NuSTAR: Unveiling the High-Energy Universe

Purbadri Ray Chaudhuri
Department of Applied Electronics and Instrumentation, Heritage Institute of Technology, Kolkata, India.
(e-mail: prc0695@gmail.com)

***Abstract*—The Nuclear Spectroscopic Telescope Array (NuSTAR) represents a monumental leap in our quest to understand the high-energy universe. Launched in 2012, this groundbreaking space observatory captures X-rays from cosmic sources at energies ranging from 3 to 79 keV, a range previously unexplored with such clarity. By using advanced focusing optics like grazing incidence optics and innovative detectors, NuSTAR has unveiled the mysteries of some of the most elusive and extreme phenomena in space, from the powerful forces surrounding black holes to the remnants of exploded stars. This paper explores the fascinating science behind NuSTAR's design and its transformative impact on high-evengy astrophysics. Through an in-depth look at its missions and discoveries and achievements, we reflect on how this remarkable telescope had not only expanded our knowledge of the cosmos but also deepened our connection to the mysteries of the universe. Ultimately, NuSTAR's contributions remind us of the beauty and wonders that lie beyond our planet, inviting us to continue exploring the infinite unknown.**

***Index Terms*—Astrophysics, Black holes, Celestial phenomena, Cosmic X-rays, High-energy astronomy, High-energy X-rays, Neutron stars, Nuclear Spectroscopic Telescope Array (NuSTAR), Space exploration, Supernova remnants, Telescope optics**

I. Introduction

The Nuclear Spectroscopic Telescope Array (NuSTAR) is a cutting-edge space-based X-ray observatory designed to explore the most energetic and extreme regions of the universe. Launched by NASA in 2012, NuSTAR is the first telescope capable of focusing high-energy X-rays (3-79 keV), providing unprecedented insights into the physics of black holes, neutron stars, supernova remnants and high-energy cosmic phenomena [6] [1]. Unlike traditional X-ray observatories, which primarily detect lower-energy emissions, NuSTAR's ability to capture hard X-rays allows it to penetrate deep into dense cosmic structures, unveiling hidden astrophysical processes.

Since X-rays, gamma rays and other high-energy electromagnetic waves are absorbed by the earth's atmosphere, they cannot be observed directly from the surface. This atmospheric shielding effectively blocks these wavelengths from reaching ground-based telescopes, making it impossible to study high-energy phenomena such as black holes, neutron stars and supernova remnants from Earth. To overcome this challenge, observatories like NuSTAR are placed above the atomsphere, often in low Earth orbit, where they can observe the universe without interference [8]. By launching telescopes into space, scientists gain access to a pristine, unfiltered view of the cosmos in wavelengths that would otherwise be obscured, allowing for groundbreaking discoveries that deepen out understanding of the high-energy universe.

NuSTAR's contributions span multiple domains of astrophysics. In the realm of black holes, it has provided detailed imaging of both supermassive and stellar-mass black holes, helping refine our understanding of their acceration disks, coronae and relativistic jets. It has also played a crucial role in studying the cosmic X-ray background (CXB), which consists of high-energy radiation from distant active galactive nuclei (AGN) that shape the large-scale structure of the universe [5] [2].

Beyond balck holes, NuSTAR has revolutionized the study of neutron stars and pulsars, uncovering their extreme magnetic fields and exotic states of matter. It has observed supernova remnants, shedding light on the process driving element formation and cosmic ray acceleration. Aditionally, NuSTAR has contributed to high-energy studies of the solar corona, offering insights into the fundamental physics of plasma and magnetic fields in our own star.

Importantly, NuSTAR's capabilities have also extended into cosmology, where it has played a role in searching for dark matter signatures-particularly in detecting potential X-ray emissions from sterile neutrino decay. Though it was not explicitly designed to probe dark energy, its observations of black hole growth, large-scale cosmic structures, and X-ray binaries indirectly contribute to understanding the forces shaping the evolving universe.

This paper explores NuSTAR's scientific impact, focusing on its role in high-energy astrophysics and its contributions to unraveling the mysteries of dark matter and dark energy. By examining its groundbreaking discoveries and ongoing research, we gain a deeper appreciation for how NuSTAR continues to reshape our understanding of the universe.

