18thInternational Conference on Space Operations, Montreal, Canada, 26- 30May2025.

SpaceOps-2025, ID # 586

Fascinating Perspectives of India's First Dedicated X-ray Polarimeter Satellite (XPoSat) Mission Operations for Polarimetry

Anand Raj R[a]*, Leo Jackson John[b], Nandini Harinath[c], Raghavendra M R[d], A K Anilkumar[e]

[a]*Space Operations Area (SpOA), ISTRAC, ISRO, Bangalore, India,* *anand@istrac.gov.in*
[b]*Space Operations Area (SpOA), ISTRAC, ISRO, Bangalore, India,* *leo@istrac.gov.in*
[c]*Space Operations Area (SpOA), ISTRAC, ISRO, Bangalore, India,* *nandini_h@istrac.gov.in*
[d]*Office Of the Associate Director, ISTRAC, ISRO, Bangalore, India,* *mrraghav@istrac.gov.in*
[e]*Office Of the Director, ISTRAC, ISRO, Bangalore, India,* *ak_anilkumar@istrac.gov.in*
*Corresponding Author

Abstract

X-ray Polarimeter Satellite marks India's inaugural mission in space-based X-ray polarimetry, positioning the nation as a prominent leader in the field of high-energy astrophysical research.As the world's second dedicated mission for X-ray polarimetry, XPoSat was successfully deployed into a 650 km low Earth orbit (LEO) with a 6° inclination via the Polar Satellite Launch Vehicle (PSLV) on January 1st, 2024. Having completed a triumphant year in orbit, the mission continues to revolutionize our understanding of extreme cosmic phenomena, including supernova remnants (SNRs), relativistic jets from accreting black holes, and other high-energy astrophysical sources. Equipped with two advanced scientific payloads, XPoSat is designed to probe the intricate geometrical structures of celestial X-ray sources and decipher the underlying emission mechanisms. The primary payload, POLIX (Polarimeter Instrument in X-rays), employs Thomson scattering to measure polarization parameter such as degree and angle of polarization within the 8–30 keV energy band, enabling critical insights into the magnetic field topology and emission processes of cosmic sources. Simultaneously, the X-ray Spectroscopy and Timing instrument called as XSPECT, surveys up to15 keV with a lower energy limit of 0.8 keV soft X-ray band, capturing high-resolution spectral insights that decode elemental composition, thermal behavior, and internal dynamics of cosmic X-ray emitters.Apart from the routine satellite bus management operations, the primary operations are: Payload Operations, Calibrations of Payload and Collision Avoidance Maneuvers. Colloquially, these operations are called as POP, CAL and CAM operations. Both POLIX and XSPECT remain continuously operational, except when the spacecraft is travelling over the SAA region. Source observations are meticulously scheduled during orbital eclipse phases, except for one orbit allocated for data downlink over Bengaluru. Calibration maneuvers involve roll and yaw scans over well-characterized astrophysical standards like the Cassiopeia A. Moreover, Space Situational Awareness (SSA) teams actively implement Collision Avoidance Maneuvers (CAM) to reduce the risks associated with potential orbital conjunctions, thereby obviating the necessity for ground track correction maneuvers.This paper delineates the multifaceted challenges encountered during XPoSat's operational tenure, including geomagnetic disturbances, prolonged exposure to SAA regions, lunar and solar eclipses, spacecraft subsystem performance deviations, and unforeseen disruptions such as ground station outages due to cyclonic conditions and communication links. Furthermore, it discusses the contingency protocols adopted for disaster management, including the activation of Alternate Spacecraft Control Centers (ASCCs) to ensure uninterrupted mission execution. By addressing these complexities, XPoSat not only showcases India's capabilities in X-ray astronomy but also establishes a robust operational framework for future high-energy astrophysics missions. The exceptional success of XPoSat is a testament to the relentless dedication, technical acumen, and unwavering commitment of the XPoSat Mission Operations Team at ISRO Telemetry, Tracking, and Command Network (ISTRAC). Their expertise in real-time mission management, precision spacecraft operations, and swift anomaly resolution has been instrumental in maintaining the mission's health and performance. Through their tireless efforts, XPoSat continues to push the boundaries of X-ray astronomy, reinforcing India's leadership in high-energy astrophysics and setting a precedent for future space exploration endeavors.

