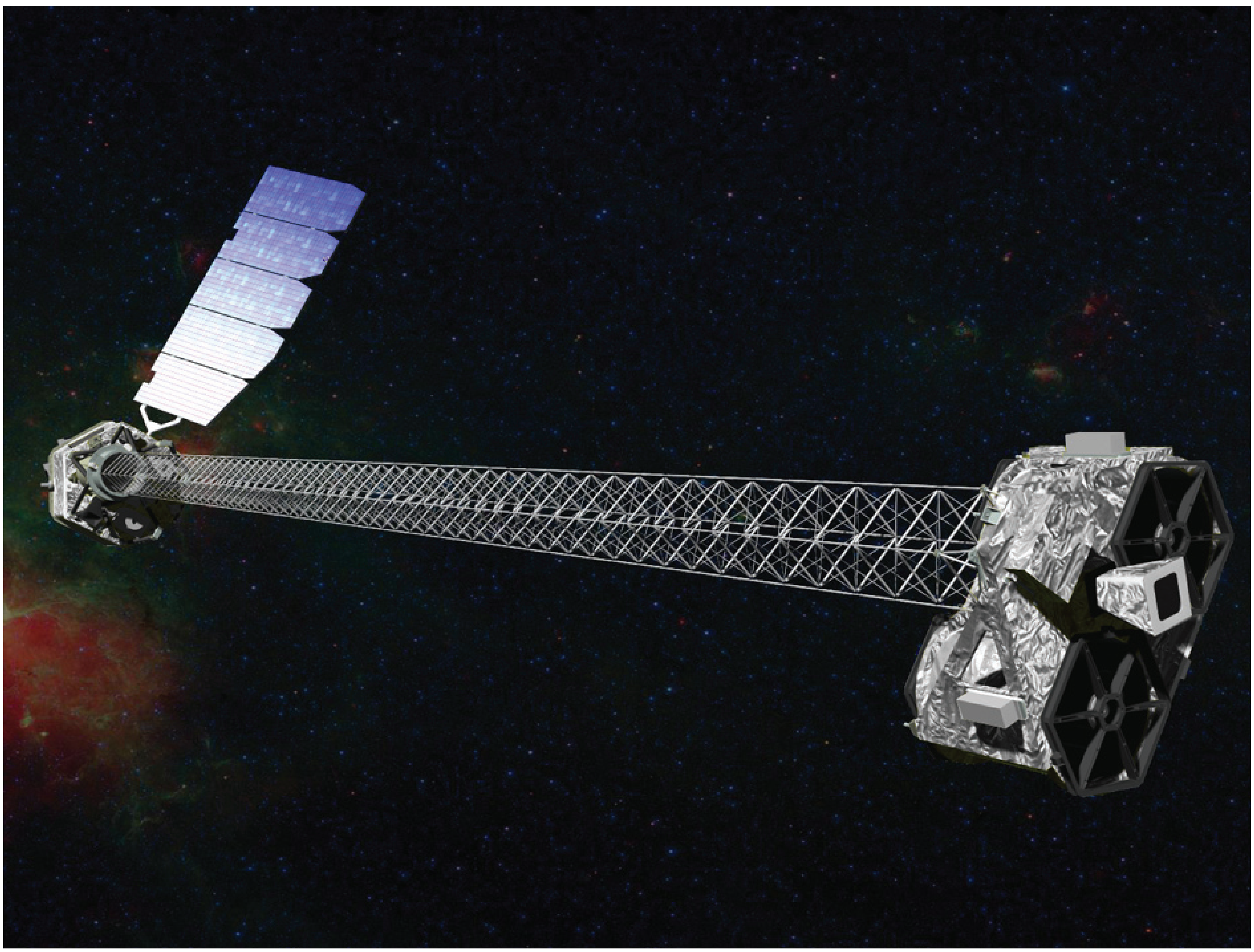
National Aeronautics and Space Administration

PRESS KIT/JUNE 2012

Nuclear Spectroscopic Telescope Array, or NuSTAR



www.nasa.gov

Media Contacts

J.D. Harrington NASA Headquarters, Washington	Policy/Program Management	202-358-5241 j.d.harrington@nasa.gov
Whitney Clavin NASA Jet Propulsion Laboratory, Pasadena, Calif.	NuSTAR Mission	818-354-4673 whitney.clavin@jpl.nasa.gov
Melissa Carpenter Orbital Sciences Corporation, Dulles, Va.	Spacecraft and Launch Vehicle	703-406-5769 Carpenter.Melissa@orbital.com
Robert Sanders UC Berkeley Berkeley, Calif.	Mission Operations	510-643-6998 rlsanders@berkeley.edu
George Diller NASA Kennedy Space Center, Fla.	Launch Operations	321-867-2468 george.h.diller@nasa.gov
Lynn Cominsky Sonoma State University, Rohnert Park, Calif.	Education and Public Outreach	707-664-2655 lynnc@universe.sonoma.edu
Lawren Markle California Institute of Technology, Pasadena, Calif.	Caltech Media Relations	626-395-3226 Lmarkle@caltech.edu

Cover: An artist's concept of NuSTAR.

For more information

http://www.nasa.gov/nustar
http://www.nustar.caltech.edu

Contents

Media Services Information

NASA Television Transmission

In the continental United States, NASA Television's Public, Education and Media channels are carried by MPEG-2 digital C-band signal on AMC-6, at 72 degrees west longitude, Transponder 17C, 4040 MHz, vertical polarization. They're available in Alaska and Hawaii on an MPEG-2 digital C-band signal accessed via satellite AMC-7, transponder 18C, 137 degrees west longitude, 4060 MHz, vertical polarization. A Digital Video Broadcast-compliant Integrated Receiver Decoder with modulation of QPSK/DBV, data rate of 36.86 and FEC 3/4 is required for reception. NASA TV Multichannel Broadcast includes: Public Services Channel (Channel 101); the Education Channel (Channel 102); and the Media Services Channel (Channel 103). Analog NASA TV is no longer available.

For digital downlink information for each NASA TV channel, schedule information for NuSTAR activities and access to NASA TV's public channel on the Web, visit **http://www.nasa.gov/ntv**.

Audio

Audio of the launch coverage will be available on "V-circuits" that may be reached by dialing 321-867-1220, -1240 or -1260.

News Conferences

A mission and science overview news conference on NuSTAR will be held at NASA Headquarters at 1 p.m. Eastern Time (10 a.m. Pacific Time) on May 30, 2012. The news conference will be broadcast live on NASA Television and at **http://www.ustream.com/nasajpl2**.

Another pre-launch media telecon will be held two days before launch at UC Berkeley's Space Sciences Laboratory. Local reporters are invited to attend in person, and dial-in information will be available for participating remotely.

Media advisories will be issued in advance, outlining details of these events.

Launch Viewing

NuSTAR launch coverage and commentary will be broadcast online at the NASA website and at **http://www.ustream.com/nasajpl2**.

Internet Information

More information on the mission, including an electronic copy of this press kit, news releases, status reports, images and video, can be found at: **http://www.nasa.gov/nustar** and **http://www.nustar.caltech.edu**.

Mission news and updates will also be posted on Twitter at @NASANustar, @NASAJPL and @NASA.

Quick Facts

NuSTAR Observatory

Spacecraft Dimensions: 3.9 by 7.2 feet (1.2 by 2.2 meters) when stowed for launch; 3.9 by 35.8 feet (1.2 by 10.9 meters) after mast is extended in space

Weight (spacecraft bus and science instrument): 772 pounds (350 kilograms)

Power: Solar arrays capable of generating 729 Watts of power

Science Instrument: Telescope consisting of two co-aligned high-energy X-ray optic units; two shielded detectors; and a connecting 33-foot (10-meter) mast to be deployed in space.

Instrument Energy Range: Detects X-rays with energies between 5 and 80 kilo electron volts (keV)

Stowed Instrument Dimensions: 3.9 by 5.3 feet (1.2 by 1.6 meters)

Instrument Weight: 377 pounds (171 kilograms)

Mission

Launch: no earlier than June 13, 2012, 11:30 a.m. Eastern Time (8:30 a.m. Pacific Time) from Ronald Reagan Ballistic Missile Defense Test Site at Kwajalein Atoll in the Marshall Islands, located in the west central Pacific Ocean

Launch Vehicle: Pegasus XL

Launch Period: any day of the year is possible

Launch Window: about 4 hours

Expected Mission Duration: Prime mission is two years, with possibility of extension up to at least five years before orbit decay

Orbit: low-inclination Earth-orbit, about 375 miles (600 kilometers) above Earth

Orbital Inclination: 6 degrees relative to equator

Orbit life: less than 25 years before re-entry

NASA Investment: approximately $165 million (design, development, launch and operations)

Why NuSTAR?