II. Dark Matter and Dark Energy in the context of NuSTAR

Dark matter and dark energy are two of the most profound mysteries in modern astrophysics, comprising about 95% of the universe's total mass-energy content. While dark matter is thought to provide the gravitational glue that holds galaxies together, dark energy is believed to drive the accelerated expansion of the universe. The NuSTAR focused on indirect dark matter detection and its contributions to understanding cosmic structures influenced by dark energy [4].

dark matter is a hypothetical form of matter that does not emit, absorb or reflect electromagnetic radiation, making it virtually invisible to conventional telescopes. Its presence is inferred from gravitational effects on visible matter, cosmic microwave background anisotropies and large scale cosmic structures.

NuSTAR's primary mission is to study high-energy X-ray sources, including black holes, neutron stars and supernova remnants. However, its capabilities also make it useful for searching for dark matter signatures, particularly in the form of X-ray emissions from sterile neutrino decay. Some of the key contributions of NuSTAR to dark matter research include:

1) Sterile Neutrino Decay: The sterile neutrino, is theorized to decay into an active neutrino and an X-ray photon. NuSTAR has searched for this characteristic X-ray emission from dark matter rich envirnoments such as the Milky Way's galactic center, dwarf spheroidal galaxies and galaxy clusters [9] [4].

2) Dark Matter Annihilation Signals: In addition to decaying particles, some dark matter models propose that weakly interating massive particles (WIMPs) could annihilate into high-energy photons [9]. NuSTAR's observations of the Galactic center and nearby galaxies provide crucial data for testing these models, ruling out or limiting possible dark matter interactions.

3) Mapping the Dark Matter Distribution: While NuSTAR cannot directly image dark matter, its observations of supernova remnants, pulsars and black holes help map out the gravitational influences of dark matter on visible structures. These studies contribute to refining our understanding of dark matter's role in galaxy formation and evolution.

Dark energy is the unknown force responsible for the accelerated expansion of the universe. it was first inferred from supernova observations in the late 1990s, and subsequent studies of microwave background and large-scale galaxy surveys have supported its existence Though NuSTAR is not explicitly designed to study dark energy, its observations contribute indirectly to our understanding of cosmic expansion and the effects of dark energy in several ways:

4) Supermassive Balck Holes and Galaxy Evolution: NuSTAR's ability to detect high-energy X-rays from supermassive black holes (SMBHs) in active galactic nuclei (AGN) helps researchers understand galaxy formation and evolution. Since dark energy influences the large-scale structure of the universe, understanding AGN activity over cosmic time provides insight into how cosmic expansion has shaped the universe's structure.

5) X-ray Binaries and Large-Scale Structure: NuSTAR's studies of X-ray binaries and supernova remnants contribute to modeling the cosmic history of star formation and feedback mechanisms that influence the large-scale structure of the universe. Understanding these processes helps refine cosmological models that include dark energy..

6) High-Energy Cosmic Background: NuSTAR's observations of the cosmic X-ray background (CXB) provide insights into the distribution and evolution of X-ray sources, helping astronomers piece together the history of structure formation in a universe dominated by dark energy [5].

In the case of dark matter and dark energy, NuSTAR's contributions are more indirect, requiring complementary data from missions like the Euclid Telescope and the James Webb Space Telescope to build a comprehesive picture.

