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NASA's *NuSTAR* Mission Brings the High-Energy Universe into Focus

by Lynn R. Cominsky (Sonoma State University)

NASA's newest "eye on the skies," the *Nuclear Spectroscopic Telescope Array*, or *NuSTAR*, was launched into low-Earth orbit on June 13, 2012. Its scientific targets are among the most extreme in the Universe, ranging from distant galaxies with super-massive black holes in their cores to city-sized, rapidly rotating neutron stars, to the heated debris created in supernova explosions. Although many objects of these types have been studied at lower energies (0.1-10 thousand electron volts, or keV) by NASA's *Chandra X-ray Observatory* (launched in July 1999), *NuSTAR* is the first focusing X-ray satellite to view the Universe at energies above 10 keV, and its energy range extends to 79 keV. (For comparison, the energy of a visible-light photon is about 2 eV.) Although there have been other X-ray experiments in orbit that operated at similar energies, *NuSTAR*'s ability to focus produces images that are much crisper and also greatly improves sensitivity compared to previous missions.

NuSTAR's Principal Investigator is Caltech Professor Fiona Harrison, and the mission is led by Caltech, managed by JPL, and implemented by an international team of scientists and engineers. Figure 1 shows an artist's conception of *NuSTAR* in orbit.

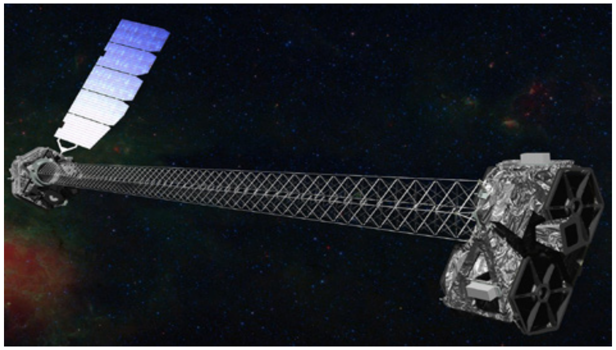

Figure 1: Artist's conception of *NuSTAR* in orbit. The two telescopes are on the lower right, and the detectors are at the far left (near the solar panel). In between is a 10-m long mast, which was deployed after *NuSTAR* reached orbit, ~620 km above the Earth. Image: NASA/JPL-Caltech

What's in a Name?

In order to understand what *NuSTAR* does, it is helpful to understand its full name: *Nuclear Spectroscopic Telescope Array*. As can be seen in Figure 1, *NuSTAR* includes two focusing X-ray telescopes, hence "Telescope Array." As well as making focused X-ray images, *NuSTAR*'s scientific capabilities also include the ability to measure the energy of each incoming X-ray, hence "Spectroscopic." And many of the X-rays that *NuSTAR* will study are emitted from nuclear lines from chemical elements that are created in supernova explosions or from the nuclei of active galaxies — hence a dual meaning for the word "Nuclear." Active galaxies are a major target for *NuSTAR*, which is studying X-rays emitted from matter falling into the supermassive black holes at galactic centers. In about two-thirds of these galaxies, the nuclei are enshrouded in large amounts of dust and gas. Lower-energy X-rays emitted by these objects are absorbed by the dust and gas, but higher-energy X-rays can pass through and be detected by *NuSTAR*. *NuSTAR* will uncover many of these hidden objects, providing a complete census of active black holes.

In Earth-bound laboratories, most emission and absorption lines that are created and detected are due to the transitions of electrons orbiting nuclei. These atomic transition lines define the world of chemistry and studying the light emitted or absorbed as electrons undergo these transitions is known as "atomic spectroscopy." At higher energies, such as are often observed by space-based X-ray instrumentation, photon lines can be emitted by the nuclei themselves, when excited and unstable nuclei decay. This is the domain of "nuclear spectroscopy" — a prime area of study for *NuSTAR*. For example, *NuSTAR* will study several young supernova remnants in (68 and 78 keV) lines emitted by ^{44}Ti (an isotope of titanium with atomic weight 44), measuring the amount of this element that was produced, and comparing the measurements to models for different supernova mechanisms. Figure 2 shows *NuSTAR*'s image of the relatively young Cassiopeia A supernova remnant, from which ^{44}Ti emission has been detected.

