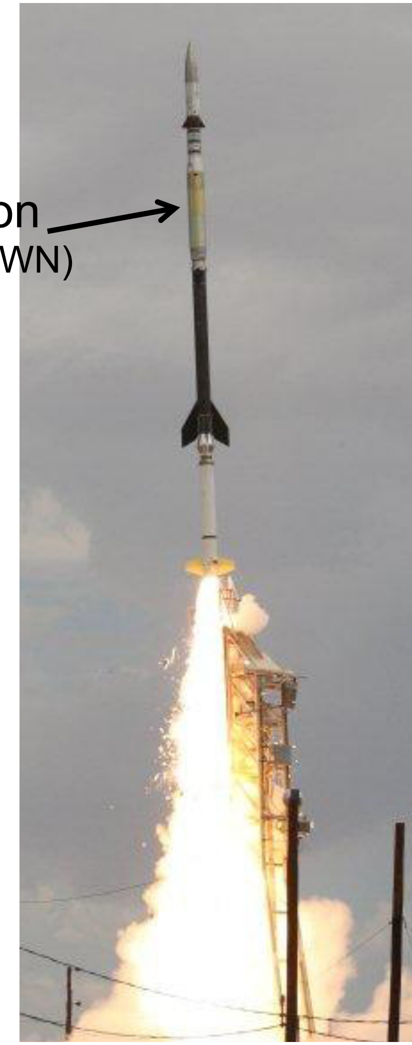
Cole: UV Spectroscopy of the Corona

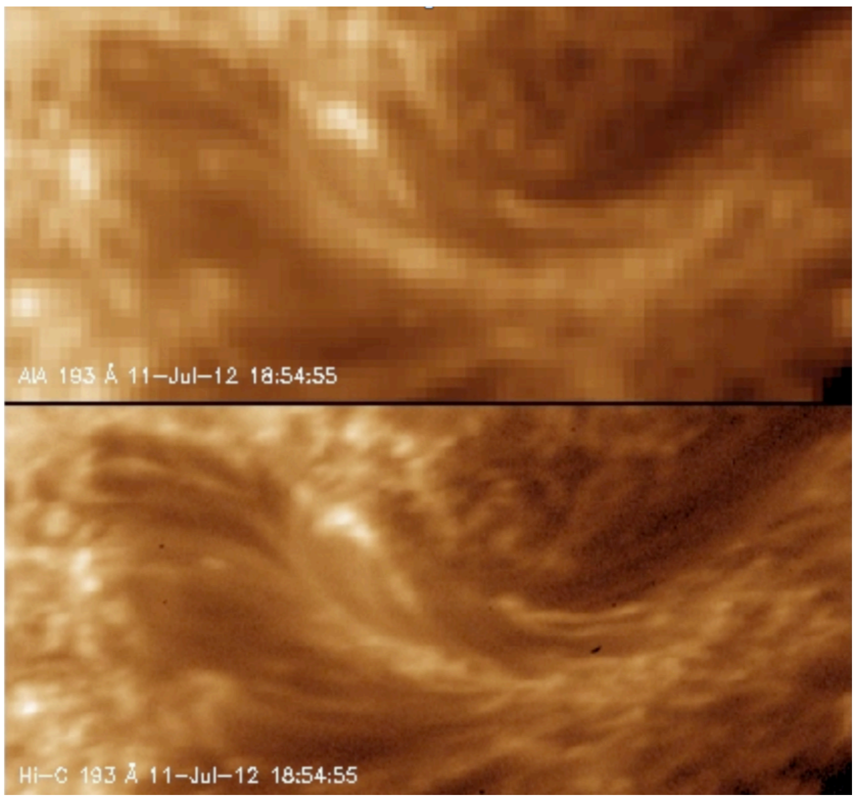
SOHO UVCS

Sounding rocket measurements of the solar corona flows formed the basis for Rottman et al. 1982 *Ap J*. article, primary motivation for SOHO mission.

Highest Resolution EUV Images Reveal How Braided Magnetic Fields Heat Solar Corona







P.I. Is Jonathan Cirtain, MSFC

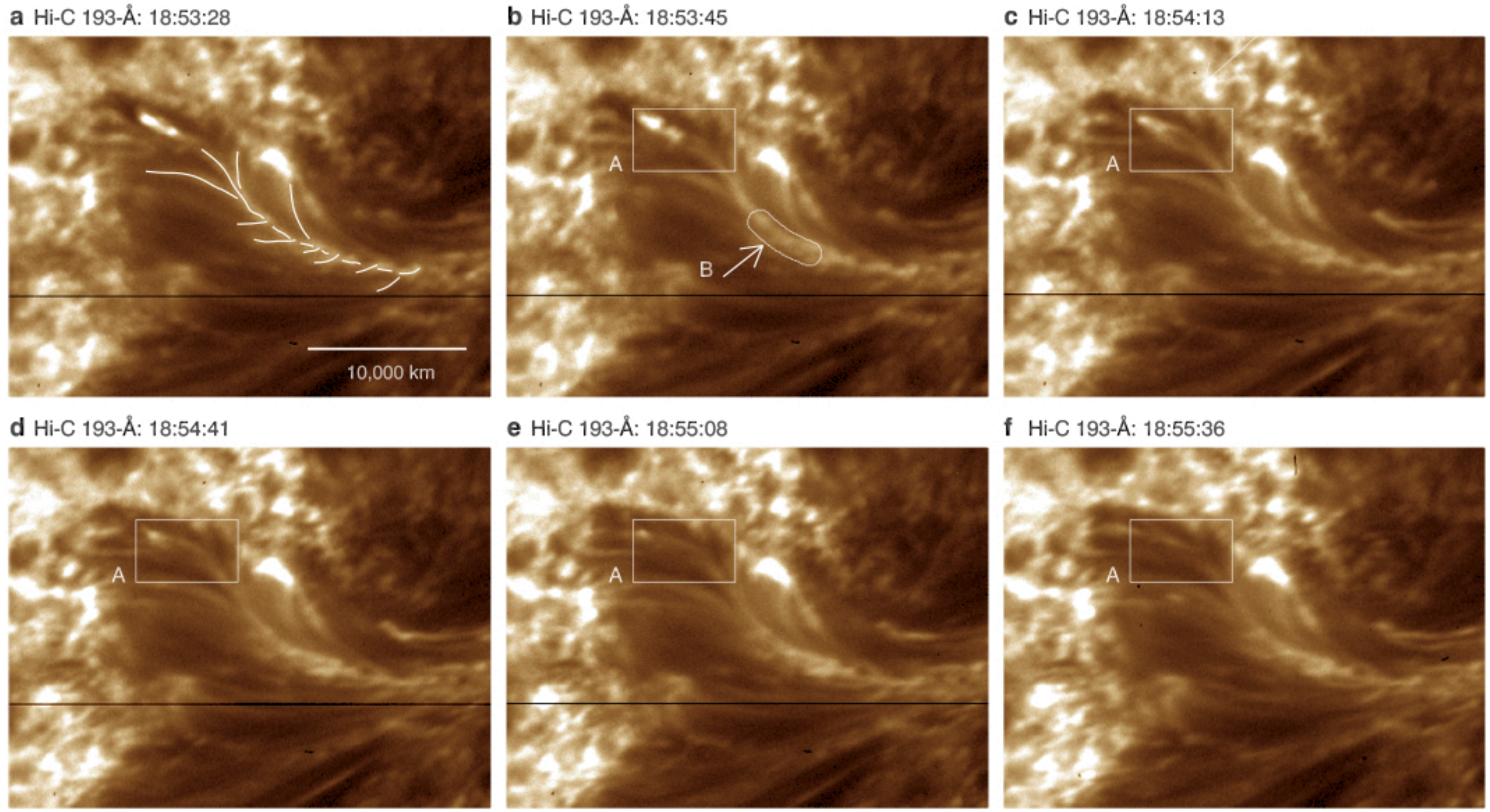
LETTER

nature International weekly journal of science

doi:10.1038/nature11772

Energy release in the solar corona from spatially resolved magnetic braids

J. W. Cirtain[1], L. Golub[2], A. R. Winebarger[1], B. De Pontieu[3], K. Kobayashi[4], R. L. Moore[1], R. W. Walsh[5], K. E. Korreck[2], M. Weber[2], P. McCauley[2], A. Title[3], S. Kuzin[6] & C. E. DeForest[7]