The universe is filled with light of many colors, including those we can't see with our eyes. The colors of the rainbow are actually just a tiny slice of a vast spectrum of light that ranges from radio waves to high-energy gamma-rays. NASA's Nuclear Spectroscopic Telescope Array, or NuSTAR, will allow astronomers to see a band of invisible light that has gone largely unexplored until now: the high-energy X-rays.

Due to advances in X-ray telescope technologies, NuSTAR will be the first space telescope to focus X-rays with the highest energies into sharp images. These are X-rays with about the same energy as those used in medical and dental offices. The observatory will see with more than 100 times the sensitivity of previous high-energy X-ray missions, and more than 10 times better resolution.

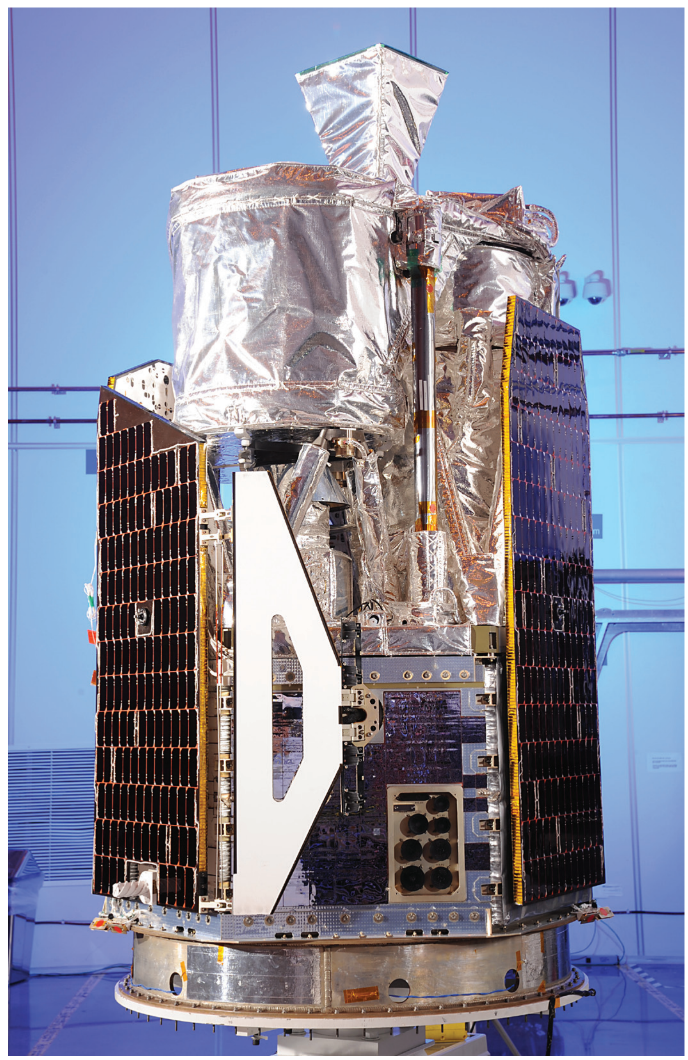
NuSTAR will advance understanding about how galaxies in the universe form and evolve. The mission will observe some of the hottest, densest and most energetic objects in the universe, including black holes, their high-speed particle jets, supernova remnants, and our sun.

In addition, NuSTAR will work in concert with other space telescopes, including NASA's Chandra X-ray Observatory, the European Space Agency's XMM-Newton and the Japanese Aerospace Agency's Suzaku mission. Together, these data will create full, vibrant pictures of exotic and energetic phenomena in space. In essence, NuSTAR is adding a new color to astronomers' palettes, helping to paint a better understanding of our universe.

How does the observatory achieve all this, considering its small size and budget? NuSTAR is part of NASA's Small Explorer program, which builds focused science missions at a relatively low cost. Several key innovations developed under NASA's supporting research & technology and balloon programs, and with contributions from many partner institutions, led to NuSTAR's advanced design.

Unlike visible light, X-rays only reflect off surfaces at glancing angles — as a rock might skip off the surface of a lake. X-ray mirrors must therefore be designed with the reflecting surfaces almost parallel to the incoming X-rays. Just one mirror isn't enough, however, to collect very much X-ray light. To intercept as much light as possible, X-ray telescopes require a series of nearly parallel mirror surfaces. This is accomplished with the use of thin, nested shells of mirrors.

The challenge for NuSTAR's mirrors is that high-energy X-ray light reflects at angles that are even more glancing, or close to parallel. As a result, more shells of carefully crafted mirrors are needed. To collect enough X-ray light, NuSTAR has two sets of 133 nested shells as thin as fingernails, with special reflective coatings.



NuSTAR in a clean room at Orbital Sciences Corporation in Dulles, Va.

X-ray telescopes also require long separations between the optics, which are the units that contain the nested mirrors and focus the radiation, and the detectors, which act as the film upon which the image is recorded. NuSTAR achieves this with a school-bus-sized 33-foot (10-meter) mast that separates the optics from the detectors. The mast is too large to launch on the low-cost vehicles required for Small Explorer missions such as NuSTAR. Instead, it is folded up inside a 3.3-foot-tall (1-meter) canister for launch, and will deploy seven days after the observatory reaches orbit.

All these innovations add up to a unique tool for studying some of the most energetic objects and events in the universe. The mission's science goals include the study of black holes — big and small, far and near — in addition to the remains of exploded stars. The observatory will also probe the dense cores of dead stars, jets streaming out of black holes at nearly the speed of light and some of the most powerful galaxies in the universe. NuSTAR will investigate how exploding stars forge the elements that make up planets and people, and it will even study our own sun's atmosphere.

In addition to these goals, surprises are to be expected. Anytime a telescope opens a new window on the universe, unimagined discoveries will abound.

NuSTAR is a Small Explorer mission led by the California Institute of Technology and managed by NASA's Jet Propulsion Laboratory, both in Pasadena, Calif., for NASA's Science Mission Directorate. The spacecraft was built by Orbital Sciences Corporation, Dulles, Va. Its instrument was built by a consortium including Caltech; JPL; the University of California, Berkeley; Columbia University, New York; NASA's Goddard Space Flight Center in Greenbelt, Md.; the Danish Technical University in Denmark; Lawrence Livermore National Laboratory, Calif.; and ATK Aerospace Systems, Goleta, Calif. NuSTAR will be operated by UC Berkeley, with the Italian Space Agency providing its equatorial ground station located at Malindi, Kenya. The mission's outreach program is based at Sonoma State University, Calif. NASA's Explorer Program is managed by Goddard. JPL is managed by Caltech for NASA.

Mission Overview

The NuSTAR spacecraft is scheduled to launch into a low-Earth orbit with a small (6-degree) inclination to the equator on a Pegasus XL launch vehicle no earlier than June 13. About 30 days after launch, the spacecraft will begin its two-year science mission. NuSTAR has the possibility of being extended for at least five additional years. The mission's orbital decay ultimately limits its duration, with re-entry of the atmosphere expected within approximately 25 years after launch.

Mission Phases

Five mission phases have been defined to describe the different periods of activity during NuSTAR's mission. These phases are: Pre-Launch, Launch & Early Orbit, Checkout & Calibration, Science Operations, and Decommissioning.

Pre-launch Phase

The pre-launch phase begins approximately 36 days before launch and extends through the aircraft take-off from Kwajalein, the journey to the drop-zone, and the actual release and ignition of the Pegasus XL vehicle.

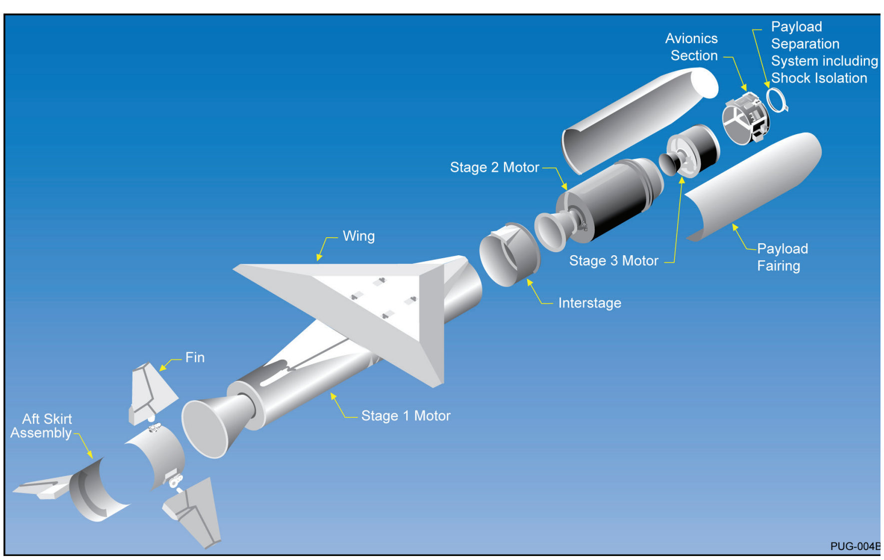
Launch and Early Orbit Phase

The Launch and Early Orbit phase begins with the ignition of the launch vehicle. This phase, about seven-days long, is characterized by launch, initial acquisition of signal and spacecraft checkout.