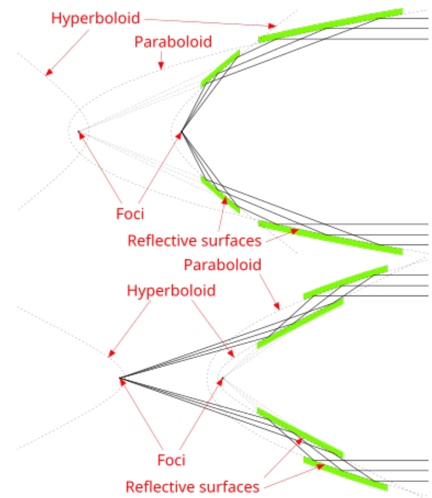

Fig. 1. Wolter telescopes of types I, II

III. Instrumentation & Technology of NuSTAR

X-rays have very short wavelengths (around 0.01 to 10 nanometers), which makes their reflection and focusing very difficult. Tradition optical mirrors, which work by normal incidence (light striking the mirror perpendicularly), fail because X-rays penetrate the material instead of reflecting. This is where grazing incidence optics comes into play. Grazing incidence optics is a technique used to focus X-rays by reflecting them at very shallow angles (a fewer degrees or less) off specially designed mirrors [7]. At normal angles, X-rays would simply pass through the mirror or be absorbed. However, at very shallow angles (typically less than 1°), X-rays can undergo total external reflection, allowing them to be redirected toward a focal point. The mirrors are arranged in a nested configuration (often Wolter Type I or type II optics as shown in Fig. 1) to increase collecting area. X-rays graze the surfaces multiple times, gradually bending toward a common focal point, resulting in a focused X-ray image. NuSTAR uses an enhanced grazing incidence optics approach with multilayer-coated mirrors to reflect and focus high-energy X-rays [7]. NuSTAR employs Wolter Type I optics, where X-rays undergo two successive reflections (paraboloidal and hyperboloidal surfaces) before reaching the detector. Traditional X-ray telescopes (like Chandra and XMM-Newton) use single-layer metallic coatings (e.g. gold or iridium) that reflect soft X-rays efficiently but fail for hard X-rays (>10keV). NuSTAR's multilayer coating consisting of alternating layers of high and low density materials (e.g. Tungsten/Carbon or Platinum/Silicon) increase reflectivity at higher energies. These coatings create constructive interference, allowing hard X-rays to be reflected efficiently [3]. Hard X-rays are harder to bend and requires a longer focal length. NuSTAR has a 10 meter deployable mast to separate the mirrors from the detector, improving focusing capability as shown in Fig. 2. Specialized X-ray detectors are used to capture, process and analyse X-ray photons. Unlike charge-coupled device detectors

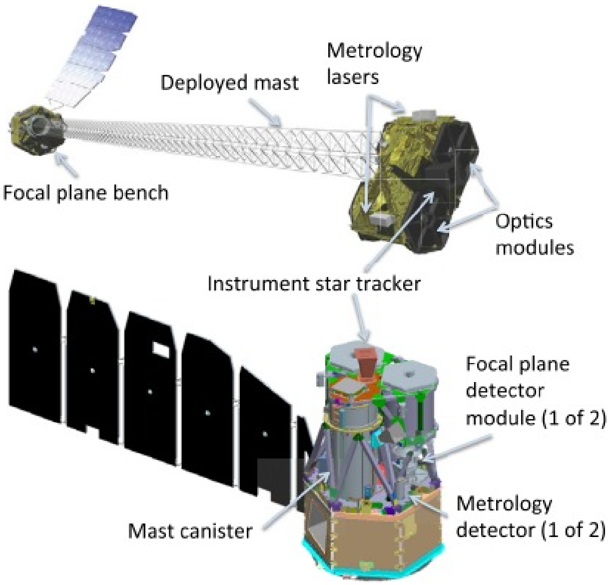

Fig. 2. The NuSTAR

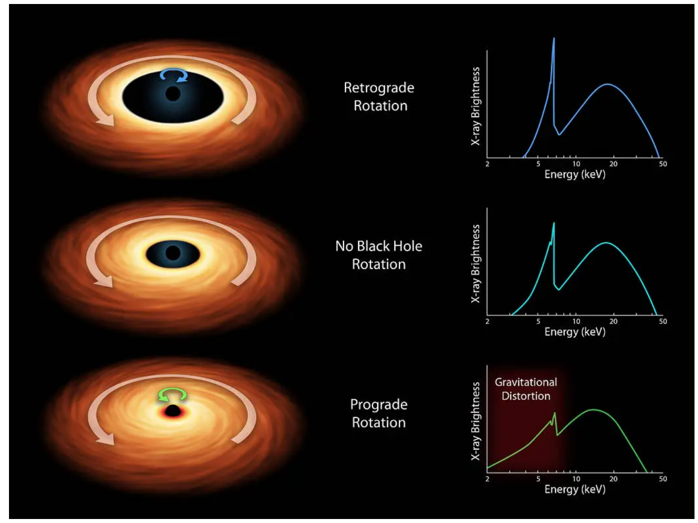

Fig. 3. Black Holes characterized by their spin

(CCD) used in soft X-ray telescopes, NuSTAR uses Cadmium-Zinc-Telluride (CZT) detectors that can directly absorb and measure the energy of hard X-rays [6]. These detectors provide high spectral resolution and can work at room temperature.