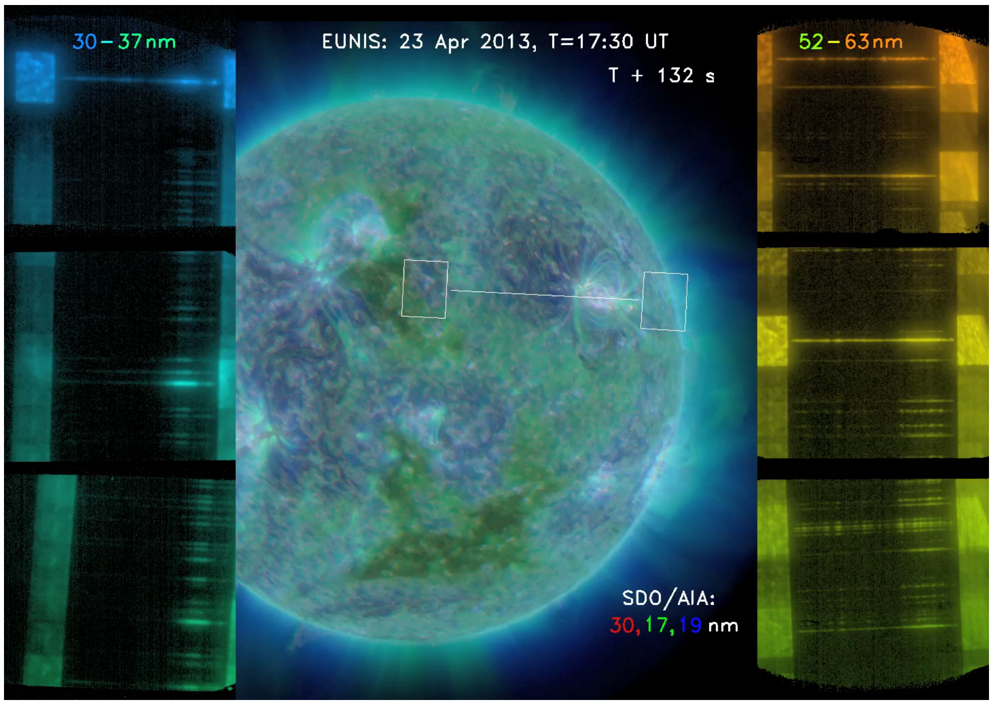


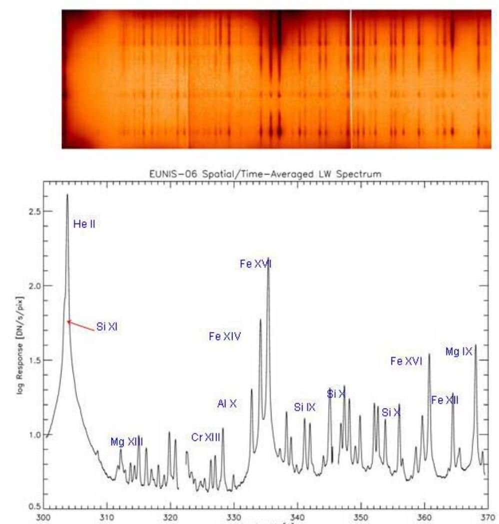
Braided Loop

Cirtain et al, 2013, Nature

Extreme Ultraviolet Normal Incidence Spectrometer (EUNIS)

- EUNIS probes the structure and dynamics of the inner solar corona with a cadence ~ 2 sec, allowing unprecedented studies of evolving and transient structures.
- High EUNIS sensitivity (>100 times greater than its predecessor) provides diagnostics of reconnection and impulsive heating at heights >2 solar radii, in the wind acceleration region.





300 – 370 Å

- Highest resolution observations of 52-63 nm of sun to date
- Many identified lines covering range: 20,000 - 10,000,000 K
- First flight demonstration of cooled CMOS active pixel sensors
- Underflight radiometric calibration of SDO, Hinode, SOHO

P.I. Is Doug Rabin, GSFC

Rocket Underflights of Satellite Missions provide critical calibrations and correlative measurements

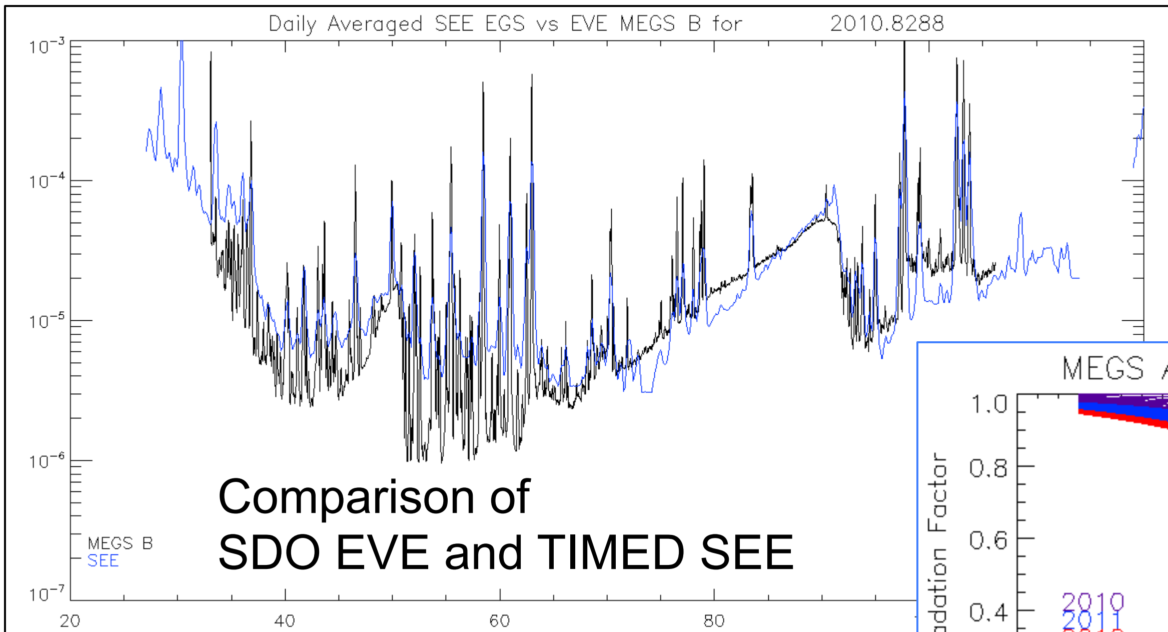
SDO EVE Calibration (Univ. Colorado, Woods) -- 4 Flights in 2010 to 2013

Primary Objective:

Provide underflight calibration for the Extreme ultraviolet Variability Experiment (EVE) aboard Solar Dynamics Observatory (SDO)

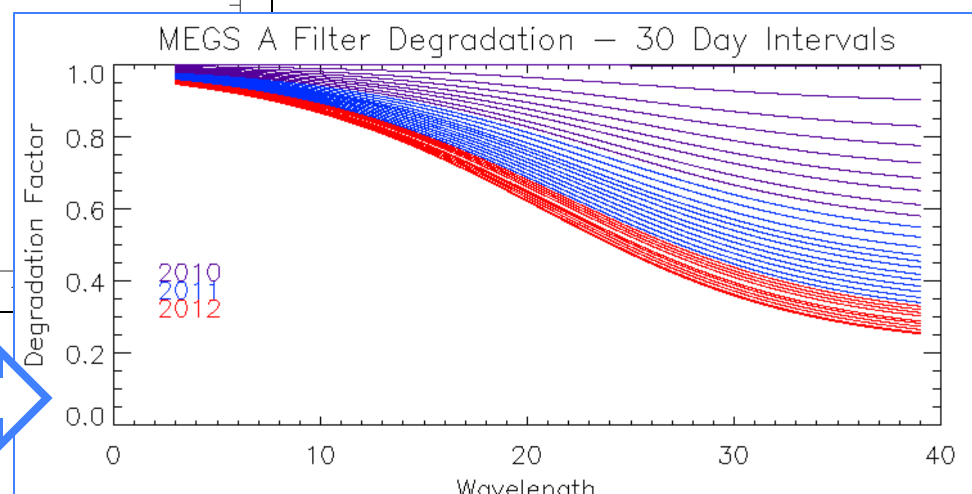
Secondary Objectives

- Provide underflight calibrations for SDO AIA, TIMED SEE, Hinode EIS, SOHO SEM
- Test fly new solar X-ray spectrometer technology (0.1-10 nm range)



Rocket underflight calibrations are critical to maintain EVE measurement accuracy to better than 10%

Model of EVE Degradation using rocket and onboard calibrations



Sounding Rocket Mission Categories

Geospace (Magnetosphere, Ionosphere, Thermosphere, Mesosphere)

In situ measurements (general)

Main requirements/features:

1. Access to altitudes too low for satellite *in situ* sampling (25-150 km region)
2. *Vertical* profiles of measured phenomena (cf. satellite *horizontal* profiles) with "available" apogees from 100 to 1500 km (or higher).
3. Slow vehicle speeds enable new phenomena to be studied; payloads "dwell" in regions of interest
4. Launches occur when geophysical "Event" is downrange -- (e.g., aurora, cusp, thunderstorms, ionospheric turbulence at equator, noctilucent clouds, electrojets, ionospheric metallic layers, etc.)
5. "Portability" provides access to remote geophysical sites
6. Launches in conjunction with ground observations (e.g., radars, lidars)