Launch Site and Vehicle

The NuSTAR spacecraft will be launched on a Pegasus XL launch vehicle manufactured by Orbital Sciences Corporation from the Kwajalein Atoll (8deg43min N, 167deg44min E). Kwajalein, one of the world's largest coral atolls, sits at the middle of the Ralik (sunset) Chain of the Marshall Islands, which lie midway between Hawaii and Australia, approximately 2,000 nautical miles (3,700 kilometers) from both.

The three-stage Pegasus is carried aloft strapped to the body of the L-1011 "Stargazer" jet aircraft (named after a fictional space ship commanded by Star Trek Next Generation's Captain Jean Luc Picard). After the L-1011 releases the Pegasus, the rocket fires and carries its scientific payload into Earth orbit. The Pegasus's first stage is 33.7-feet (10.3-meters) long and 4.2 feet (1.3 meters) in diameter, with an engine thrust of 163,000 pounds (726,000 Newtons). The second stage is 4.2-feet (1.3-meters) long and 4.2 feet (1.3 meters) in diameter, with an engine thrust of 44,000 pounds (196,000 Newtons). The third stage is 4.4-feet (1.3-meters) long and 3.2 feet (0.97 meters) in diameter, with an engine thrust of 8,000 pounds (36,000 Newtons). Overall, the Pegasus rocket is 55.6-feet (16.9-meters) long, 4.2 feet (1.3 meters) in diameter, has a wingspan of 22 feet (6.7 meters), and weighs 51,300 pounds (23,269 kilograms). All three stages burn solid propellant.



NuSTAR will launch on a Pegasus XL rocket, built by Orbital Sciences Corporation, Dulles, Va.

Launch Timing

Launch is scheduled for no earlier than June 13, 2012. A four-hour launch window is designed to optimize lighting conditions when NuSTAR enters orbit and deploys its solar arrays. Unlike planetary spacecraft, which must be launched during fixed windows of time in certain years and months in order to reach a particular planet, NuSTAR may be launched on any day of the year as long as the launch site is available.

Takeoff and Launch Vehicle Powered Flight

The L-1011 carrier aircraft, with the Pegasus launch vehicle and the NuSTAR spacecraft strapped to its belly, will take off from Kwajalein's Bucholz Auxiliary Airfield and climb to an altitude of about 39,000 feet (11,900 meters). About 100 miles (160 kilometers) off the coast of Kwajalein, the carrier aircraft will release the Pegasus rocket, which will drop for about 5 seconds, then ignite its first-stage motor.

After the first stage burns for 70 seconds, it will drop away and the second stage will ignite, burning for about a minute and a half. While the second stage is burning, pyrotechnic devices will be fired to release the nose cone, or fairing, that encapsulates the observatory. When the second stage burns out, the rocket and spacecraft will coast for about five minutes. The third stage will then ignite as it approaches the west coast of Africa and fire for 68 seconds.

Ten minutes after the initial release from the L-1011 aircraft, NuSTAR will separate from the Pegasus rocket's third stage. At this point, NuSTAR will be in its final orbit — a low-Earth equatorial orbit at an altitude of approximately 340 miles (600 kilometers) and an inclination of 6 degrees. The equatorial orbit is particularly important for NuSTAR as it will minimize exposure to the South Atlantic Anomaly, the region centered above the southern Atlantic Ocean where the Earth's inner Van Allen belt makes its closest approach to the Earth's surface. Satellites at altitudes of a few hundred miles, or kilometers, and in orbits inclined relative to the equator experience intense particle radiation during passages through the South Atlantic Anomaly. The anomaly can be particularly problematic for high-energy X-ray telescopes due to the high level of radioactive background it generates. If encountered, the radioactive background would generate signals that mimic the cosmic X-ray emission NuSTAR aims to detect.

To preclude any possibility of a collision with the observatory, the Pegasus' third stage will execute a maneuver after spacecraft separation. Three seconds after NuSTAR separates from its launch vehicle, the Pegasus' third stage will execute a 90-degree turn. The third stage will then pause five minutes, and execute an additional 90-degree turn. It will fire its small thrusters next, until its propellant gas is depleted, slowing it slightly. Eventually, the rocket stage will re-enter Earth's atmosphere and burn up.

First Minutes in Orbit

When NuSTAR separates from the Pegasus, the satellite's system that controls its orientation in space, or "attitude," will begin to stabilize it, and the spacecraft solar arrays will be deployed. Around this time, the first signal from the spacecraft will be received on the ground via the Tracking and Data Relay Satellite System. Over the following week, NuSTAR personnel will perform a series of checkouts to ensure that all spacecraft subsystems are operating nominally.

Checkout and Calibration Phase

The approximately 23-day checkout and calibration phase of the mission begins with the spacecraft team declaring that the spacecraft is in a state that will support the instrument deployment and power-on. At that time, the instrument electronics will be powered on in-orbit for the first time, the mast will be deployed, and the X-ray telescope will be checked out and calibrated. This phase will be concluded once the instrument team and spacecraft team have determined that the observatory is capable of supporting science operations.

Mast Deployment

After the optics bench is released, the NuSTAR instrument's 32.8-foot-long (10-meter) mast will be deployed. This deployment, which will take about 25 minutes, will provide the required separation between the instrument's two optics modules and their respective X-ray detectors. The deployment will be commanded from the ground. Once the mast has been deployed, the mast deployment system will power off autonomously, and the spacecraft will reorient to wait for ground command.

Optical System Alignment and Instrument Calibration

The NuSTAR science team will take advantage of one of two bright X-ray sources, either the bright quasar 3C273 or the Crab supernova remnant, to help properly align the optical units and the detectors, or focal plane. Once the spacecraft is pointed to the chosen source, data will be collected and downloaded to NuSTAR mission operations for evaluation. A mast adjustment mechanism incorporated into the optical system will make any final refinements expected after launch and deployment.