Figure 2: This is *NuSTAR*'s view of the historical supernova remnant Cassiopeia A, located 11,000 light-years away. Blue indicates the highest energy X-ray light, where *NuSTAR* has made the first resolved image ever of this source. Red and green show the lower end of *NuSTAR*'s energy range, which overlaps with NASA's high-resolution Chandra X-ray Observatory.
Image: NASA/JPL-Caltech/DSS

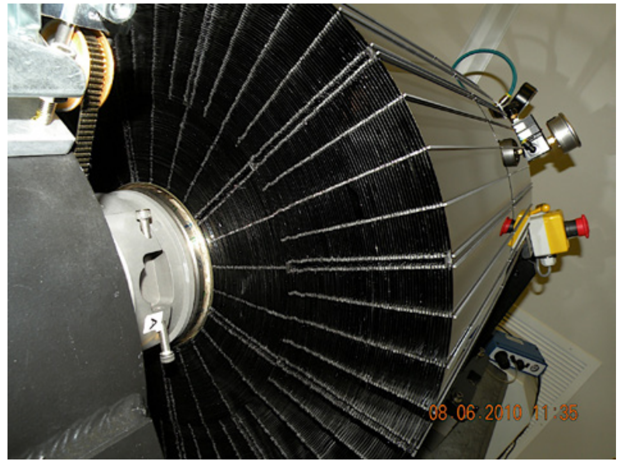

Figure 3: A portion of one of *NuSTAR*'s telescopes. Looking closely, one can see the 133 nested mirrors forming concentric circles, and portions of many different axial segments. The glass in the outer 44 mirrors is coated with ~200 alternating layers of tungsten and silicon, while the inner layers are coated with multi-layers of platinum and carbon.
Image: NASA/Columbia University/Todd Decker

How does *NuSTAR* focus X-rays?

It isn't easy to focus X-rays. Unlike visible light, X-rays are only efficiently reflected at very small angles. In order to focus the higher-energy X-rays that *NuSTAR* detects, several new technologies had to be developed. The *NuSTAR* telescopes do not resemble visible-light telescopes — for example, each telescope consists of 133 mirrors, nested like Russian dolls. Each of the mirrors is made of either 12 or 16 glass segments, coated with alternating layers of high- and low-density elements. Figure 3 shows a close view of part of one of the *NuSTAR* telescopes.

These "multi-layers" extend the energy range that the optics reflect. To achieve focus at a point 10 meters distant, the X-rays bounce twice from surfaces that are approximately conical. This type of telescope is similar to the "Wolter-1" configuration used in NASA's Chandra Observatory. The grazing incidence optics focusing scheme is illustrated in Figure 4 below.

How does *NuSTAR* Detect X-rays?

Also critical for *NuSTAR* was the technological development of special solid-state detectors that reside on the focal plane. Since high-energy X-rays fly through most materials without depositing much of their energy, detectors had to be developed that would capture the X-rays, revealing both their energy and their position. *NuSTAR*'s detectors are made of a 2 x 2 array of solid-state chips comprised of cadmium, zinc and tellurium (CdZnTe). Each chip has 32 x 32 individual pixels that are read out independently, providing energy and position information as often as once every 2.5 milliseconds. The detectors are surrounded by an "anti-coincidence" shield made of cesium-iodide (CsI) crystals, which emit signals when hit by high-energy photons coming from a direction that is not along the

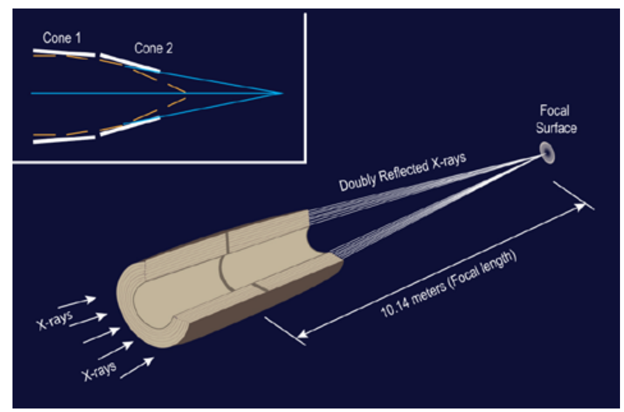

Figure 4: *NuSTAR*'s focus is achieved by reflecting the x-rays at very shallow angles from two mirror surfaces that are approximately conical in shape. The focal surface is located at a distance of 10.14 m from the X-ray optics.
Image: NASA/*NuSTAR*/Sonoma State/A. Simonnet