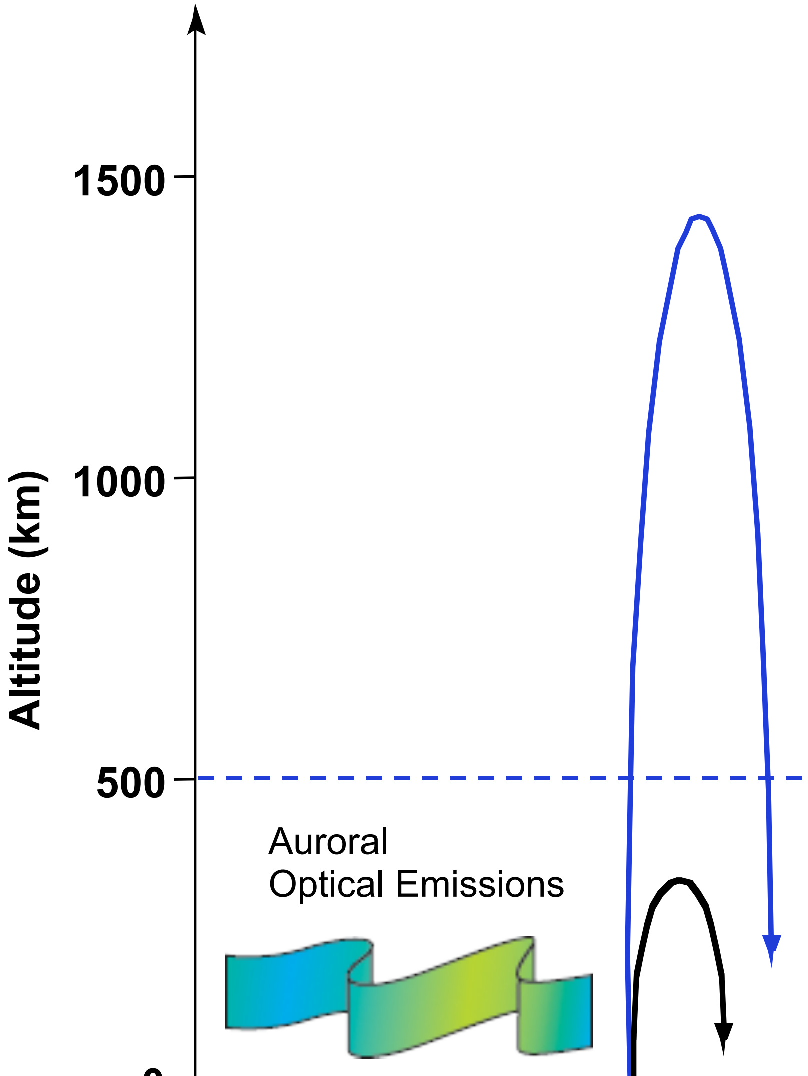
(Continued)

Geospace (Magnetosphere, Ionosphere, Thermosphere, Mesosphere)

Main requirements/features (continued):

7. Alignment of payload to predetermined orientations -- e.g., alignment of spin axis along the magnetic field direction or alignment of "ram" instruments along the velocity vector throughout flight (upleg and downleg).
8. Payloads may be small and symmetric, thus minimizing perturbations to medium
9. Multiple payloads (clusters) with separate telemetry launched on single rocket
10. Multiple, simultaneous launches (e.g., high and low apogees, different azimuths)
11. Luminous trails released along trajectory provide tracers of geophysical parameters such as upper atmospheric winds
12. Flights in conjunction with orbital missions (e.g., Dynamics Explorer, TIMED)
13. Tether capabilities (e.g., 2 km tethers between payloads have been flown)
14. Collection of stratosphere/mesosphere samples (e.g., 24 underflights of UARS)

Auroral Physics on Sounding Rockets: Understanding Particle Acceleration in Nature



Higher altitude rockets with high resolution instruments opened the door to a whole new class of auroral physics phenomena.

- **Field Aligned Electron Bursts**
- **Ion Conics**
- **Lower Hybrid Solitary Structures**
- **Large Amplitude Alfvén Waves**
- **Intense Langmuir Waves**
- **Shock-Like Electric Fields**

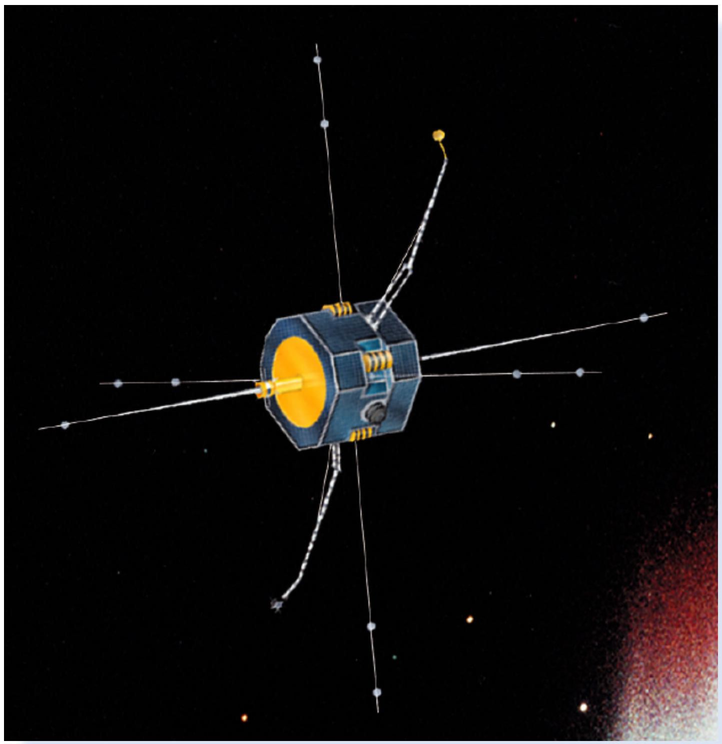
New Physics

Early Rocket Observations (1960's, 70's)

Discovered the source of auroral light is due to keV electron beams

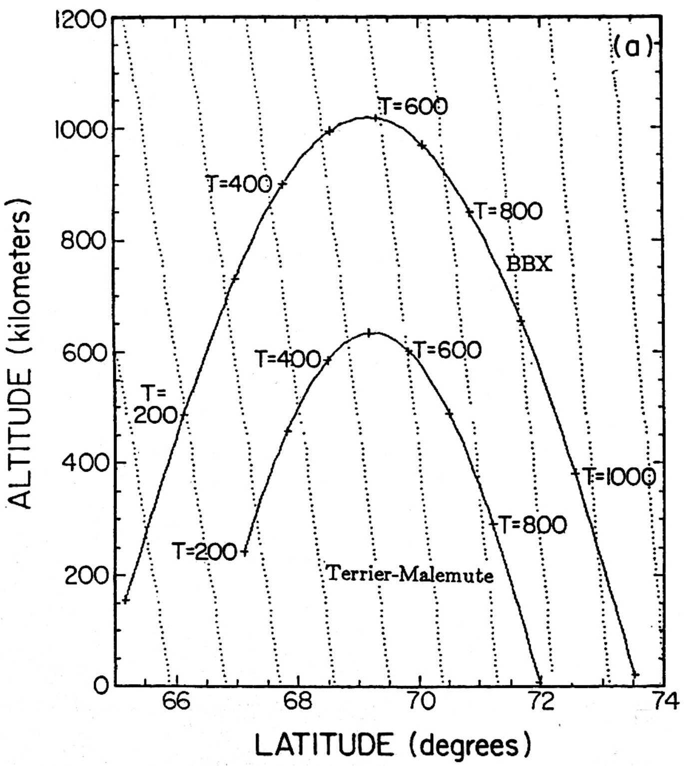
Explored auroral optical emissions, Ionosphere fields, currents, effects, etc.

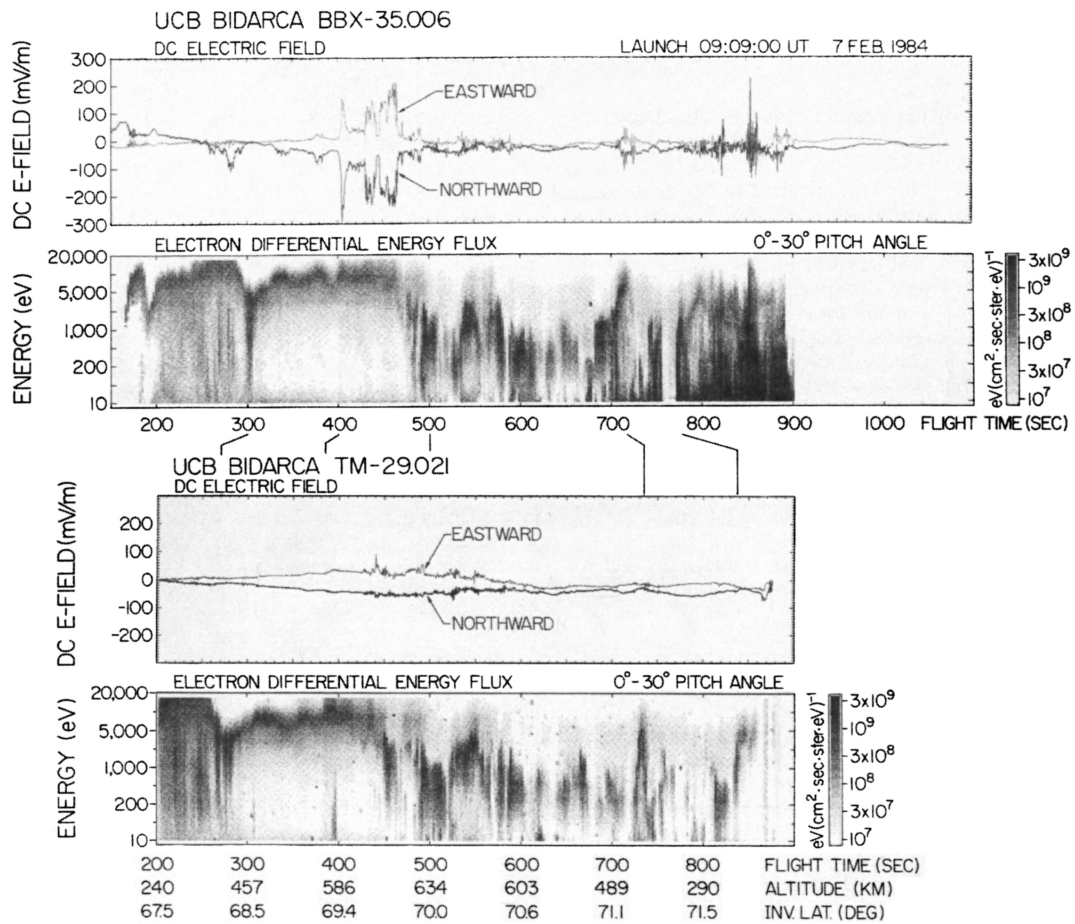
Auroral Zone Rocket Discoveries Formed the Springboard for NASA's FAST Satellite