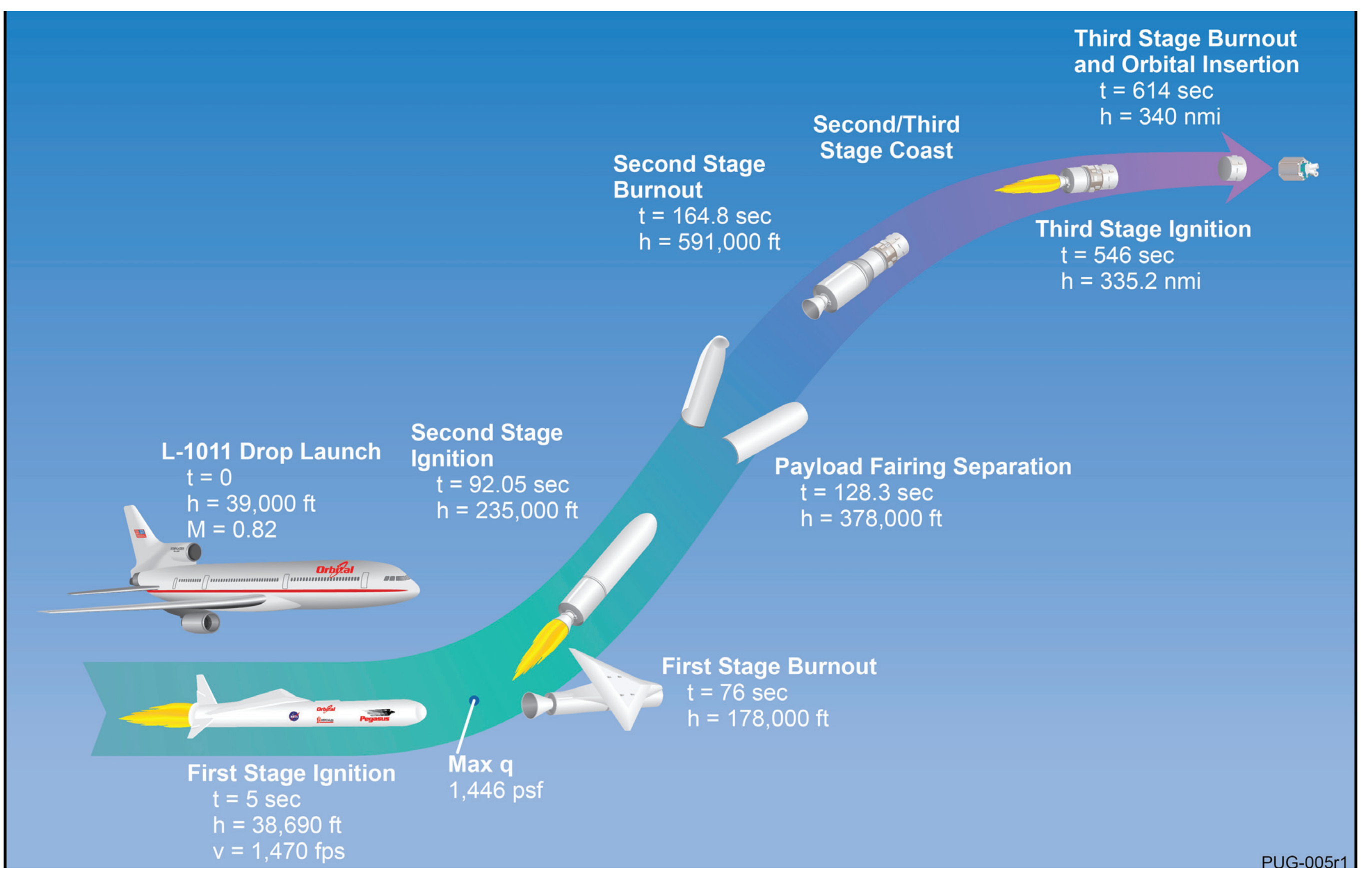
Science Operations Phase

The initial science operations mission phase is expected to begin approximately 30 days after launch and will last approximately two-and-a-half years. During this phase, the observatory will be directed at designated X-ray targets (previously selected from a catalog of candidates by the NuSTAR science team) for extended periods, i.e., upwards of two weeks or more. After a target has been fully explored, the observatory will reorient itself to begin another extended observation. Following completion of the initial science operations period, it is anticipated that NuSTAR will commence an extended science operations mission phase for a period of up to two years, dependent upon the outcome of the NASA Astrophysics Division Senior Review of Operating Missions. Potential subsequent science mission extensions will be subject to the Senior Review process.

The observatory will be operated from the Mission Operations Center located at UC Berkeley Space Sciences Lab. The science data will be sent to the Science Operations Center located at the Space Radiation Laboratory at the California Institute of Technology.

Decommissioning Phase

This mission phase begins 14 days prior to the end of mission. The purpose of this mission phase is to reduce the spacecraft to as inert a state as possible. The spacecraft's instrument, communications and attitude control system will be commanded off. It is required that within approximately 25 years, the dormant NuSTAR will re-enter and burn up in Earth's upper atmosphere.



Timeline of NuSTAR launch milestones.

Spacecraft

The integrated NuSTAR observatory consists of a single science instrument rigidly mounted to a spacecraft infrastructure, or bus, containing the avionics, power and attitude (pointing) control systems. The science instrument itself is made up of two benches, one for the optics and one for the focal plane. At launch, the benches are mounted on either end of a canister that contains the folded-up mast. These two benches are coupled during launch, separation and initial checkout. The benches are separated by non-explosive actuators and as the mast deploys, unfolding out of its canister, the two benches move apart until the mast is fully deployed and latches into place.

In its stowed-for-launch configuration, the observatory is compact and approximately 3.7 feet (1.1 meters) in diameter and 6.3-feet (1.9-meters) tall; these dimensions are driven by the need to fit within the fairing of the Pegasus launch vehicle. In its deployed configuration after reaching orbit and extending the mast, the observatory is 37.3-feet (11.4-meters) long, or approximately the length of a school bus.

Spacecraft Bus (and Focal Plane Bench)

The spacecraft bus (which contains the focal plane bench) has an aluminum honeycomb sandwich structure, and weighs 380 pounds (173 kilograms). The spacecraft bus is a compact structure 3.3 by 3.7 by 1.8 feet (1.0 by 1.1 by 0.5 meters). The bus provides all of the usual spaceflight capabilities in its respective subsystems: radio frequency communications, electrical power, command and data handling, attitude control, thermal control, and mechanical, electrical and thermal support to the instrument. The bus also provides the mechanical and electrical interfaces to the launch vehicle.

The spacecraft was built by Orbital Sciences Corporation, and its design is based on the company's LEOStar-2 bus.

Attitude Control and Determination Subsystem

The NuSTAR observatory's attitude control subsystem is a three-axis stabilized zero-momentum system. It utilizes reaction wheels combined with torque rods for attitude control. The attitude determination system is based around the Danish Technical University microASC star tracker supported by an Inertial Reference Unit (gyroscope), a magnetometer and several coarse sun sensors.

Command and Data Handling Subsystem

The spacecraft Command and Data Handling subsystem consists of three processors — the OnBoard Computer and the Uplink Card in the Central Electronics Unit, and the Attitude and Power Electronics microcontroller. The Command and Data Handling system provides control over all spacecraft functions including commanding (real-time and stored commands), payload data storage and playback, housekeeping data storage/playback, power subsystem management support, thermal subsystem management support, attitude control and instrument interface control.

Downlink of real-time and stored spacecraft bus and instrument housekeeping telemetry is handled via the Downlink Card in the Central Electronics Unit, along with the high-rate science playback data from the instrument.

Electrical Power Subsystem

The power system consists of a direct energy transfer system utilizing a solar array with a surface area of 29 square feet (2.7 square meters) capable of generating 729 watts of power. For power storage, NuSTAR has two lithium-ion batteries with a total capacity of 48 amp-hours.