Keywords: X-ray astronomy, Polarimetry, Emission mechanism, Thomson Scattering, X-ray Spectroscopy and Timing, Mission Operations Management.

Nomenclature

E - Energy of an X-ray Photon
$h = 6.62607015 \times 10^{-34}$ Js, Planck's constant

$c = 2.99792458 \times 10^8$ m/s, Velocity of light
λ - Wavelength of X-ray
ν - Frequency of X-ray
$eV = 1.60218 \times 10^{-19}$ J, Electron Volt

Acronyms/Abbreviations

XPoSat - X-ray Polarimeter Satellite
LEO - Low Earth Orbit
PSLV - Polar Satellite Launch Vehicle
SNR - Supernova Remnants
POLIX - Polarimeter Instrument In X-rays
XSPECT - X-ray Spectroscopy and Timing
RRI - Raman Research Institute
SAG - Space Astronomy Group
NASA - National Aeronautics and Space Administration
URSC - U R Rao Satellite Center
ISTRAC - ISRO Telemetry Tracking and Command Network
ISRO - Indian Space Research Organization
POP - Payload Operations
CAL - Calibrations
CAM - Collision Avoidance Maneuvers
SAA - South Atlantic Anomaly
GT - Ground Track
GPD - Gas Pixel Detectors
ISRO - Indian Space Research Organization
IXPE - Imaging X-ray Polarimetry Explorer
STScI –Space Telescope Science
CCD - Charge Coupled Devices
SCD - Swept Charge Devices
LMXB - Low-mass X-ray binaries
FOV - Field of View
CAS-A - Cassiopeia A, prominent X-ray celestial source
CXB - Cosmic X-ray Background
GCR - Galactic Cosmic Ray
CAM - Collision Avoidance Maneuver
SAA - South Atlantic Anomaly
ASCC - Alternate Control Center
FDIR - Fault detection, isolation, and recovery
AGN - Active Galaxy Nuclei
PV - Performance Verification
CME - Coronal Mass Ejection
SEU - Single Event Upset
LEO - Low Earth Orbit
TTC - Telemetry and Tracking and Commanding

1. Introduction

X-ray spectroscopy and polarimetry stand as two pivotal techniques in unraveling the universe's most extreme and enigmatic phenomena, including the catastrophic explosions of supernova remnants (SNRs) and the relativistic particle jets expelled by accreting black holes. Advances in X-ray spectroscopy have significantly enhanced our ability to precisely determine the elemental composition, structural characteristics, and thermal properties of distant celestial entities. Simultaneously, breakthroughs in X-ray polarimetry such as the integration of state-of-the-art Gas Pixel Detectors (GPDs) to achieve highly sensitive polarization measurements across diverse energy spectra have revolutionized our understanding to an advanced state. This helps us to understand the physical properties and the x-ray emission mechanism of astrophysical sources, in a better manner. Recognizing the transformative potential of these techniques, space agencies worldwide are actively contributing to their evolution.

India has emerged as a key player in this scientific frontier with the launch of XPoSat, the nation's first dedicated X-ray polarimetry mission and the second such mission globally. Deployed into a 650 km low-Earth orbit with a 6° inclination via PSLV on January 1, 2024, XPoSat is designed to probe the polarization characteristics of high-energy astrophysical sources. Its primary payload, POLIX (Polarimeter Instrument in X-rays), developed by the X-ray Astronomy Laboratory at the Raman Research Institute (RRI), Bengaluru, employs Thomson scattering to measure the polarization measurements of X-ray photons from 8keVup to 30 keV. These observations provide critical insights into the magnetic field configurations, emission processes, and intrinsic geometry of cosmic sources. Simultaneously, the X-ray Spectroscopy and Timing instrument called as XSPECT, designed by the Space Astronomy Group (SAG) at URSC, surveys up to 15 keV with a lower energy limit of 0.8 keV soft X-ray band, capturing high-resolution spectral insights that decode elemental composition, thermal behavior, and internal dynamics of cosmic X-ray emitters. Notably, POLIX serves as a complementary instrument to NASA's IXPE mission [3], which operates in the lower 2–8 keV band, and hence polarization measurements are covered from 2 keV to 30 keV by both missions.