- Auroral physics discovered on sounding rockets formed the basis of FAST Small Explorer Satellite
- FAST in-situ instruments were developed on rockets (e.g., "Top Hat" electrostatic detectors, double probes, plasma wave Interferometers)
- FAST experimenters, including P.I., had extensive prior experience with sounding rockets

Dual-Rocket Observations of Electrostatic Shocks in the Auroral Zone

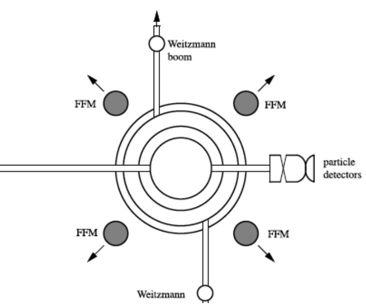




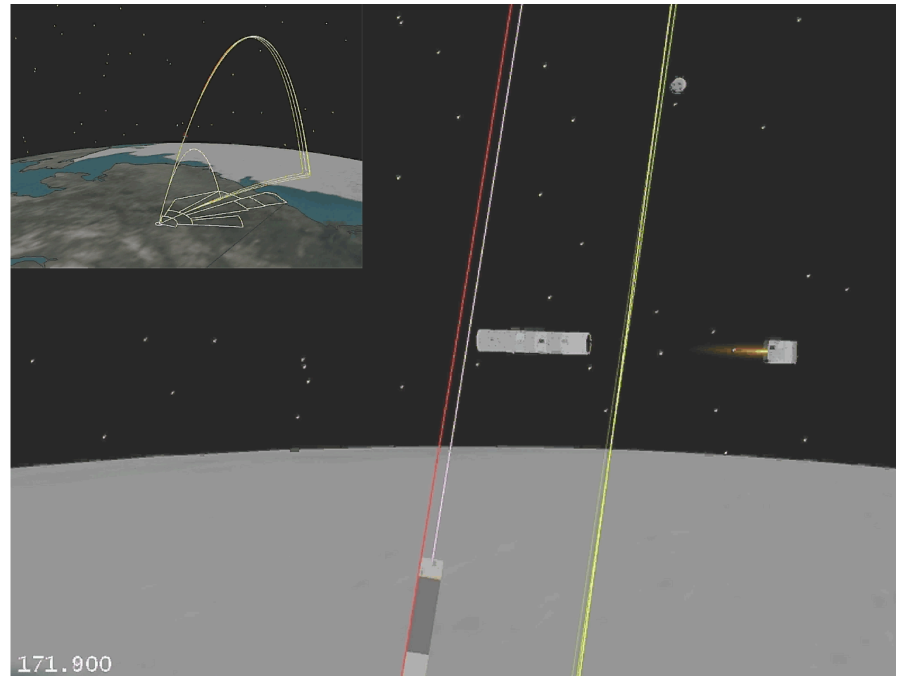
[Boehm et al., JGR, 1990]

Multiple-Payloads Reveal Temporal-Spatial Scales within Aurora, Alfvén Waves, Electrostatic Structures

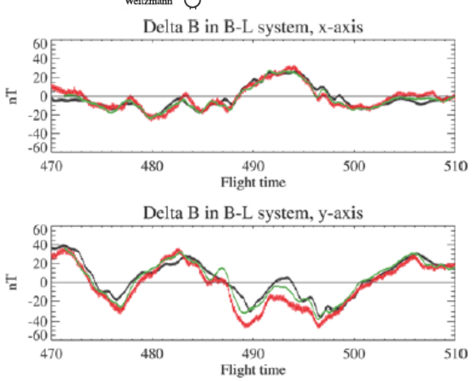
- Numerous missions utilize multiple sub-payloads to investigate the temporal-spatial structure, Alfven waves within the aurora
- To achieve > km scale spacings, sub-payloads have included small rockets (e.g., Lessard, Conde rockets)



8 cm dia. magnetometers

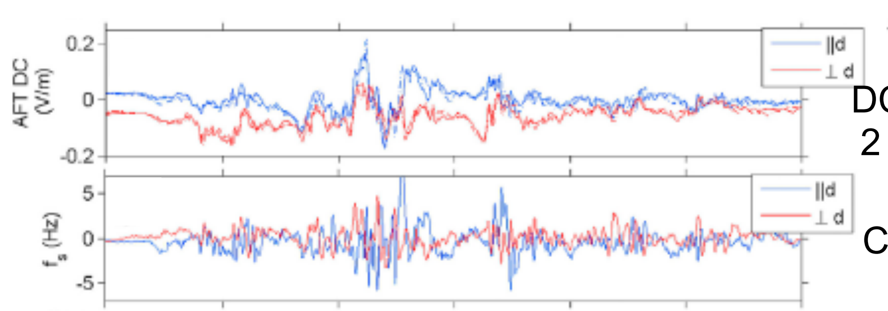


Lessard rocket simulation/WFF



Separated magnetometers permit direct curl **B** measurements of **J**

Zheng et al., 2003



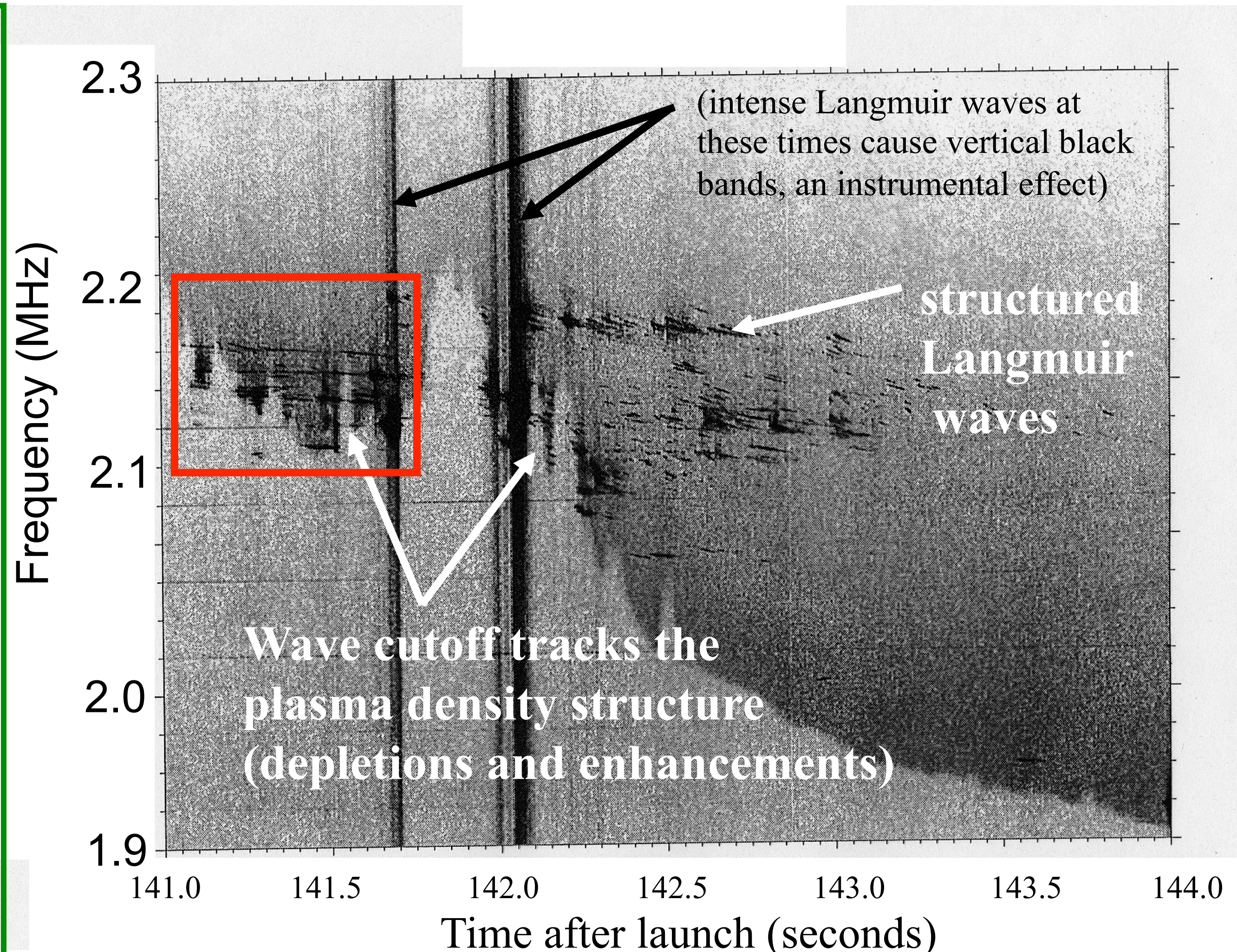
DC E Fields 2 payloads

Calculated Shear

Lundberg et al., 2012

Structured Langmuir Waves and Other HF Modes in Auroral Region Revealed by High Telemetry