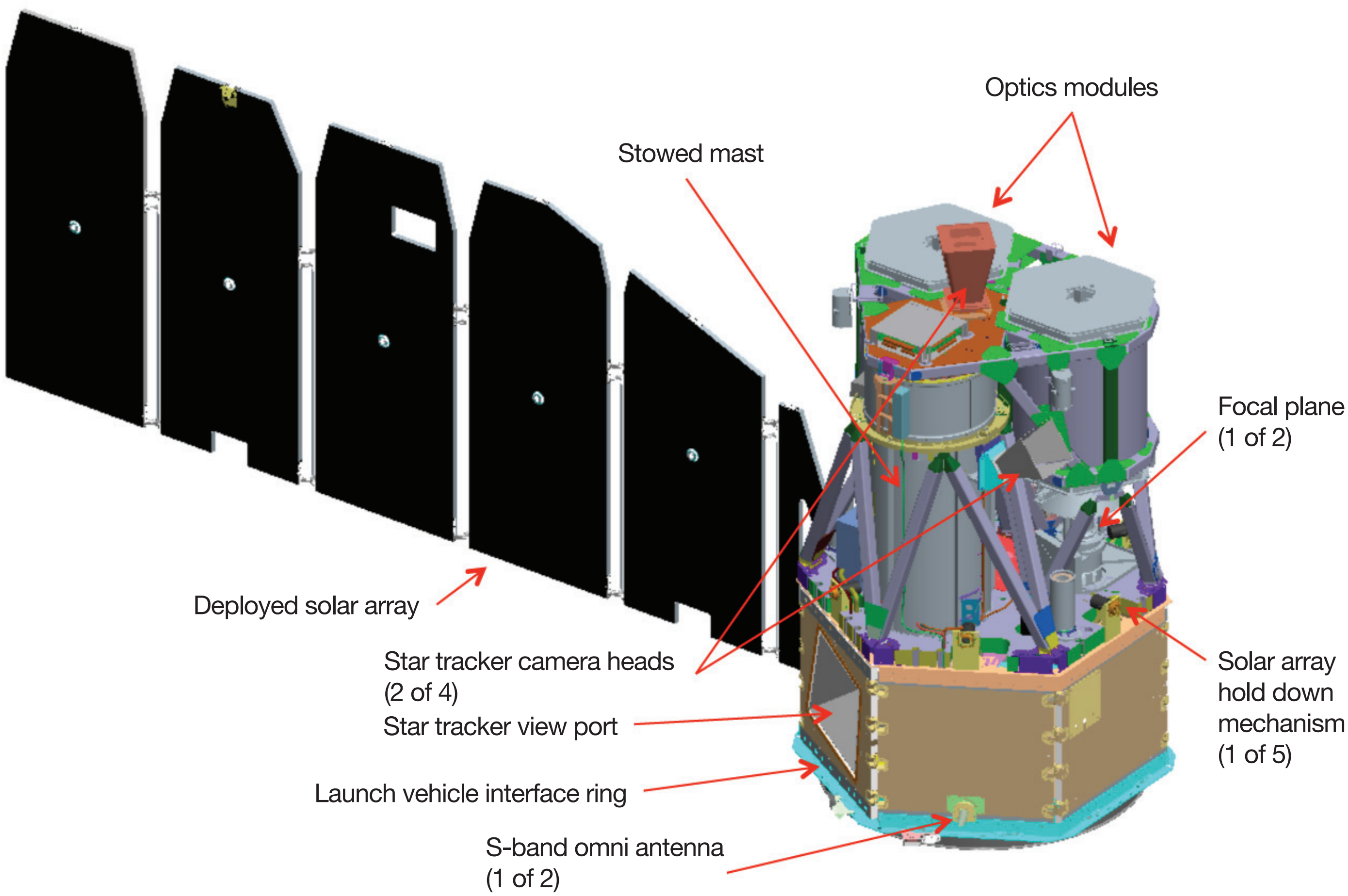
Communications Subsystem

Communications with the ground is accomplished via an S-band communications subsystem and two omnidirectional antennae, compatible with the Italian Space

Agency's tracking station in Malindi, Kenya, as well as with NASA's Tracking and Data Relay Satellite System for critical event coverage. The antenna configuration and coverage allows for commanding in all attitudes and downlink in most attitudes. The S-band communications subsystem has a redundant receiver.

Thermal Control Subsystem

The thermal control subsystem consists of passive elements (multilayer insulation blankets and radiator panels) and heaters. It protects the spacecraft by maintaining the temperatures within the flight-allowable limits.



The NuSTAR observatory, with key components labeled.

Telescope

Since Galileo's first homemade telescope in 1609, astronomers have been using mirrors and lenses to focus light and study the cosmos. X-rays are a form of light like the visible light we see with our eyes, but they have wavelengths about the size of an atom, or 10,000 times smaller than that of visible light. X-rays interact with matter and reflect off surfaces very differently than visible light.

As a result, focusing X-ray light requires a different type of design than traditional telescopes. Most of the designs in use for astronomical telescopes are based on variations of the same basic "reflector geometry," first invented by Hans Wolter in 1952. As explained below, this technology exploits the fact that more X-rays can be reflected when they hit surfaces at very small, glancing angles.

Telescopes operating in the low-energy part of the X-ray band have flown on numerous missions, but until now, no space telescope has focused high-energy X-rays into sharp images. Over the last decade, the technologies behind high-energy X-ray telescopes have seen significant breakthroughs, with NuSTAR's design being at the forefront, and the first to be launched into orbit.

The NuSTAR telescope consists of three main parts: the optics, or mirrors, which focus the light; the detectors, which record the image; and an extendable mast, which holds the optics and detectors at the required 33-foot (10-meter) separation distance once in orbit. NuSTAR has two optics units aligned to look at the same location on the sky. The two sets of images are added together on the ground to see fainter objects.

NuSTAR will detect high-energy X-rays with energies ranging from 5 to 80 keV, or kilo electron volts (keV). For reference, NASA's Chandra X-ray Observatory detects low-energy X-rays between 0.1 and 10 keV.

Optics

X-rays don't behave like visible light. They have much higher energies and only reflect off surfaces at glancing angles, like stones skipping off the surface of a lake. While visible light can reflect off a mirror at essentially any angle, an X-ray hitting a flat surface head-on will be absorbed.

Telescope designs that focus X-rays must therefore use mirrors that are nearly parallel to the incoming X-ray beam. This is accomplished with conical mirrors. An individual mirror has two near-conical sections — a front and a back — so that X-rays reflect twice before heading toward the focal plane, where the light is focused. The two reflections are required to remove distortions that would otherwise arise in the image.

A single mirror by itself will only intercept a small amount of light because its surface is nearly parallel to the incoming beam of radiation. To increase the collecting area, X-ray telescopes use multiple mirrors, often called shells, with different sizes, nested inside each other. Each shell's surface has a slightly different angle relative to the incoming radiation, so that they all focus X-rays to the same spot on the focal plane.

This type of design, called grazing-incidence X-ray optics, has been used on previous low-energy X-ray missions, including NASA's Chandra X-ray Observatory. The challenge faced by NuSTAR is to extend these optics to higher energies, which require even smaller, or more glancing, reflecting angles. Because the surfaces must be almost parallel to the beam, many more reflectors are needed. They must also be thin so they don't block too much light. The Chandra mirror has four shells, each between 0.8 to 1.2 inches (2 to 3 centimeters) thick, whereas NuSTAR requires 133 shells that are 0.008 inch (0.02 centimeter) thick — about the thickness of a fingernail.

To efficiently reflect the light in NuSTAR's energy range, specialized coatings are deposited on the reflecting surfaces. These coatings, similar to anti-reflective coatings on sunglasses, consist of hundreds of thin films alternating between light and dense materials. While coatings on sunglasses reduce reflections, NuSTAR's coatings are designed to enhance them. Each film in the coatings is just a few atoms thick.

To manufacture NuSTAR's optics, very thin, smooth glass segments were formed, coated with the specialized films and mounted into two optic modules. Each shell, or layer, is made up of between 12 and 24 pieces. The curved pieces were carefully crafted at NASA's Goddard Space Flight Center in Greenbelt, Md. Flexible, thin glass just like that found in laptop and cell phone screens, was shaped by placing it over molds, and then heated in ovens to temperatures of 1,100 degrees Fahrenheit (593 Celsius). As the glass was heated, it bent to the appropriate rounded shape. More than 9,000 individual mirror segments were created for NuSTAR's nested mirrors.

The reflective coatings, consisting of alternating layers of platinum and carbon, or tungsten and silicon (depending on the shell) were applied in a specially designed vacuum chamber at the Danish Technical University Space Centre in Denmark. The complex, tightly nested arrangement of mirror pieces was assembled at Columbia University's Nevis Laboratory just outside New York, N.Y. Starting from the inside out, each piece was carefully added to a growing barrel, spaced apart by graphite and held together by epoxy.

One of two optics units making up NuSTAR's telescope.

Detectors

To register the image focused by the optics, NuSTAR requires high-energy X-ray detectors capable of measuring the position and energy of the incoming X-rays. In this case, the detectors are called focal-plane detectors because they reside where light from the telescope is focused. The detectors electronically register each X-ray interaction, building up an image over time. Similar to the digital detectors used in cell-phone cameras, these detectors are made of a crystalline material divided up into pixels, which absorb X-rays and in the process create an electronic signal. The challenge in making the NuSTAR detectors was to find a material dense enough and with the right properties to block penetrating high-energy X-rays. Further, very sensitive electronics had to be custom designed to accurately measure the tiny signals produced by X-ray interactions.

NuSTAR's focal-plane detectors are manufactured from crystals of cadmium-zinc-telluride, a semiconductor material with the ability to stop high-energy X-rays. The detectors are printed with a 32 by 32 pattern of pixels. Each pixel is connected to an input on a low-noise readout chip designed for NuSTAR by the Caltech team. The readout chip measures the X-ray energy to better than one part in 60, which is important for looking for signatures of radioactivity in the remnants of exploded stars. Four of these detectors are placed in a two-by-two array to make up the 64 by 64 pixel focal plane.

The focal plane detectors are shielded by a well of material that is itself a particle and X-ray detector. These shields register high-energy photons and cosmic rays that impact the focal plane from directions other than along the NuSTAR optical axis. Such events are the primary background for NuSTAR and must be properly identified and subtracted to identify high-energy photons from cosmic sources. NuSTAR rejects background X-rays by ignoring any signal from a detector that occurs at the exact same time a background event is recorded on the shield.

The optics and detector technologies were successfully tested on a balloon-borne experiment, called the High Energy Focusing Telescope, in 2005. Fiona Harrison, the principal investigator of NuSTAR, was also the principal investigator of that project. Collaborating institutions were NASA, Caltech, Columbia University, the Danish Technical University and the Lawrence Livermore National Laboratory in Livermore, Calif.