IV. Characterizing Black Holes: Mass, Spin and Observational Techniques

Black holes, some of the most mysterious and extreme objects in the universe, are primarily characterized by two fundamental properties: mass and spin. While mass determines the gravitational pull of the black hole, spin—often denoted as the dimensionless spin parameter (a*)—defines how the black hole drags spacetime around it. Since black holes are regions of space where gravity is so intense that not even light can escape, they cannot be observed directly. Instead, their presence is inferred by studying the effect they have on their surroundings, particularly through their influence on nearby matter, gravitational lensing, and the radiation emitted from hot accreting material. Spin in black holes refers to their angular momentum, the measure of how much they rotate around their own axis. This property is a consequence of the conservation of angular momentum, which means that when a star collapses into a black hole, any residual rotation is retained and even amplified due to the drastic reduction in size. The spin parameter (a*) ranges from 0 (a non-rotating Schwarzschild black hole) to 1 (a maximally spinning Kerr black hole). One of the key effects of black hole spin is frame-dragging, predicted by Einstein's General Relativity. When a black hole spins, it twists the surrounding spacetime, pulling everything—including light and matter—around it in a phenomenon known as the Lense-Thirring effect. The faster the spin, the more dramatic the effect, which influences the structure of the accretion disk, the formation of relativistic jets, and even the properties of the event horizon itself. Black holes are by definition invisible because light cannot escape their gravitational pull [10]. However, the Event Horizon Telescope (EHT) has allowed astronomers to image black holes for the first time by observing the shadow they cast against the backdrop of glowing material [3].

When matter falls toward a black hole, it does not plunge directly into it; instead, due to the conservation of angular momentum, it forms a rotating accretion disk around the black hole. This disk is composed of ionized gas and dust, which become compressed and heated as they spiral inward due to friction and turbulence. The material closer to the event horizon orbits faster due to the strong gravitational pull, leading to differential rotation, where inner layers move faster than the outer ones, creating intense frictional forces [8].

This friction converts gravitational potential energy into thermal energy, heating up the gas to extreme temperatures. Near the event horizon, temperatures can reach millions of degrees Kelvin, causing the disk to emit high-energy radiation, particularly in the X-ray band [8]. This is why X-ray telescopes such as NuSTAR, Chandra, and XMM-Newton are essential tools for studying black holes. The X-ray spectrum of an accretion disk provides critical information about the inner edge of the disk, which in turn helps determine the spin of the black hole.

The immense gravitational potential energy of matter falling toward a black hole gets converted into kinetic and thermal energy. As material moves inward, it picks up speed due to the black hole's intense gravitational pull, reaching velocities close to the speed of light. This is particularly evident in relativistic jets, which are powerful streams of particles ejected along the black hole's rotational axis. These jets, often seen in active galactic nuclei (AGN) and quasars, are thought to be powered by magnetic fields interacting with the spinning black hole and its accretion disk. The spin of a black hole is primarily determined through X-ray spectroscopy techniques. One of the most widely used methods is X-ray reflection spectroscopy, which involves analyzing the X-rays that bounce off the inner regions of the accretion disk. Since the inner edge of the disk is determined by the innermost stable circular orbit (ISCO), which depends on spin, measuring how close the disk extends to the black hole allows us to infer its spin [5].

Additionally, graphs of X-ray emission spectra differ between non-rotating (Schwarzschild) and rotating (Kerr) black holes(see Fig.3). In a non-rotating black hole, the X-ray spectrum is relatively simple, with a clear peak and a less extended redshifted wing. However, in a rotating black hole, the strong frame-dragging effects stretch and skew the X-ray spectrum, producing a broad and asymmetric profile. These differences in spectral lines and their shifts allow astronomers to determine the black hole's spin.