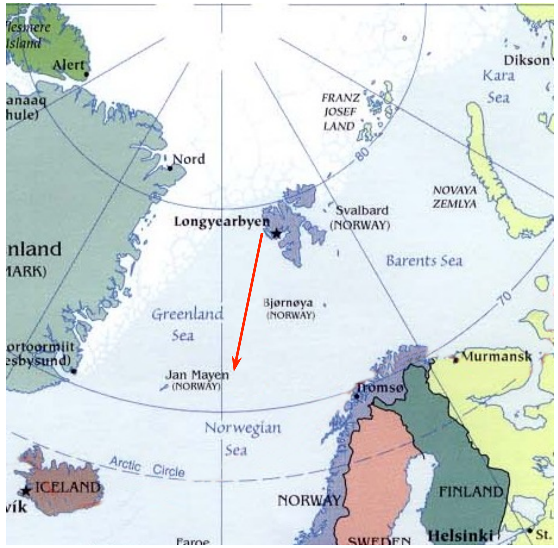
- High Telemetry Rates (>100's of MB/s) have opened the door to new physics of HF plasma waves in the aurora
- Detailed wave structure reveals complex wave-particle interactions, exchange of energy
- Clear wave "cut-offs" provide unprecedented information regarding plasma structure
- Dartmouth sensitive wave receivers (LaBelle, P.I.) have revealed important features of Langmuir waves -- critical to understanding this basic phenomenon of Nature

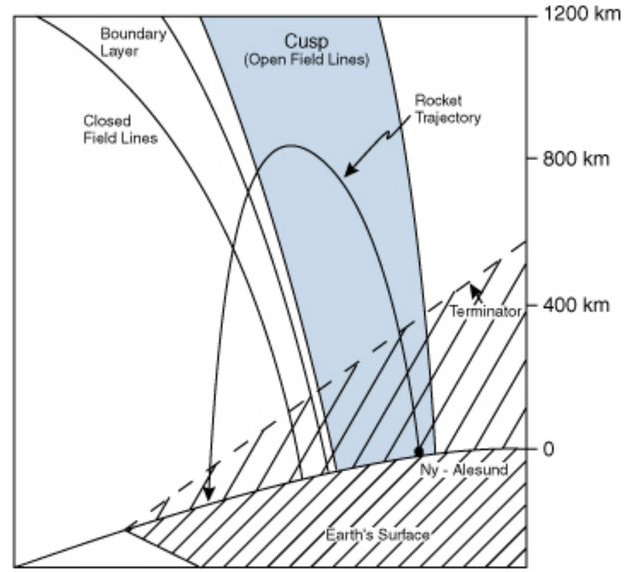


[McAdams and LaBelle 1999]

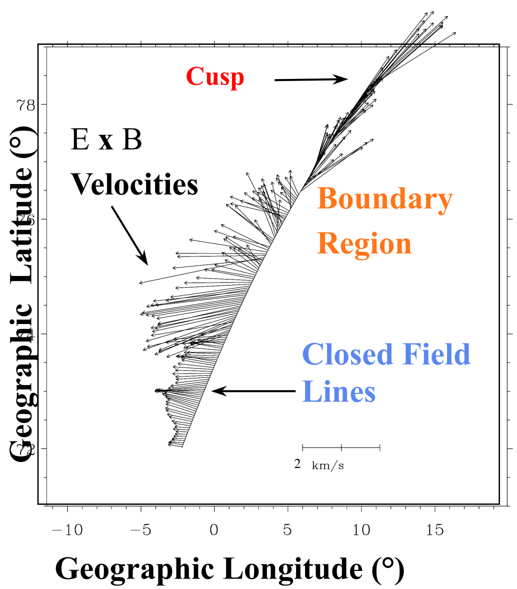
Direct Measurements in the Cusp from Spitzbergen

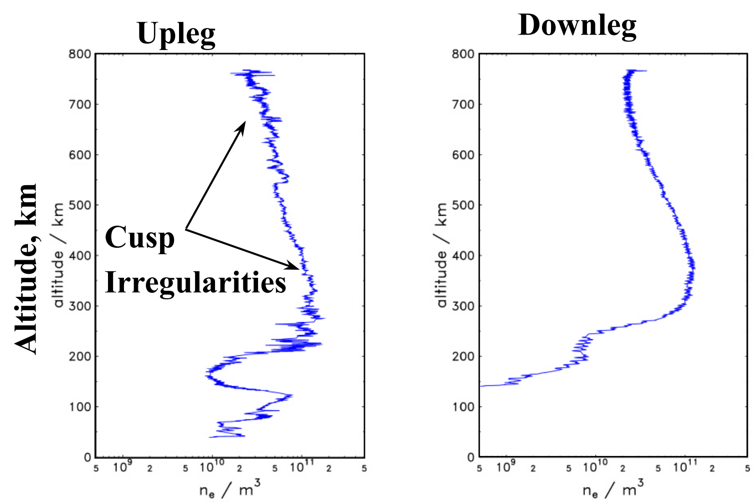
Experiment Location and Geometry:





Electric field, plasma density reveal complex electrodynamics at open/closed magnetic field line boundary.

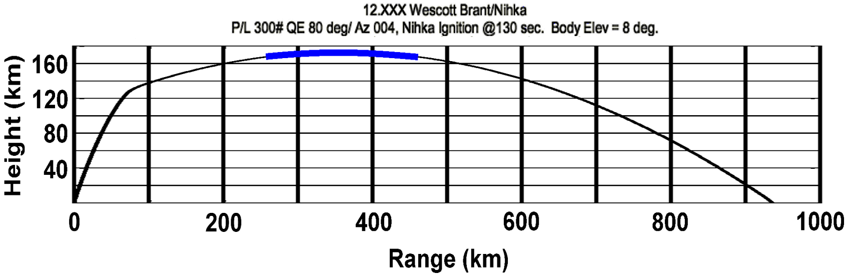




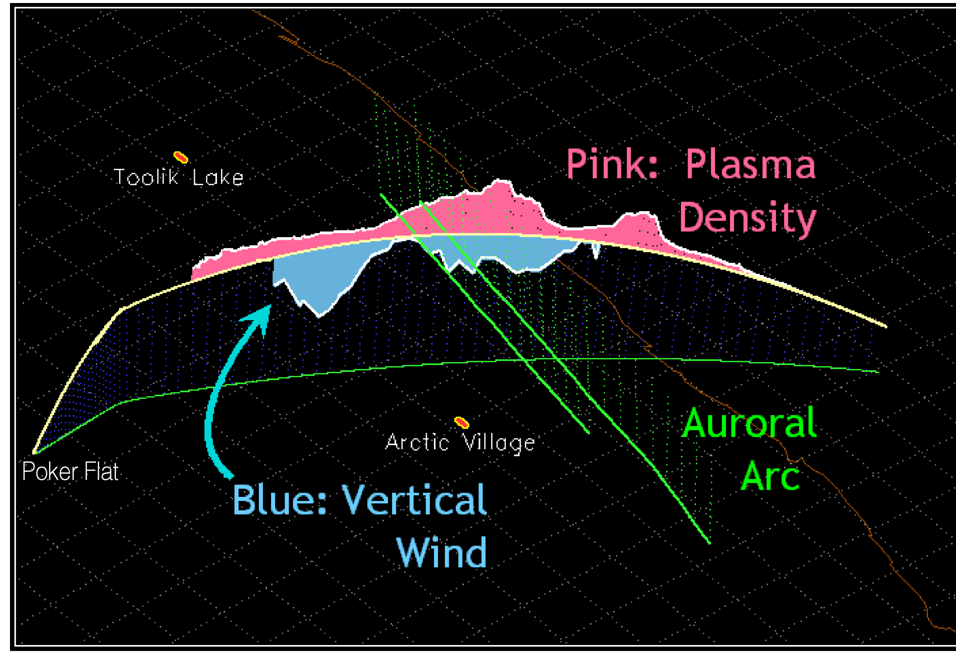
Plasma Density

Data: R. Pfaff, GSFC

NASA's first "Tailored" Trajectory Reveals Vertical, Horizontal Winds over Auroral Arc



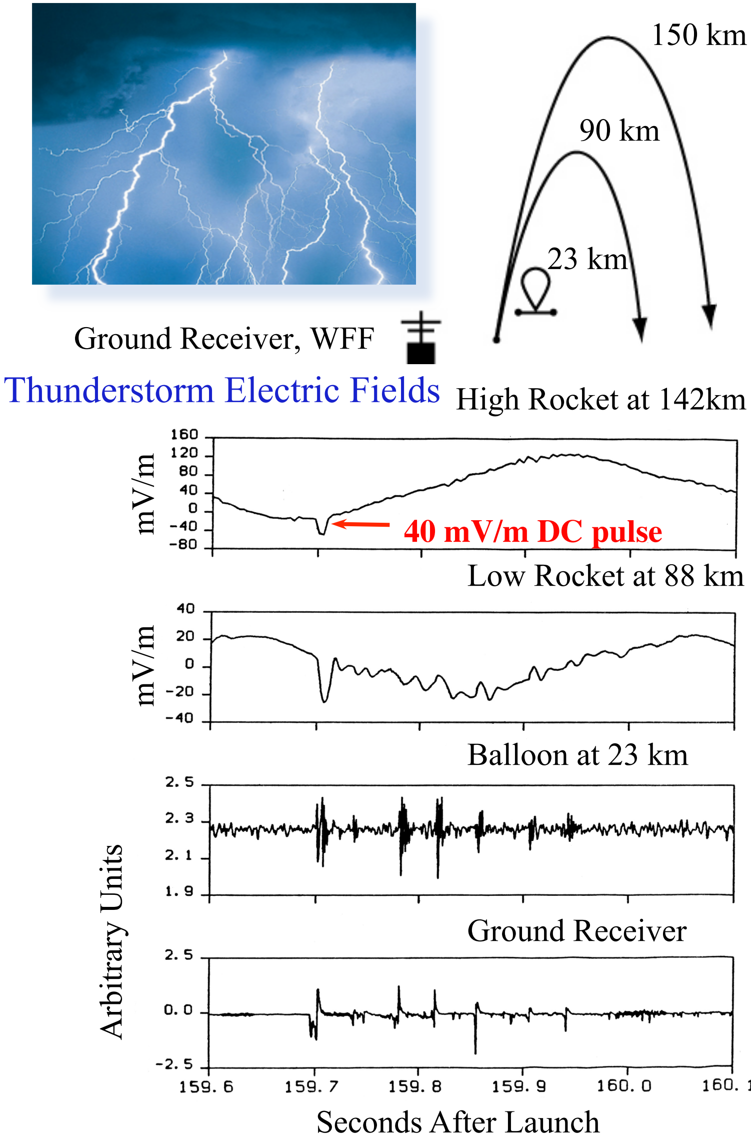
Puffed chemical release "trail"