The mission operations of XPoSat and the multifaceted challenges encountered in its execution are discussed in this paper. The Mission Operations Team at ISTRAC, operating in seamless round-the-clock shifts, ensures meticulous spacecraft bus management and continuous telemetry monitoring. In parallel, the automation of mission operations is being progressively integrated across all ISRO missions, enhancing efficiency and operational reliability. Apart from the routine satellite bus management operations, the primary operations are: Payload Operations, Calibrations of Payload and Collision Avoidance Maneuvers. Colloquially, these operations are called as POP, CAL and CAM operations. The execution of Payload Operations follows a structured command uplink strategy, wherein POP commands including payload activation sequences, source pointing directives, and observational parameters are uploaded one day in advance for execution on the subsequent day. Both XSPECT and POLIX payloads remain continuously operational, with the exception of periods when XPoSat transits through the South Atlantic Anomaly (SAA), where heightened radiation exposure necessitates temporary payload deactivation. To optimize observational efficiency, source pointing is exclusively scheduled during the orbital eclipse phase in each orbit, except for one designated orbit where scientific data is downlinked to ground stations in Bengaluru. For Payload Calibrations (CAL), XPoSat is precisely oriented towards well-characterized celestial calibration sources, such as Cassiopeia A (CAS-A) supernova remnant (SNR), with both roll and yaw scan maneuvers executed to refine instrument accuracy. Meanwhile, Collision Avoidance Maneuvers (CAMs) are directed by the Space Situational Awareness (SSA) Team to mitigate the risk of close encounters with orbital debris or other space objects. Notably, XPoSat's orbit remains inherently stable, eliminating the need for routine Ground Track (GT) maintenance maneuvers. These meticulously coordinated operational strategies are instrumental in ensuring the mission's longevity and its ability to deliver high-fidelity X-ray polarimetry and spectroscopy data.

The primary objective of this paper is to elucidate the intricate challenges encountered in the Mission Operations Management of XPoSat, which has successfully completed its first year in orbit. These challenges encompass a spectrum of critical factors, including mitigation strategies for South Atlantic Anomaly (SAA) transits, the impact of geomagnetic storms, operational constraints during solar and lunar eclipses, spacecraft subsystem performance deviations, and unforeseen disruptions in ground segment support and communication link availability. Addressing these complexities is imperative to ensuring uninterrupted scientific operations and maximizing mission efficiency. This paper is structured to provide a comprehensive analysis, beginning with the scientific rationale for selecting the operational energy band of X-ray photons, followed by a concise overview of the XPoSat mission profile. It then presents the first-light observations from the XSPECT payload, the inaugural scientific measurement obtained by POLIX, an in-depth discussion on the various operational challenges faced, and concludes with key insights derived from the mission's first-year performance.

2. Selection of Energy Band

X-ray photons are classified in terms of their energies as low, medium and high energy photons. X-ray photon's energy is *hv* joules as given by Planck-Einstein relation where h is Planck's constant and *v*is frequency. X-ray photons having energies less than 15 keV are classified as low energy X-ray photons while the X-ray photons from 15 keV to 100 keV are called as medium range X-ray photons. Beyond 100 keV, the X-ray photos are classified as high energy photons. In X-ray astronomy, Low energy X-ray photons are typically used to study the soft X-ray emission from celestial bodies typically in regions high energy X-rays are completely absorbed by interstellar particles. Low energy X-ray photons are widely used in the researches of SNRs, Accretion disks around black holes, neutron stars, galaxies, etc. to discover their structures, dynamics, temperature, density, and magnetic field distributions etc.