V. Comparing X-ray Observatories

NuSTAR (Nuclear Spectroscopic Telescope Array) represents a significant advancement in X-ray astronomy by being the first telescope to focus high-energy X-rays (above 10 keV), enabling unprecedented observations of black holes, neutron stars, and supernova remnants. Compared to other X-ray observatories like Chandra, XMM-Newton, and RXTE, NuSTAR stands out due to its ability to capture sharp images in the hard X-ray band (3–79 keV) with focusing optics rather than the traditional collimators or coded masks [6]. This results in greater sensitivity and resolution, allowing astronomers to measure black hole spin more accurately through X-ray reflection spectroscopy. Table I provides a comparison of NuSTAR with other major X-ray telescopes, highlighting its unique advantages in energy range, imaging capabilities, and spectral resolution.

TABLE I
Comparison of NuSTAR with Other Major X-ray Telescopes

Telescope	Energy Range (keV)	Resolution (arcsec)	Key Features
NuSTAR	3–79	58 (HPD)	First focusing hard X-ray telescope, deep sky surveys
Chandra	0.1–10	0.5	High-resolution soft X-ray imaging, excellent spectroscopy
XMM-Newton	0.1–15	6	Large effective area, superior spectral resolution, optical/UV observations
Swift (XRT)	0.2–10	18	Rapid X-ray follow-ups, multi-wavelength capabilities
Suzaku	0.2–600	120	Broad energy range, deep X-ray observations

VI. Conclusion

The NuSTAR mission represents a pivotal advancement in high-energy astrophysics, demonstrating the power of focused hard X-ray observations in unraveling some of the most complex and extreme processes in the universe. By bridging the observational gap between soft X-ray telescopes like Chandra and the higher-energy gamma-ray observatories, NuSTAR has redefined our ability to study black holes, neutron stars, supernova remnants, and the cosmic X-ray background with unprecedented clarity.

One of NuSTAR's most significant contributions lies in its ability to directly measure black hole spin, offering a critical observational parameter that informs models of accretion physics, jet formation, and relativistic energy extraction. Furthermore, its capability to penetrate dense astrophysical environments has allowed for deep studies of obscured active galactic nuclei (AGNs), shedding light on the growth and evolution of supermassive black holes over cosmic time. Beyond individual source studies, NuSTAR has also provided key constraints on potential dark matter candidates, particularly through its search for sterile neutrino decay signatures.

However, the impact of NuSTAR extends beyond its individual discoveries. Its success underscores the importance of technological innovation in X-ray optics, demonstrating the effectiveness of multilayer-coated grazing incidence mirrors for focusing hard X-rays—an advancement that will inform the design of future high-energy observatories, such as the upcoming Athena and Lynx missions. In addition, its findings continue to pose fundamental questions regarding the nature of black hole accretion flows, the physics of ultra-dense stellar remnants, and the unexplored mechanisms of high-energy particle acceleration.

While NuSTAR has significantly advanced our understanding of the high-energy universe, its observations are part of a larger, evolving framework of astrophysical research. The interplay between X-ray, optical, and multi-messenger astronomy—incorporating gravitational waves and neutrino studies—will be crucial in building a more complete picture of the energetic universe. Future missions will expand upon NuSTAR's legacy, refining our understanding of the most violent and enigmatic cosmic phenomena.

References

[1] NASA NuSTAR Mission Page *https://shorturl.at/yq7BD*.

[2] NASA's NuSTAR Archive *https://shorturl.at/O9ckw*.

[3] Caltech NuSTAR Publications *https://shorturl.at/pGUf3*

[4] THE NUCLEAR SPECTROSCOPIC TELESCOPE ARRAY (NuSTAR) HIGH-ENERGY X-RAY MISSION Fiona A. Harrison, William W. Craig, Finn E. Christensen, Published 2013 May 30 • © 2013. The American Astronomical Society. *https://shorturl.at/arwHT*

[5] Observing Black Holes Spin Christopher S. Reynolds Institute of Astronomy, Cambridge, CB3 OHA , *https://arxiv.org/abs/1903.11704*

[6] Wikipedia "NuSTAR" *https://en.wikipedia.org/wiki/NuSTAR*

[7] Wikipedia "Wolter Telescope" *https://shorturl.at/rnci3*

[8] The Science of NuSTAR – 10 years of Exploring the Energetic Universe (YouTube) *https://youtu.be/LOcWrheC16Q?si=e0nrcGbmi0V9x070*

[9] NuSTAR tests of sterile-neutrino dark matter: New Galactic bulge observations and combined impact *https://arxiv.org/pdf/1908.09037*

[10] The Theory of Everything by Stephen W Hawking