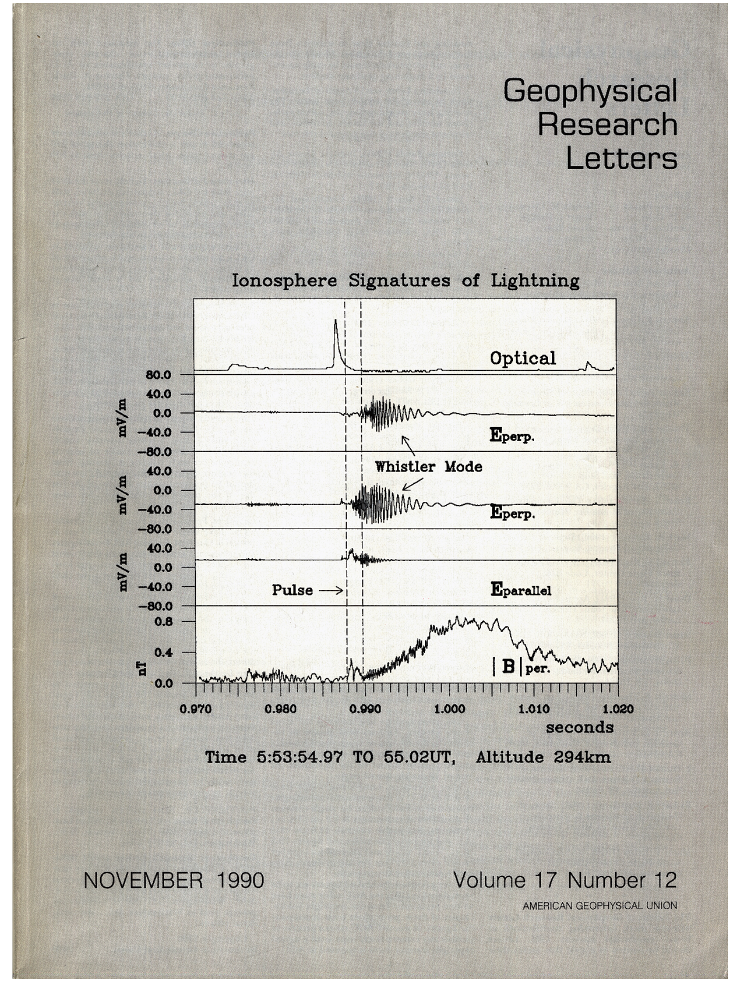
- HEX project (Univ. Alaska) measured *vertical* winds by deploying a *near-horizontal* chemical trail over a large horizontal trajectory that traversed a stable auroral arc.
- This required actively re-orienting the rocket prior to 3rd-stage ignition. (First for NASA.)
- Results revealed *downward* winds in the vicinity of the arc, defying the usual presumption that Joule heating would drive neutral upwelling near arcs. Downward wind was also accompanied by an unexpectedly large divergent velocity gradient in the zonal direction.
- Results a complete surprise, suggest upper atmosphere gravity waves dominate physics.

Conde, Craven, Wescott -- Univ. of Alaska

Direct Penetration of Lightning Electric Fields in the Ionosphere, High T/M Reveals new Wave Physics



[Kelley et al., JGR, 1985]

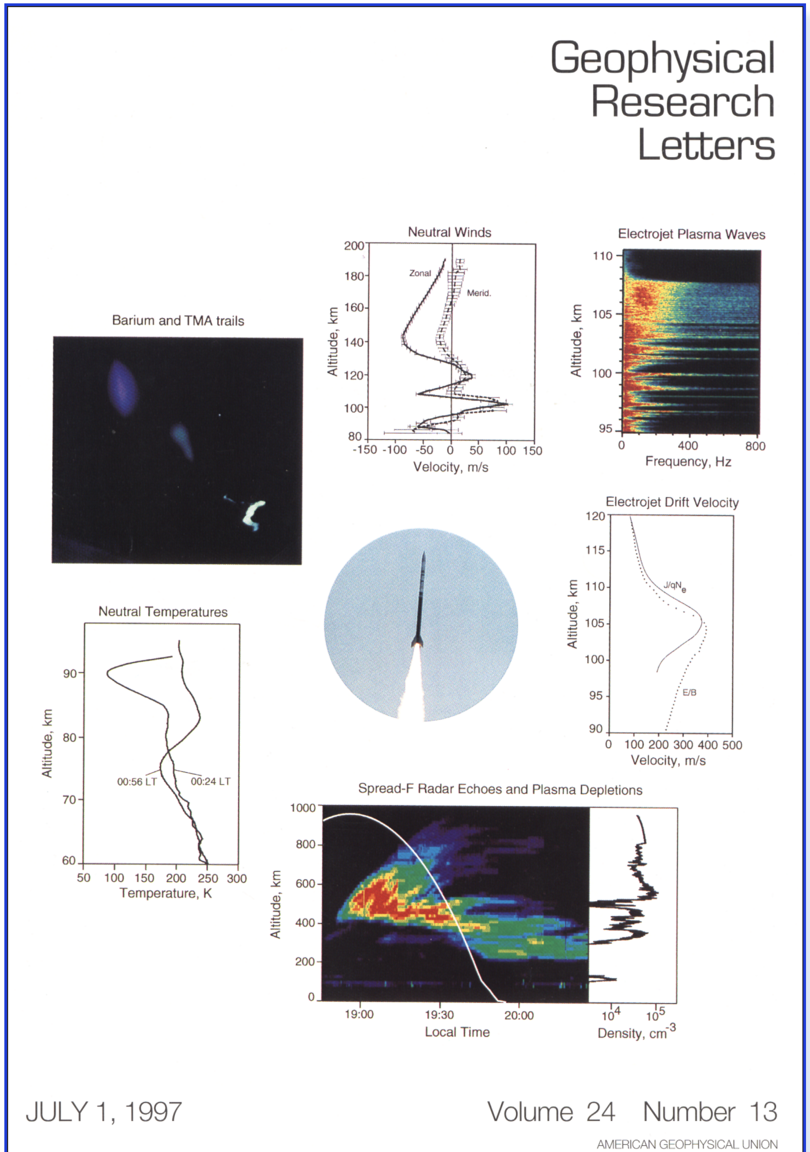


Detailed wave measurements show how sferics with parallel E-fields convert to whistler mode.

High T/M rates (~10 Mbps) make this possible

NASA Guará Campaign

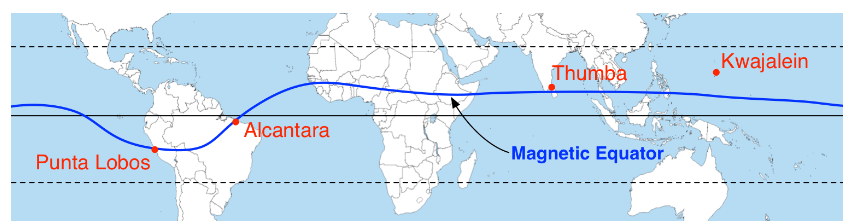
13 Rocket Launches at the Magnetic Equator in Brazil


Geophysical Research Letters

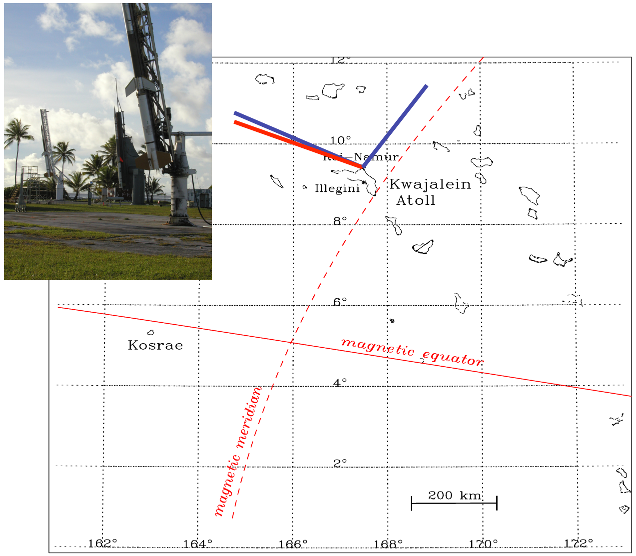
JULY 1, 1997 Volume 24 Number 13
AMERICAN GEOPHYSICAL UNION