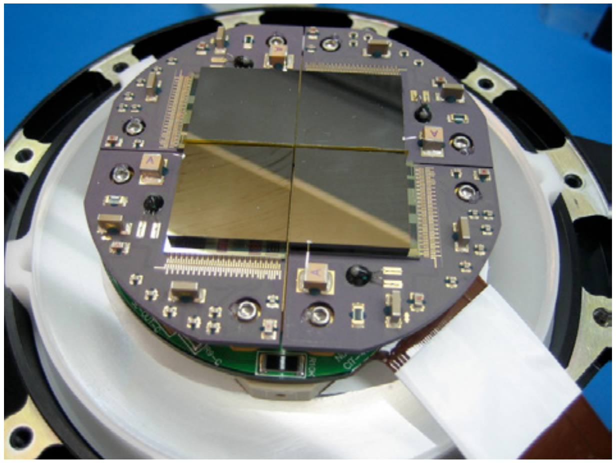

Figure 5: One of the flight detectors for *NuSTAR*, showing the 2 x 2 array of CdZnTe detectors and supporting electronics. Each detector has 32 x 32 pixels, and each pixel subtends a region of 12 arc seconds on the sky. The full array images a field approximately 12 arcmin by 12 arcmin, or slightly less than a quarter the size of the full moon. Image: NASA/JPL-Caltech

optical axis or by charged particles. Any event that triggers both the shield and the detectors is rejected as background by on-board computers. Figure 5 shows one of the *NuSTAR* focal plane detectors.

The *NuSTAR* Launch

NuSTAR is a Small Explorer mission, and is therefore relatively inexpensive (less than ~10% of the cost compared to Great Observatories like *Chandra* and *Hubble*). In order to stay within the budget allocated, *NuSTAR* had to launch on a compact rocket, and therefore could not be launched in the extended (on-orbit) configuration shown in Figure 1. Instead, *NuSTAR* was folded up inside the nose cone of a Pegasus XL launch vehicle, built by Orbital Sciences Corporation. The Pegasus, in turn, was carried off the ground to an altitude of ~40,000 feet by the "Stargazer" L-1011 airplane, taking off from the Kwajalein Atoll in the Marshall Islands.

Once in orbit, *NuSTAR* unfolded its extendible mast to separate the optics and the detectors so that focus could be achieved. Figure 6 shows the stowed configuration of *NuSTAR* as it was when placed in the nose cone of the Pegasus for launch.

What is *NuSTAR* seeing?

The baseline science program for *NuSTAR* lasts

Figure 6: *NuSTAR* in its "stowed" configuration prior to launch. *NuSTAR*'s height in this configuration is 1.93 m. After launch, the mast extended so that *NuSTAR* appears as shown in Figure 1 (page 1). Image: NASA/JPL-Caltech/Orbital Sciences Corp.

for 25 months, encompassing five main scientific objectives:

1. studying selected regions of the sky to uncover super-massive black holes lurking in the cores of distant galaxies (also known as "Active Galactic Nuclei" or AGN). *NuSTAR* is especially interested in targeting those AGN which are shrouded in gas and dust, rendering them difficult to observe with lower-energy X-rays;
2. mapping the central regions of the Milky Way to study the population of X-ray emitting neutron stars and black holes;
3. studying X-rays from young supernova remnants, including their ^{44}Ti emission;
4. contributing to multi-wavelength campaigns observing jets emitted from AGN; and
5. observing X-rays from supernovae in the Local Group and from a specific type of supernova (Type Ia) used in cosmological measurements

Studying Black Holes

Figure 7 (page 4) shows *NuSTAR*'s view of IC 342, a beautiful nearby spiral galaxy. The two magenta spots are blazing black holes first detected at lower-energy X-ray wavelengths by NASA's *Chandra X-ray Observatory*. With *NuSTAR*'s higher-energy X-ray data, astronomers can try to figure out why these black holes are so bright — at least 10 times as bright as the stellar-mass black holes that are usually found in the outskirts of galaxies. (Our own Galaxy has at least 20 well-studied stellar-mass black holes, detected due to their presence in binary systems with normal stellar companions.) The two black holes in IC 342 cannot be supermassive black holes or they would have sunk to the galaxy's center. Instead, they may be intermediate in mass, or there