The Mast

Bridging the mirrors and the detectors is a mast, a little over 33 feet (10 meters) long. Because X-rays graze off the mirrors at nearly parallel angles, X-ray telescopes require long focal lengths (the distance between the optics and the detectors, or focal plane). NASA's Chandra X-ray Observatory, which also has a 33-foot (10-meter) focal length, accomplishes this with a large, fixed structure, which required the space shuttle to launch. But NuSTAR is a NASA Small Explorer mission that must launch on a compact, low-cost rocket. The solution is an extendable mast, which is stowed in a canister approximately 3.3-feet (one-meter) tall during launch. About a week after launch, the mast will unfold, driven out by a motor in a process that takes about 25 minutes.

The articulated mast, built by ATK Aerospace Systems, Goleta, Calif., is based on a design used to establish a 197-foot (60-meter) separation between the two antennae of the Shuttle Radar Topography Mission (SRTM), which flew on the Space Shuttle Endeavour in February 2000 and made high-resolution elevation (topographic) maps of most of our planet. The mast is low weight, compact and provides a stiff and stable structure connecting the precisely aligned benches.

After the mast is deployed in space, scientists will check that the optics units and focal plane detectors are properly aligned. An adjustment mechanism is built into the mast, which allows for the alignment of the optics bench to be precisely altered if needed.

Laser Metrology System

Tiny changes in the position of the mast will also occur throughout the mission. The structure is not perfectly rigid and undergoes slight thermal distortions, particularly when going in and out of Earth shadow.

A laser metrology system will measure changes in the relative position of the optics bench and the focal plane via two lasers mounted on the optics bench that are paired with two position-sensitive detectors mounted on the focal plane. A star-tracker device on the optics bench provides additional angular information. These data will be used to correct for the small mast movements during image processing on the ground.

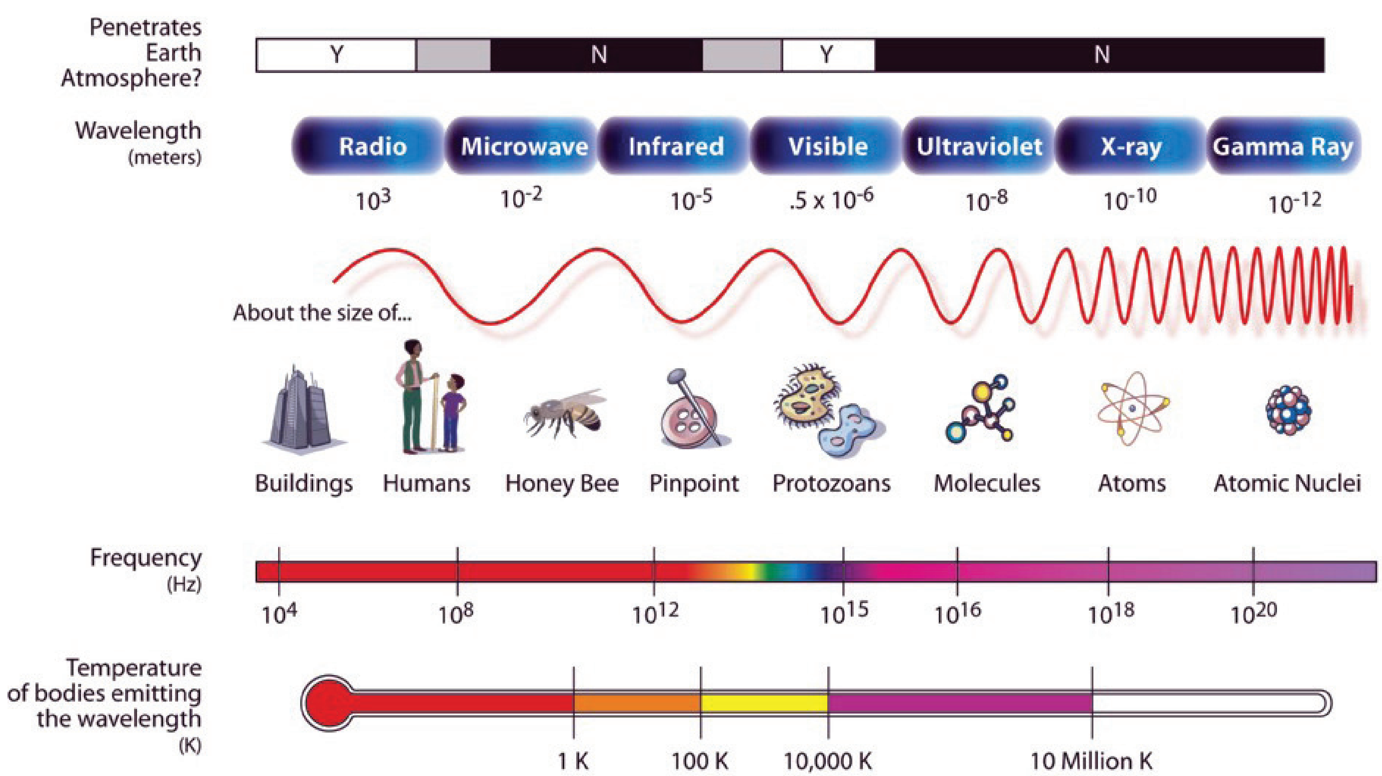
X-Ray Eyes

Doctors use high-energy X-rays to see through your skin and take pictures of your bones, and fictional superheroes like Superman use X-ray vision to see through buildings. High-energy X-rays, which have much shorter wavelengths than visible-light photons, can penetrate certain materials. The same is true in the cosmos. High-energy X-rays can travel through gas and dust, so telescopes with high-energy X-ray eyes can see behind walls of obscuring material.

X-rays cannot, however, penetrate our atmosphere because it is actually quite thick. As a result, X-ray telescopes must operate from space.

What types of objects emit X-rays? The hottest, densest and most energetic objects in the universe glow with X-rays. The hotter the object, the more light it radiates at higher energies. Our bodies, for example, have temperatures of hundreds of kelvins (about 98 degrees Fahrenheit), and glow with lower-energy infrared light we can't see with our eyes. The surface of our sun has a temperature of 6,000 kelvins (approximately 10,000 degrees Fahrenheit) and is glowing predominantly with visible light. Feeding black holes, supernova remnants and other objects with temperatures of millions of kelvins (degrees Fahrenheit) shine with X-rays.

The Electromagnetic Spectrum



Science Overview

NuSTAR will dramatically change the way astronomers view the high-energy X-ray sky. The mission's main objective is to obtain detailed images of regions of the sky at these energies. Despite NuSTAR's small size and low cost, it will have more than 10 times better resolution and more than 100 times better sensitivity than any previous mission working in this high-energy regime.

The five primary science goals for its two-year baseline mission are:

- to locate supermassive black holes;
- to locate the remnants of collapsed stars;
- to map historic supernova remnants;
- to observe high-energy gamma-ray sources; and
- to quickly observe supernovae in the local universe right after they happen, should they occur during the mission's lifetime.

Black Holes

When enough matter is packed into a small region, it inevitably collapses to form a black hole — a tear in the fabric of space-time. The name "black hole" comes from the fact that even light cannot escape the overpowering grasp of the matter's gravity. Black holes formed in the early universe, and by "swallowing" matter, stars and even other black holes, they grew over the course of cosmic time. Smaller black holes are also being created throughout the cosmos as massive stars end their lives. When a massive star explodes, it hurtles matter into space; if the star is massive enough, then its core will collapse into a black hole.

When a black hole "feeds" from matter falling onto it, the matter forms a swirling disk, heats up to very high temperatures and then disappears from view forever. The hot matter reaches up to hundreds of millions of degrees in temperature and radiates copious amounts of X-rays.

NuSTAR will search for these telltale X-rays streaming from regions close to the invisible black holes. It will observe known black holes, and discover new ones, of many sizes. The smallest the observatory can see are peppered throughout our Milky Way galaxy, and have masses as low as a few times that of our sun. The largest black holes are formed at the centers of galaxies, and can have masses up to millions or billions of times the mass of our sun. NuSTAR will also observe a poorly understood class of objects known as "ultraluminous X-ray sources," some of which are considered likely intermediate-mass black holes, with masses a few thousand times that of our sun.

In our galaxy, the mission will probe the crowded center, where unseen black holes are lurking. High-energy X-rays can penetrate deeper through gas and dust than lower-energy X-rays, so NuSTAR will find new, hidden stellar relics. Working in coordination with a vast network of other facilities, including NASA's Chandra X-ray Observatory, NuSTAR will also peer into the "monster in the middle" of our galaxy, a sleeping supermassive black hole about four million times the mass of our sun, and address questions about its mysterious behavior.