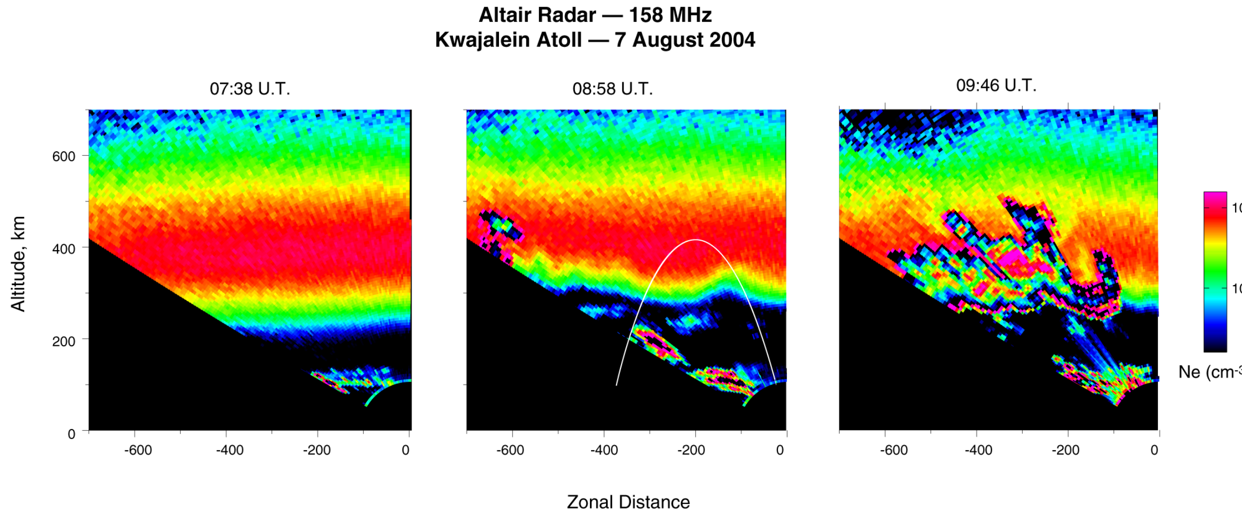
Observations include several significant "Firsts":

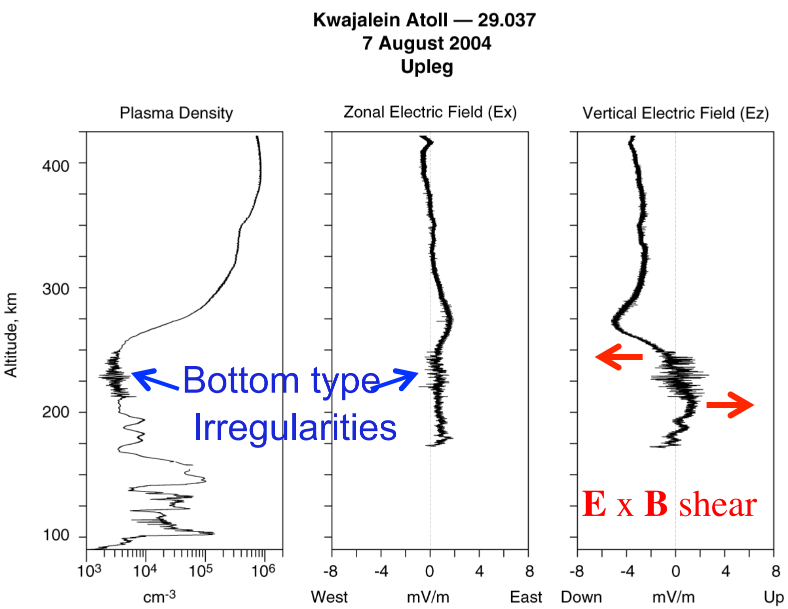
- Polarization DC electric field that drives the equatorial electrojet
- High altitude (>800 km) DC and wave electric fields gathered in a Spread-F plume
- Neutral wind gradients associated with enhanced E-fields at sunset
- Gravity wave breaking in the equatorial mesosphere
- Primary two-stream wave spectra and phase velocities in electrojet.



Vertical Profiles of Electrodynamics at Onset of Equatorial Spread-F Reveals E x B Shear believed to "Trigger" instability, bottomside waves





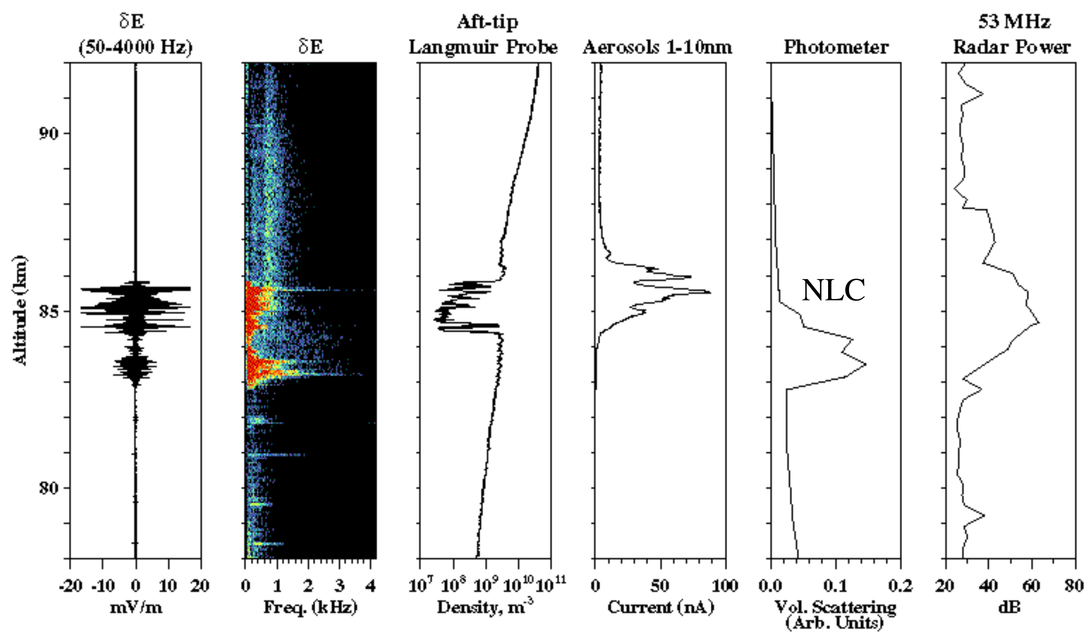


- Vertical electric fields prove the existence of strong shear flow and retrograde drifts in the bottomside F-region prior to onset of ESF.
- Rocket data show that bottom-type irregularities reside in valley region, below where the density gradient is steepest.
- Bottom-type irregularities shown to be viable "seeds" of equatorial spread-F.
- Cornell University (Dave Hysell, P.I.)

Rocket Measurements of Noctilucent Clouds (NLC): A Near-Earth Icy, Dusty Plasma

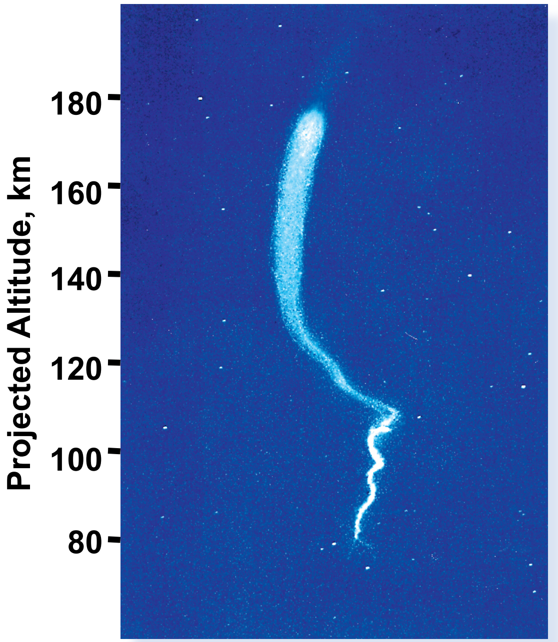
- NLC located in high latitude summer mesosphere.
- Lowest neutral temperatures in atmosphere.
- Possible indicators of anthroprogenic change
- Region of very intense radar echoes
- Complex aerosol chemistry, dynamics, electrical charge distributions.

Data from rocket flight into NLC with intense radar echoes from Andoya, Norway



[see Goldberg et al., GRL, 2001.]