Figure 7: This new view of spiral galaxy IC 342, also known as Caldwell 5, includes *NuSTAR* data, which are shown in the color magenta, superimposed on a visible-light view highlighting the galaxy and its star-studded arms. Image: NASA/JPL-Caltech/DSS

may be something else going on to explain their extremely energetic state. *NuSTAR* will help solve this puzzle by studying the energy of the X-rays emitted by matter falling onto the black holes to understand how they can radiate so brilliantly.

Closer to home, *NuSTAR* has also viewed Sagittarius A* (Sgr A*), the 4-million solar mass black hole at the center of our own Milky Way Galaxy. During observations in July 2012, *NuSTAR* was lucky enough to catch the black hole emitting an X-ray flare, the signature of a clump of dust and/or gas falling into the black hole. These are the first, focused high-energy X-ray views of the area surrounding Sgr A*, which is hidden behind large quantities of dust and gas. Compared to giant black holes at the centers of other galaxies, Sgr A* is relatively quiet. Active black holes tend to gobble up stars and other fuel around them and often emit jets of fast-moving material and high-energy light. Sgr A*, however, does not seem to eat very much, and has no strong jets of emission. Studying a wide spectrum of light from Sgr A* will help astronomers learn more about its peculiar eating habits. Figure 8 shows *NuSTAR*'s image of Sgr A* including images taken before, during and after the flare.

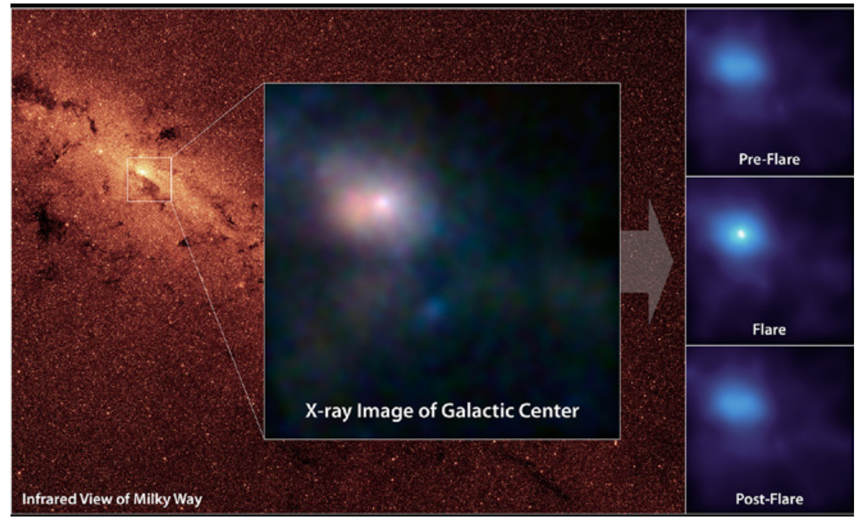

Figure 8: In the main image, the brightest white dot is the hottest material located closest to the black hole, and the surrounding pinkish blob is hot gas, likely belonging to a nearby supernova remnant. The time series at right shows a flare caught by *NuSTAR* over an observing period of two days in July; the middle panel shows the peak of the flare, when the black hole was consuming and heating matter to temperatures up to 180 million degrees Fahrenheit (100 million degrees Celsius). The main image is composed of light seen at four different X-ray energies. Blue light represents energies of 10 to 30 kiloelectron volts (keV); green is 7 to 10 keV; and red is 3 to 7 keV. The time series shows light with energies of 3 to 30 keV. Image: NASA/JPL-Caltech

