The Nuclear Spectroscopic Telescope Array (NuSTAR)

A New View of the High Energy Universe

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and NuSTAR Team
Project Overview (1)

**Salient Features**
- PI-led (PI: Fiona Harrison, Caltech) SMEX mission
- *NuSTAR* will carry the first high-energy X-ray focusing telescope
- *NuSTAR* partners include Caltech, JPL, GSFC, Orbital, ATK, UCB, DNSC and Columbia University
- JPL managed project
- Launch readiness date: August 15, 2011
- Science operations: 2 years

**Science**
- *NuSTAR will open a new window on the Universe by making maps of the high-energy X-ray sky (6 keV to 79 keV) that are more than 100 times deeper than from any previous mission*
- **Objective 1**: Determine how massive black holes are distributed through the cosmos, and how they influence the formation of galaxies like our own
- **Objective 2**: Understand how stars explode and forge the elements that compose the Earth
- **Objective 3**: Determine what powers the most extreme active black holes
Mission Overview (2)

Orbital
- 5° or 27° inclination
- >550 km circular

Spacecraft
- Three-axis attitude control

Instrument
- Two hard x-ray telescopes
- 10 meter focal length

Mission Profile:
Long pointed observations of survey fields, specific science targets, ToOs.

Daily data downlinks, infrequent uplinks.

Mission Operations
- TDRSS
- UCB
- Mission operations center (UCB)
- Science operations center (Caltech)
- Science team
- Science Archive (HEASARC)
NuSTAR Observatory
X-ray Observation

The Electromagnetic Spectrum

- **Frequency (Hz)**
  - $10^2$
  - $10^3$
  - $10^4$
  - $10^5$
  - $10^6$
  - $10^7$
  - $10^8$
  - $10^9$
  - $10^{10}$
  - $10^{11}$

- **Wavelength (m)**
  - $10^2$
  - $10^3$
  - $10^4$
  - $10^5$
  - $10^6$
  - $10^7$
  - $10^8$
  - $10^9$
  - $10^{10}$

- **Photon Energy (eV)**
  - $10^1$
  - $10^2$
  - $10^3$
  - $10^4$
  - $10^5$
  - $10^6$
  - $10^7$
  - $10^8$
  - $10^9$

- **Penetrates Earth Atmosphere?**
  - Y
  - N

- **Wavelength (meters)**
  - Radio
  - Microwave
  - Infrared
  - Visible
  - Ultraviolet
  - X-ray
  - Gamma Ray

- **Temperature of bodies emitting the wavelength (K)**
  - 1 K
  - 100 K
  - 10,000 K
  - 10 Million K

- **About the size of...**
  - Buildings
  - Humans
  - Honey Bee
  - Pinpoint
  - Protozoans
  - Molecules
  - Atoms
  - Atomic Nuclei
The High Energy Focusing Telescope (HEFT)
Birth of a Neutron Star & Supernova Remnant

Birth of a Neutron Star and Supernova Remnant
(not to scale)

red giant

Core Implosion → Supernova Explosion → Supernova Remnant
To map young remnants to understand how stars explode and distribute the elements

*NuSTAR will be a new tool for looking inside of a supernova; probing down to the very core.*

The explosion (theory)  The remnant

Steve Boggs, UC Berkeley, for the *NuSTAR* Science Team
NuSTAR’s map of the hard X-ray sky

INTEGRAL/IBIS - 2 x 2 degrees.

NuSTAR simulated image - 2 x 2 degrees.
Crab Nebula: Remnant of an Exploded Star (Supernova)

Radio wave (VLA)  Infrared radiation (Spitzer)  Visible light (Hubble)

Ultraviolet radiation (Astro-1)  Low-energy X-ray (Chandra)  High-energy X-ray (Integral)
Crab Nebula: Remnant of an Exploded Star (Supernova)

- Radio wave (VLA)
- Infrared radiation (Spitzer)
- Visible light (Hubble)
- Ultraviolet radiation (Astro-1)
- Low-energy X-ray (Chandra)
- High-energy X-ray (HEFT) *** 15 min exposure ***
Optics: X-ray Reflection

X-rays bend slightly toward the surface (opposite from visible light)

\[ n = 1 - \delta - i\beta \quad \delta \sim 10^{-3} \]
Optics: X-ray Total External Reflection

Critical condition for total external reflection

Critical angles are very small (< 1 degree)
Optics: Nested Mirror Segments

Need two conic sections to eliminate aberrations
Optics: Multilayer Coating

Constructive interference

Air / Vacuum
Mirror coating 1
Mirror coating 2
Mirror coating 1
Mirror coating 2
Mirror coating 1
Mirror coating 2