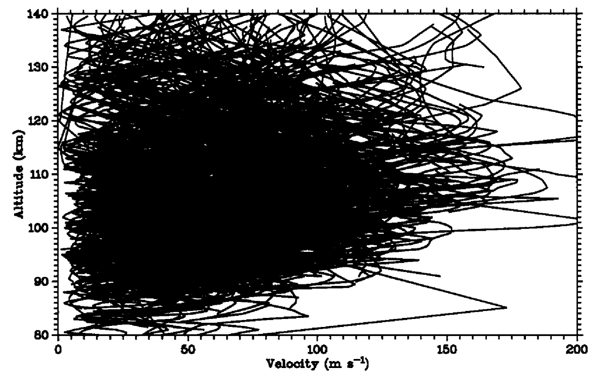
Jet Streams in Geospace?
Anomalous Transport Experiment (ATREX)



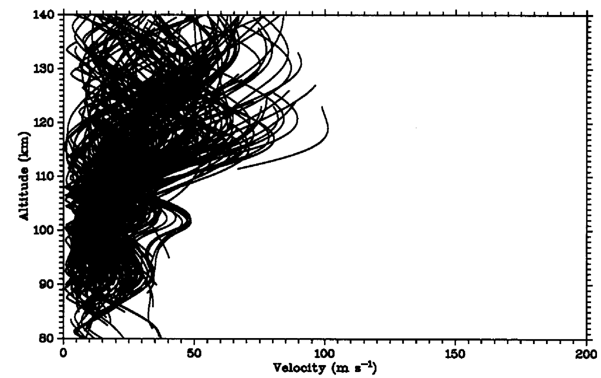
Neutral Winds (80-140 km)

Large, variable, *not* understood

Wind Data



Model Results

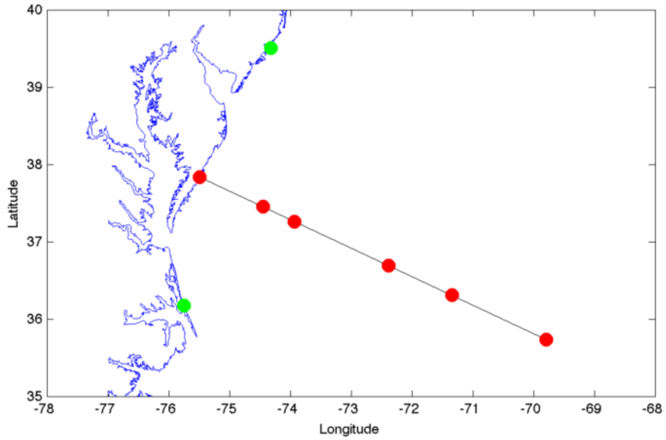


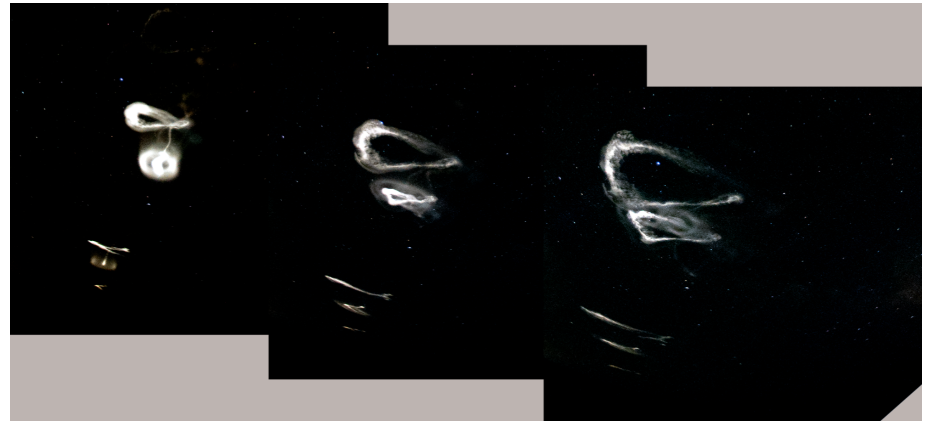
[Larsen et al., 2000]

- Over 500 rocket measured wind profiles over 4 decades have revealed very strong winds between 100-110 km, with peak amplitudes of 100-150 m/s.
- NRL tracked Shuttle exhaust products and showed rapid movement from mid latitudes to the polar regions in a period as short as a day or two.
- Although high wind speeds were not surprising, transport across a large part of the globe so rapidly was unexpected.
- Observations showed a strong coherent flow, of the type typically associated with an atmospheric jet stream.

P.I. Is Miguel Larsen, Clemson

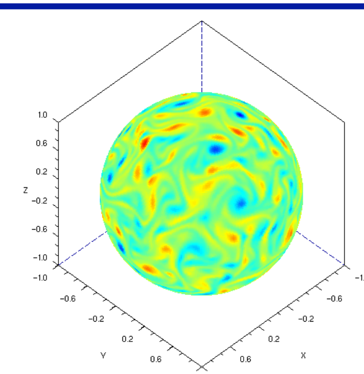
Anomalous Transport Experiment (ATREX) (Continued)





- To investigate this "Geospace jet stream", 5 rockets with a TMA chemical tracer were launched within a few minutes from Wallops with all the trails visible at the same time.
- Rapid expansion of trails near 100 km due to high-speed winds is evident in all five trails.
- Trails closest to launch site show loop structure due to rotation of winds with height, showing evidence that high-speed flows are large-scale features, consistent with idea that they are part of a large circulation feature.

Determining if this type of turbulence exists is a key objective of ATREX since 2-D turbulence is a means for producing large-scale coherent winds.



2-d Turbulence on sphere
Image: O. Pannekoucke web site
Météo-France and CNRS, France

P.I. Is Miguel Larsen, Clemson

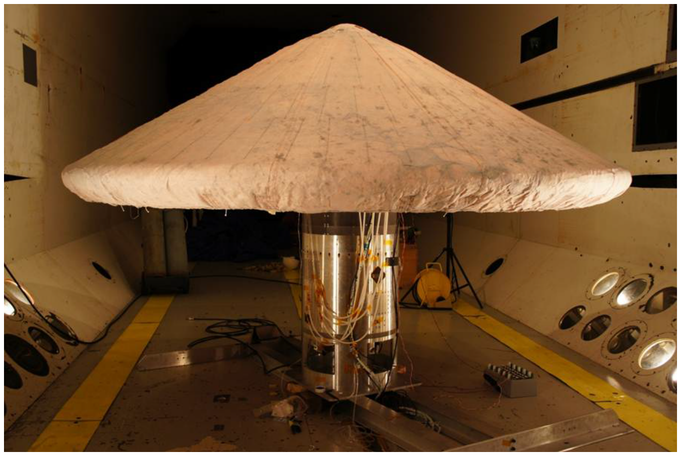
Sounding Rocket Mission Categories

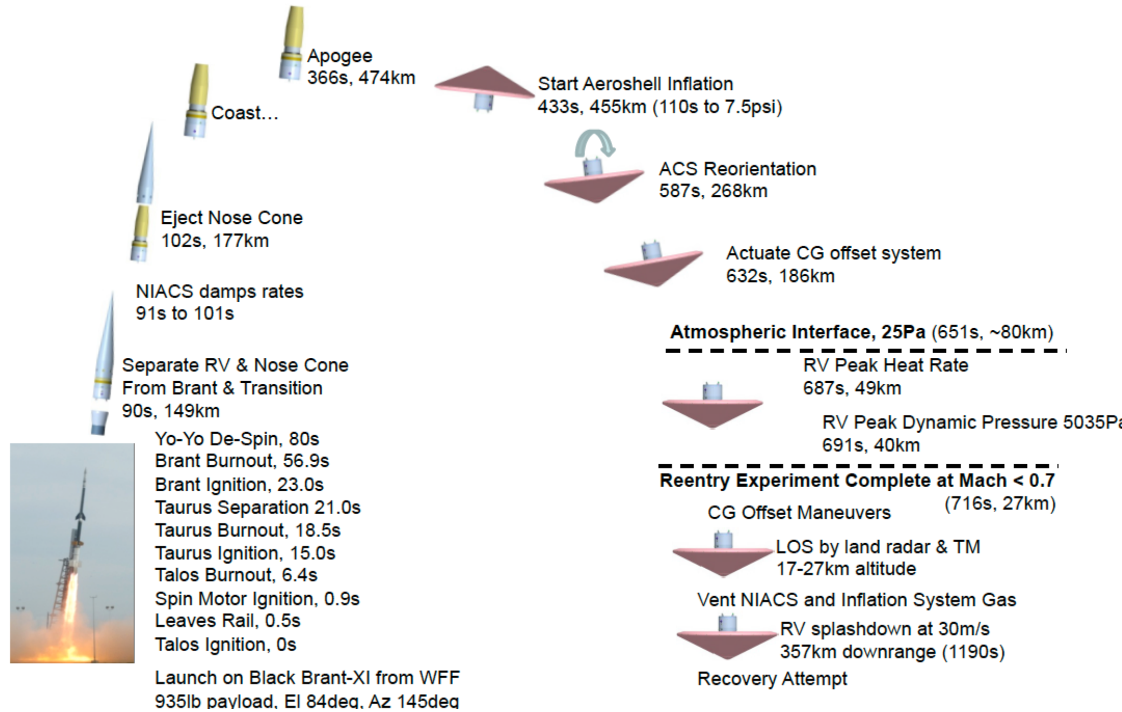
Special projects

- Aerobraking tests, re-entry technology testing, etc.

  Large descent velocities of several km/sec (afforded by high apogee) typically sought to simulate re-entry tests.

Inflatable Re-Entry Vehicle Tests with Langley Research Center





- Inflatable Re-Entry Vehicle (IRVE-3)
- Third flight of the inflatable re-entry concept
- Execute flight-test to demonstrate inflation and survivability at relevant dynamic pressure
- Validate analysis and design techniques used by re-entry vehicle (RV)

Technology Roadmap

Technology Roadmap developed jointly by WFF and the Sounding Rocket Working Group

- High Altitude Sounding Rocket
- Small Mesospheric "Dart" payload
- High altitude recovery of payloads,
- Air retrieval of sounding rocket payloads

Summary

- NASA Sounding Rocket Program provides a wide range of technical capabilites including unique launch vehicles, payload capabilities, and range operations.

- Program has served space science exceedingly well:

  Astrophysics -- Planetary -- Solar -- Geospace

- Sounding rockets look forward to continued innovation and show great promise for the future