Activity: Make Your Own Pulsing Neutron Star

Not quite as massive as black holes, neutron stars are another type of highly energetic object being studied by *NuSTAR*. Formed by the collapse of the core of a star during a supernova explosion, neutron stars have typical masses between 1.4 and 3.2 times the mass of our Sun. With radii of only about 10 km, a teaspoon full of neutron star "stuff" would weigh as much as Mt. Everest (about 100 million tons)! Neutron stars also have extremely strong magnetic fields, reaching strengths as much as 10^{15} (one thousand trillion) times that of Earth. These powerful magnetic fields channel beams of fast-moving particles and highly energetic light away from the neutron stars, along an axis that is not aligned with the star's spin-axis. When the jets rotate through our line-of-sight, we see a pulse of light; hence these systems are often seen as "pulsars." (The word pulsar was originally coined to mean to "pulsating radio source", but pulsations have since been detected from many neutron stars at other wavelengths ranging up to gamma rays.) In this activity, you will build a model of a pulsar, and your students can learn a bit about electronics as well.

Materials: For each pulsar, you will need:

- 2 light emitting diodes (LEDs)
- 1 flat, round watch battery (CR-232 or similar)
- Cellophane or masking tape
- Model Magic, Play-Doh or modeling clay
- String or a toothpick

Procedure: First, demonstrate the phenomenon of pulsing by holding a flashlight at an angle to your

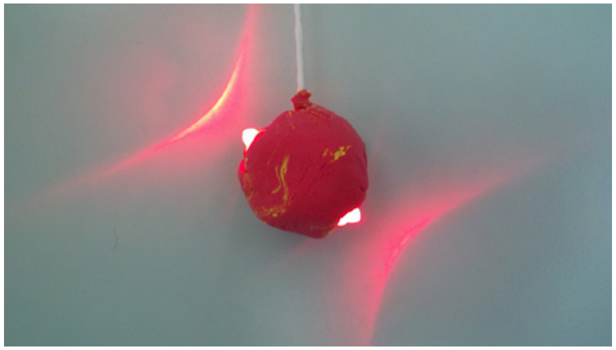

Figure 9: A model pulsar made with 2 red LEDs, a CR-232 battery, Model Magic and string. Image: NASA/Sonoma State

body and spinning around. The student activity can be done alone or in pairs. Distribute the materials to each group or individual. Tell them that their goal is to use the materials in order to make a pulsar that can be spun around in order to see the flashes of light as it goes by just like they saw the flashlight beam when you spun around.

Encourage your students to experiment with the materials you have provided to build a pulsar. A good first step is to try to light one of the LEDs with the battery. It may take them a while to discover that the LED will only light with its leads connected to the battery in one specific orientation. Once they have managed to light both lights, it may be helpful to tape the LEDs onto the battery before covering it with a ball of the modeling material. A string or toothpick can be inserted into the modeling material so that the finished model can be spun around to produce pulses. See Figure 9 for a typical pulsar model.

Additional Resources

NASA's Portal Web Site for *NuSTAR*:
http://www.nasa.gov/nustar

Caltech's *NuSTAR* mission web site:
http://www.nustar.caltech.edu

Watch a recent video featuring PI Fiona Harrison discussing *NuSTAR* on PBS:
http://science.kqed.org/quest/video/black-holes-objects-of-attraction/

For more details of the *NuSTAR* launch, see:
http://www.nasa.gov/mission_pages/nustar/launch/

For an animated video showing the extension of the *NuSTAR* mast on orbit, see "*NuSTAR* in Space":
http://www.nustar.caltech.edu/multimedia-gallery/videos

The Make Your Own Pulsar Activity is part of the Supernova Education Unit:
http://xmm.sonoma.edu/edu/supernova/snguide5.pdf

Links to additional educational material related to *NuSTAR*:
http://www.nustar.caltech.edu/education-outreach/for-teachers

Other High Energy Astrophysics Resources for Teachers

Harvard-Smithsonian Center for Astrophysics education page
http://www.cfa.harvard.edu/hea/epo.html

NASA High Energy Astrophysics Science Archive Research Center (HEASARC): Education and Public Outreach page
http://heasarc.gsfc.nasa.gov/docs/outreach.html

Fermi Gamma-ray Space Telescope Education and Public Outreach
http://fermi.sonoma.edu/

Chandra X-Ray Observatory education page
http://chandra.harvard.edu/edu/

Swift Mission Education and Public Outreach
http://swift.sonoma.edu/

NASA's Imagine the Universe!
http://imagine.gsfc.nasa.gov