Reflected X-ray

Low-energy X-rays
High-energy X-rays

HEFT multilayer coating
IR coating

Reflectivity (θ=12°)

Energy (keV)
Optics Construction

Combine small angles with multi-layer coatings
many nested shells (72 HEFT, 130 NuSTAR)
coatings with up to 700 layer pairs
thinnest pairs: 25 angstroms!
Detector: CdZnTe

Doctors’ approach: photographic film
Efficiency: 2%

Low-energy X-ray astronomy: silicon CCDs
Efficiency for high-energy X-rays: 10%

Conventional detectors are too inefficient.
Focal Plane Detector

Cadmium zinc telluride (CdZnTe):
High atomic numbers (Z=48,30,52)
=> High electron binding energy
=> Over 99% efficiency in trapping high-energy X-rays.

Underneath: Custom electronics for X-ray detection and amplification; built as integrated circuit (ASIC); compact, low-power, low-noise.

Side view schematics:
- CdZnTe detector
- Custom electronic chip
- Connecting wires are all narrower than human hair

Flip-chip bonding: a pioneer in 1990s
Mast: Focal Length

- The thermally stable deployable mast provides a 10.14 meter focal length between the tip-mounted optic assemblies and their corresponding base-mounted focal plane assemblies.
Mast: Deployment

**Mast and Adjustment Mechanism** - The mast and adjustment mechanism are responsible for providing a stable, 10.14 meter separation between the focal plane assemblies and the tip mounted optic modules.

**Optical Bench** – The optical bench is responsible for structurally supporting the two optics modules, three metrology lasers, an optic bench electronics box, a star tracker, and a rear-facing camera.

**Focal Plane Bench Assembly** – The focal plane bench assembly is responsible for structurally supporting the mast/canister, two focal plane assemblies, three metrology detectors, the central electronics box, two star trackers, and a magnetometer.


**Metrology**

NuSTAR metrology System measures orientation that individual X-ray photons arrives from

All data processing is post processing

All measurements are relative to initial in-flight calibration

Metrology System consists of

- Optical Bench Mounted Star Tracker
- 2 laser beams and corresponding position sensitive detectors

Metrology system measures:

- Inertial orientation of optical bench
- Lateral displacement of focal bench relative to optical bench

Metrology system does NOT measure:

- Distance between optical bench and focal plane bench
- Inertial orientation of focal bench

Update rate: ~100 Hz

Accuracy: 150 microns
Metrology: Testbed

- X-ray optics
- X-ray Detectors
- 10 m deployable mast
- Mast canister
- Star Tracker
- Metrology Laser
- Metrology Detector
- Optics Bench
- Detector Bench

10 meters

September 10, 2008
AIAA Space 2008
Spacecraft

Orbital Sciences Corporation heritage LEOStar spacecraft

Command & Data Handling
- Standard MIL-STD-1553 and RS-422 Interfaces
- Standard CEU + Mission Unique Card (MUC) Accommodates Payload Needs

Electrical Power
- Single Wing Deployed Single Axis GaAs Solar Arrays
- 16 A-Hr Battery
- Heritage Power Regulation Electronics
- Power Converter Box

Software and Fault Protection
- Execution of Stored and Real-Time Command Sequences
- Safe Hold Mode Protects Spacecraft During Faults

Thermal Control
- MLI & Silver Teflon for Passive Thermal Control
- Thermistors and Heaters for Component Thermal Control

RF Communication
- 32 kbps S-band Uplink, 2 Mbps S-band Downlink
- 2 Omni Antennas Provide Near Spherical Coverage

Mechanical
- Aluminum Facesheet Over Aluminum Honeycomb Bus
- Carbon Fiber Over Aluminum Honeycomb Arrays

Attitude Control
- 3-axis Stabilized Zero Momentum System
- Star Tracker Provides Attitude Data
- Gyro Provides Rate Data
- Sun Sensors Provide Attitude Data in Safe Hold
- TAM & Torquers for Momentum Control
Mission Schedule

- System Requirements Review
  - July 9, 2008
- Project Preliminary Design Review
  - June 9, 2009
- Project Critical Design Review
  - February 2, 2010
- Instrument Delivery to Observatory I&T
  - November 12, 2010
- Observatory I&T
  - November 13, 2010 - June 24, 2011
- Launch
  - August 15, 2011
- Science Operations
  - September 15, 2011 – October 1, 2013
The Future: *NuSTAR*

Simulated NuSTAR image

- 40" angular resolution
- Sensitivity $\sim 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (20-40 keV; 10$^6$ s).

Michael Muno (Caltech) for the *NuSTAR* team