It Is Rocket Science…

Remarkable Discoveries from NASA’s Sounding Rocket Program

Goddard Scientific Colloquium

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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
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
Program serves numerous scientific disciplines:

-- Astronomy
-- Planetary
-- Solar
-- Geospace
  (Magnetosphere/Ionosphere/Thermosphere/Mesosphere)
-- Microgravity
-- Special Projects
  (e.g., Aero-braking and Re-entry Studies)
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
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 XII

Black Brant IX
Current “Stable” of Sounding Rocket Motors at Wallops Flight Facility
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)  
  \textit{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

Comet Hale-Bopp -- 6 April 1997
JHU-NASA Sounding Rocket 36.156 UG

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

• 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.

Searching for Signatures of First Light in the Extragalactic Background

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

Cosmic Infrared Background Experiment (CIBER)

EBL from Reionization  EBL from galaxies

400 kyr  500 M  1 Gyr  5 Gyr  13 Gyr

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

CIBER discovers a silicate absorption band in Zodical dust

Tsumura et al. 2010

Fraunhofer lines
Silicate absorption

 normalized ZL spectrum : ZL

wavelength [µm]

0.7 0.8 0.9 1 2

O 400 kyr 500 M 1 Gyr 5 Gyr 13 Gyr

Time

EBL from Reionization
EBL from galaxies

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° 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

Accurate pointing (< 0.1 deg) needed.

Lightweight primary mirror; 0.5m dia, 4.5 kg

S. Chakrabarti, Boston University, P.I
New X-Ray Detector Developed on Sounding Rockets

• 1st Detection of diffuse emission in 172 A 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 cm²) 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

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

Telescope to Rocket Interface “Bulkhead”

Telescope within Rocket

Entrance Aperture (Behind Door)

Telescope Section (Entrance Aperture DOWN)

P.I. Is Jonathan Cirtain, MSFC
Energy release in the solar corona from spatially resolved magnetic braids

J. W. Curtin¹, L. Golub², A. R. Winebarger¹, B. De Pontieu³, K. Kobayashi⁴, R. L. Moore¹, R. W. Walsh⁵, K. E. Korreck², M. Weber², P. McCauley², A. Title³, S. Kuzin⁶ & C. E. DeForest⁷

Braided Loop
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.

- 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%

Comparison of SDO EVE and TIMED SEE

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)
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

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, Alfvén waves within the aurora.
- To achieve > km scale spacings, sub-payloads have included small rockets (e.g., Lessard, Conde rockets).

8 cm dia. magnetometers

Separated magnetometers permit direct curl $\mathbf{B}$ measurements of $\mathbf{J}$

Lessard rocket simulation/WFF

Zheng et al., 2003

Lundberg et al., 2012

DC E Fields 2 payloads

Calculated Shear
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

[intense Langmuir waves at these times cause vertical black bands, an instrumental effect]

[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.

Data: R. Pfaff, GSFC
NASA’s first “Tailored” Trajectory Reveals Vertical, Horizontal Winds over Auroral Arc

- 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 3\textsuperscript{rd}-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

Ground Receiver, WFF
Thunderstorm Electric Fields

High Rocket at 142 km
Low Rocket at 88 km
Balloon at 23 km
Ground Receiver

40 mV/m DC pulse

Detailed wave measurements show how sferics with parallel E-fields convert to whistler mode.
High T/M rates (~10 Mbps) make this possible

[Kelley et al., JGR, 1985]
NASA Guará Campaign
13 Rocket Launches at the Magnetic Equator in Brazil

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 $E \times B$ 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 anthropogenic 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)

• 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.

Neutral Winds (80-140 km)
Large, variable, not understood

[Larsen et al., 2000]
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.
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 (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 capabilities 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