In the distant universe, the mission will spend months hunting for hidden black holes buried in the hearts of dusty galaxies. All galaxies are thought to harbor supermassive black holes at their cores. Most of these, like our Milky Way black hole, are dim at all wavelengths of light. They are sometimes thought of as "sleeping" and are undetectable in even nearby galaxies. However, some fraction of black holes, the so-called active ones, swallow dust and gas and shine brightly. Of these active black holes, about two-thirds are thought to have gone undetected due to obscuring layers of dust. NuSTAR will uncover many of these hidden objects, providing a complete census of active black holes.

NuSTAR data will be used together with that from other telescopes studying different wavelengths, such as NASA's Hubble Space Telescope (visible light); NASA's Spitzer Space Telescope (infrared), Chandra and XMM-Newton (both low-energy X-rays). Some NuSTAR observing programs will simply use existing, archival data from these other observatories, while other programs will require coordinated scheduling. For example, working with XMM-Newton, NuSTAR is planning to spend several weeks doing coordinated observations of powerful, active galaxies with the goal of making precise measurements of the rate with which their central supermassive black holes are spinning. Such measurements are not possible by either telescope individually, but by working together, NuSTAR and XMM-Newton will inform astronomers about the physical conditions near the galaxy's central engine, as well as probe how supermassive black holes form.

Surveys of well-studied fields in the sky by NuSTAR will also help solve the enigma of how black holes and galaxies grow and evolve together.

Stellar Corpses

Black holes are the end state of the most massive stars in the universe. Other less massive stars leave behind different types of stellar remnants when they die. For example, stars that aren't quite big enough to produce black holes, but are still massive enough to explode, result in neutron stars. These are incredibly dense objects. If the sun were a neutron star, its matter would be squeezed into something the size of Pasadena. When neutron stars form, collapsing in supernova blasts, their atoms are crushed, forcing the electrons and protons together, and leaving mainly neutrons.

When even less massive stars die, such as our sun, they don't fully explode. Instead they puff up into red giants, and then shed their outer layers. The cores of these stars also collapse into compact objects, called white dwarfs.

NuSTAR will search for all of these stellar embers, primarily in the center of our galaxy, as well as examine known ones. When these embers are in binary star systems, they can accrete material from their partners. As this material falls onto the dense core, it heats up, radiating high-energy X-rays. The observatory will give astronomers a new tool to study our galaxy's stellar graveyard, revealing how the remains are distributed.

The mission will look at other types of exotic, dead stars too. One class of neutron star, called magnetars, have the most intense internal magnetic fields known in the universe, quadrillions of times greater than Earth's. As the magnetic fields decay, powerful bursts are triggered lasting milliseconds to years. NuSTAR will provide new insight into these mysterious, poorly understood objects.

NuSTAR will also probe pulsars, another class of neutron star that send out beams of radiation as they rotate around like a lighthouse beacon. These objects produce powerful winds carrying particles at nearly the speed of light. When the winds hit surrounding material, they heat it up, forming unusual nebulae. NuSTAR will help understand the physics of this dramatic process.

How Do Stars Explode?

Another one of the mission's goals is to understand how the elements all around us, including the chemicals making up our bodies, were forged inside stars. When the most massive stars explode as supernovae, they synthesize and disseminate a range of elements, including the heaviest ones, such as iron. Without supernovae, there would be no iron circulating around in your blood, nor gold for making jewelry. The heavier elements are also needed to seed new generations of stars.

NuSTAR will offer a new way to examine this cycle of life, death and rebirth in the universe. It will thoroughly study two well-known supernova remnants: Cassiopeia A in our galaxy, and SN 1987A in a small neighboring galaxy. Astronomers using NuSTAR will be able to sift through the remains of these exploded stars by measuring the amount, distribution and speed of radioactive material released by the explosion. In particular, the isotope Titanium 44 (^{44}Ti) is a critical diagnostic of supernova explosions, since it comes from near the "fallback region" of the explosion. Some models predict ^{44}Ti is ejected into the cosmos as part of the colossal explosion. Other models predict that ^{44}Ti fails to reach sufficient speeds to escape, and instead falls back on to the stellar corpse leftover from the blast. NuSTAR observations of historic, nearby supernovae will test these models.

Despite being well studied, exactly how a supernova explosion occurs is still unknown. NuSTAR will help reveal the physics behind the moment when a massive star erupts, lighting up the cosmos like fireworks. Such information is fundamental for understanding how the elements are forged and distributed by these massive explosions.

Energy Extremes

A small fraction of the most exotic supermassive black holes exhibit extreme behavior — spewing out jets of material moving very close to the speed of light. These jets can be so powerful that they choke off the creation of stars, leading to the death of the surrounding galaxy. The processes that create these jets, and which accelerate the high-energy particles within them, are not understood. By teaming up with observatories that see in various bands, from radio to high-energy gamma-rays, NuSTAR will help unravel the exotic physics underlying these extreme black holes.

Witnessing a Star's Death Throes

Another goal of NuSTAR is to witness a supernova as it unfolds. This would only be possible if such an event occurs during the mission's lifetime, and at close enough distances for the observatory to see it. A supernova resulting from the death of a massive star is estimated to occur once every 30 years or so in our galaxy. About every five years, a much more luminous type of supernova, believed to result from the violent detonation of a white dwarf star, occurs in the space between our galaxy and the nearest cluster of galaxies, called the Virgo cluster. The 2011 Nobel Prize in Physics was awarded to a team of astronomers who used this second type of explosion to map the expansion history of the universe. Their work provided conclusive evidence that the expansion rate of the universe is increasing, implying the existence of a mysterious force dubbed "dark energy." NuSTAR observations can shed light on how this detonation happens. Such observations, called targets of opportunity, will be the highest priority for the observatory when they occur.

Other Science

NuSTAR will also observe flaring stars, star-forming galaxies, distant clusters of galaxies and more. Closer to home, it will measure X-rays coming from our sun's corona — an outer atmosphere consisting of scorching hot gases. The observatory will be much more sensitive to solar X-rays than the previous X-ray mission studying the sun, NASA's Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), and will provide detailed images of flares, loops and other eruptions from the sun's surface. NuSTAR has the ability to reveal tiny flares on the sun, called "nanoflares," if they exist, and answer the long-standing mystery of how the solar corona is heated.

As is typical of most NASA Small Explorer missions, during its two-year baseline mission, NuSTAR will not have a Guest Observer program in which members of the larger astronomy community can apply for time on the telescope. However, assuming the continued health of the NuSTAR observatory, the mission team will propose for an extended mission, during which guest investigators can participate in the NuSTAR science.

Key NuSTAR Team Members

Name	Title	Institution
Fiona Harrison	Principal Investigator	California Institute of Technology
Yunjin Kim	Project Manager	Jet Propulsion Laboratory
Grace Baird	Spacecraft Bus Chief Engineer	Orbital Sciences Corporation
Manfred Bester	Mission Operations Manager	Space Sciences Laboratory
Steven Boggs	Co-Investigator	UC Berkeley
Finn Christensen	Optics Coatings Lead	Danish Technical University
Whitney Clavin	Media Relations	Jet Propulsion Laboratory
William Craig	Instrument Manager	Livermore National Laboratory
Lynn Cominsky	Education and Outreach Lead	Sonoma State University
Karl Forster	Science Operations Center Manager	California Institute of Technology
Charles Hailey	Optics Lead	Columbia University
Vicky Kaspi	Galactic Science Team Lead	McGill University
David Oberg	Spacecraft Bus Program Manager	Orbital Sciences Corporation
Daniel Stern	Project Scientist	Jet Propulsion Laboratory
Jason Willis	Project Systems Engineer	Jet Propulsion Laboratory
William Zhang	Goddard Optics Lead	Goddard Space Flight Center

The science team includes researchers from more than 20 additional institutions world-wide, including Durham University and Stanford University/ KIPAC.

X-ray Missions: Past and Present

NuSTAR continues a strong tradition, dating back 60 years, of X-ray astronomy from space. Starting in the late 1950s, early experiments were performed on short-duration rocket payloads. The first orbiting X-ray satellite was Uhuru, launched in December 1970, and the first fully imaging X-ray satellite was the Einstein Observatory, also known as HEAO-2, launched in November 1978. This work led Riccardo Giacconi, an Italian-American astrophysicist, to win the Nobel Prize in Physics in 2002 for "for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources."

Why do we need another X-ray satellite? NuSTAR, for the first time, brings the telescope technologies employed by Einstein and its successors for low-energy X-rays into the higher-energy X-ray band. This radical shift in technology provides NuSTAR with vast improvements in both resolution and sensitivity. NuSTAR will be a pathfinder, opening a new window on the high-energy X-ray universe.

Several X-ray missions currently in operation or nearing launch are described below.

- NASA's Chandra X-ray Observatory is the third of NASA's family of four Great Observatories, a group that includes the Hubble Space Telescope, the Spitzer Space Telescope, and the Compton Gamma-Ray Observatory. Chandra, which launched from the Space Shuttle Columbia in July 1999, works in the low-energy X-ray regime (0.1 to 10 kilo electron volts or keV). NuSTAR extends similar grazing-incidence X-ray technology employed by Chandra to higher energies. NuSTAR has several approved observing programs planned in coordination with Chandra, including monitoring of the supermassive black hole that resides at the center of the Milky Way galaxy.

- XMM-Newton (European Space Agency), also known as the X-ray Multi-mirror Mission, is Europe's flagship counterpart to Chandra. XMM-Newton, which launched in December 1999, also employs grazing-incidence X-ray optics in the low-energy X-ray regime (0.1 to 15 keV). NuSTAR has several approved programs planned in coordination with XMM-Newton, including observations of extremely luminous supermassive black holes, which will measure the rate at which the black holes are spinning. Working together, NuSTAR and XMM-Newton will make significantly more precise measurements than possible by either facility individually.

- INTEGRAL (European Space Agency), the INTErnational Gamma-Ray Astrophysics Laboratory, launched in October 2002. This telescope contains a suite of instruments designed to study the high-energy sky, both with X-rays and with even higher-energy gamma-rays. The instrument that has the most overlap with NuSTAR, called the Imager on-Board the INTEGRAL Satellite or IBIS, observes large swaths of the sky from 15 keV to 10 mega electron volts (MeV). Unlike IBIS, NuSTAR will focus the X-ray light, giving it better resolution and sensitivity for observing smaller patches of sky.

- NASA's Swift Gamma-Ray Burst Mission launched in November 2004 as part of NASA's Medium Explorer program. Swift's primary science objective is to study "gamma-ray bursts," employing three science instruments for rapid follow-up of these tremendous cosmic explosions at ultraviolet, optical and X-ray energies. The Burst Alert Telescope (BAT) instrument monitors 25 percent of the sky instantaneously at a time in the high-energy X-ray band (15 to 150 keV), looking for new, extremely energetic events. This instrument is designed to see large portions of the sky at low resolution. It signals the telescope to autonomously slew to the cosmic events, and follow-up with its other instruments in more detail, including a lower-energy X-ray instrument. This information is then automatically conveyed to the science community who then deploy ground-based facilities to study and understand the cosmic explosions before they fade away. NuSTAR will work in a similar energy band to Swift's BAT instrument, but focuses the X-ray light, giving it much improved resolution and sensitivity.

  The NuSTAR team plans several observations in coordination with Swift, including a survey of bright galaxies radiating high-energy X-rays and gamma-rays. The telescopes will complement each other, improving our understanding of the physics and demographics of supermassive black holes. Because the high-energy emission from these galaxies varies, simultaneous coverage is essential, requiring careful coordination between the science and mission operation teams.

- Suzaku (Japan), formerly Astro-E2, was launched in July 2005, replacing the Astro-E mission that was unfortunately lost during launch in February 2000. Suzaku includes focusing, grazing-incidence optics that work in the low-energy X-ray regime (0.2 to 12 keV), as well as non-focusing X-ray technologies that work at higher energies (10 to 600 keV). This broad energy capability complements NuSTAR. There are plans for several joint calibration and science campaigns between NuSTAR and Suzaku.

- NASA's Fermi Gamma-Ray Space Telescope, launched in June 2008, is a joint venture primarily between NASA and the United States Department of Energy. Fermi works at higher energies than NuSTAR, reaching the MeV and GeV range, and scans the sky about 16 times a day for the variable objects that dominate the cosmos at these extreme energies, such as supermassive black holes with jets pointing toward Earth. One of the key NuSTAR science objectives is to coordinate observations with Fermi, studying the jets spewing from black holes at close to the speed of light. Such observations, which will be done in coordination with ground-based facilities working in the radio, optical, infrared and tera electron volt (TeV) gamma-ray regime, will help astrophysicists understand the physics of particle acceleration in these extreme sources.

- Astro-H (Japan, with important NASA participation), JAXA's successor X-ray mission to Suzaku, also known as the New X-ray Telescope (NeXT), is planned for launch in 2014. Astro-H has several instruments, including a low-energy X-ray calorimeter spectrometer and the second focusing high-energy X-ray optics after NuSTAR's. Astro-H can perform low- and high-energy X-ray observations simultaneously; NuSTAR is able to perform similar science by working in coordination with Chandra, Suzaku, Swift, and/or XMM-Newton. The Astro-H high-energy imager works in a similar energy band as NuSTAR (5 to 80 keV) with a similar effective area. Astro-H expects to have typical angular resolution of 60 to 90 arcseconds (half-power diameter), slightly poorer than the current best estimate of 50 arcsecond performance expected for NuSTAR.

NASA's Explorer Program

NuSTAR was developed as a Small Explorer mission under NASA's Explorer Program.

The Explorer Program is the oldest continuous program within NASA. It has launched more than 90 missions, beginning with the Explorer 1 launch in 1958 and including the Nobel Prize-winning Cosmic Background Explorer (COBE) mission. The early Explorer missions were managed by JPL for the U.S. Army.

The objective of the Explorer Program is to provide frequent flight opportunities for world-class scientific investigations from space. Explorer missions are focused science missions led by a principal investigator with prescribed baseline mission lifetimes of typically three years in duration or less. They are selected via a highly competitive announcement of opportunity process. The program currently administers only principal investigator–led heliophysics and astrophysics science investigations; in the past, it covered more fields of science.

The Explorer Program seeks to enhance public awareness of and appreciation for space science and to incorporate educational and public outreach activities as integral parts of space science investigations.

Individual Explorer missions are independent, but share a common funding and NASA oversight management structure. The program is designed to accomplish high-quality scientific investigations using innovative, streamlined and efficient management approaches. It seeks to contain mission cost through commitment to, and control of, design, development and operations costs.

The Explorer Program is part of NASA's Science Mission Directorate. The Explorer Program Office is hosted at NASA's Goddard Space Flight Center in Greenbelt, Md.

Operating Explorer Missions

Mission name	Launch date
Advanced Composition Explorer (ACE)	August 25, 1997
Transition Region and Coronal Explorer (TRACE)	April 1, 1998
Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)	February 5, 2002
INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL)	October 17, 2002
Swift	November 20, 2004
Suzaku	July 10, 2005
Two Wide Angle Imaging Neutral-Atom Spectrometers (TWINS)	A) June 2006: B) March 2008
Time History of Events and Macroscale Interactions during Substorms (THEMIS)	February 17, 2007
Aeronomy of Ice in the Mesosphere (AIM)	April 25, 2007
Coupled Ion-Neutral Dynamics Investigations (CINDI)	April 16, 2008
Interstellar Boundary Explorer (IBEX)	October 19, 2008

Explorer Missions in Development

Mission name	Official launch date
Infrared Imaging Surveyor Mission (IRIS)	December 2012
ASTRO-H	February 2014

Program/Project Management

The NuSTAR mission is managed for NASA's Science Mission Directorate, Washington, by NASA's Jet Propulsion Laboratory, Pasadena, Calif.

At NASA Headquarters, John Grunsfeld is the associate administrator for the Science Mission Directorate. Chuck Gay is deputy associate administrator for the Science Mission Directorate. Paul Hertz is director of NASA's Astrophysics division. Mark Sistilli is the NuSTAR program executive. Lou Kaluzienski is the NuSTAR program scientist. At NASA's Goddard Space Flight Center in Maryland, Tom Venator is the NuSTAR mission manager and William Zhang is the NuSTAR mission scientist.

The mission's principal investigator, Fiona Harrison, is at the California Institute of Technology in Pasadena.

At JPL, Yunjin Kim is the project manager, and Daniel Stern is the project scientist. Caltech manages JPL for NASA.

NASA's Launch Services Program (LSP) at Kennedy Space Center in Florida is responsible for government oversight of launch vehicle preparations at Vandenberg Air Force Base, spacecraft ground support and NuSTAR integration with the Pegasus XL rocket. On launch day, LSP is responsible for countdown management and the tracking, data acquisition and telemetry support required for the launch.