In X-ray astronomy, low-energy photons are extensively used to study soft X-ray emissions from celestial objects, as higher-energy X-rays are heavily absorbed by interstellar dust, a cosmic medium of fine stardust particles dispersed between stars. These low-energy photons are instrumental in probing SNRs, accretion disks around black holes, neutron stars, galaxies, and other astrophysical structures, revealing key properties such as temperature, density, magnetic field configurations, and dynamical processes.

Studying low-energy X-rays in X-ray astronomy presents significant challenges, primarily due to their strong absorption by Earth's atmosphere, necessitating the deployment of space-based instruments for effective observations. Additionally, detectors in such instruments must possess exceptionally high sensitivity and superior energy resolution to accurately capture faint astrophysical signals. To meet these demands, XSPECT operates in the 0.8–15 keV energy range, offering an energy resolution of less than 200 eV at 5.9 keV and an efficiency exceeding 10%, making it a complementary payload to POLIX. Unlike XSPECT, POLIX utilizes Thomson Scattering, wherein incoming X-ray photons interact with free electrons in a lithium/beryllium scatterer, transferring energy without loss, while the polarization of the scattered photons is preserved. Thomson Scattering is only significant when the energy of the incoming X-ray photons is much smaller than the rest mass energy of an electron (511 keV), ensuring that the electron does not gain significant velocity from the interaction. The following are the two predominant reasons for the selection of this energy range. Firstly, the energy range from 8 keV to 30 keV are optimal for scattering process. Secondly, IXPE is already operating from 2 keV to 8 keV and hence the continuation from this range which is starting from 8 keV and 30 keV has been selected for XPoSat. Hence, polarization measurements are covered from 2 keV to 30 keV by both missions together.

3. XPosat Mission Profile

As India’s first mission in X-ray polarimetry and only the second of its kind globally, XPoSat is equipped with two state-of-the-art scientific payloads, designed to revolutionize our understanding of high-energy cosmic environments. The primary payload, POLIX, meticulously measures the degree and angle of polarization within the medium X-ray energy range (8–30 keV), providing an unprecedented probe into the magnetized structures of celestial sources. Complementing this, XSPECT delivers high-resolution spectroscopic and timing data in the 0.8–15 keV energy band, enabling a profound exploration of the structural, thermal, and compositional properties of cosmic entities.

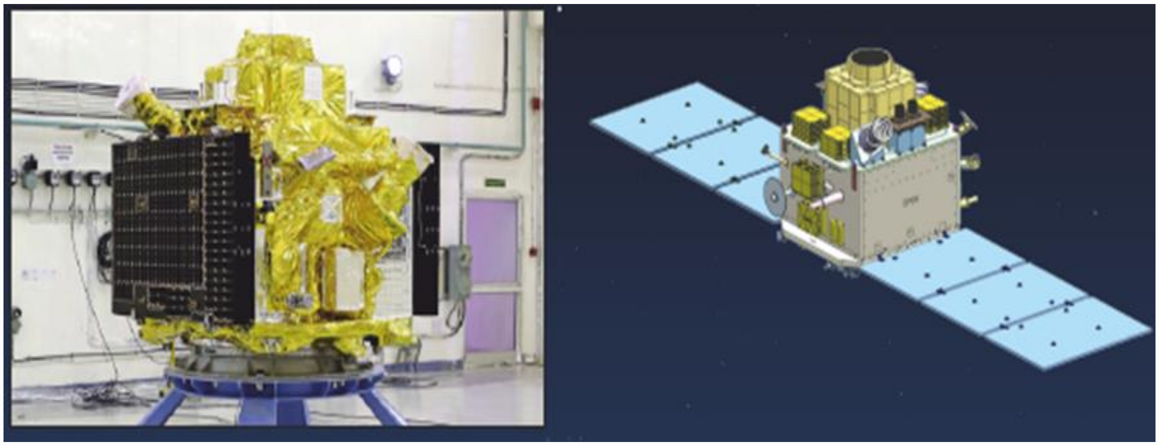


Fig.1 XPoSat Mission stowed and deployed views (Courtesy: ISRO Website)

The origins of X-ray emissions from black holes, neutron stars, pulsar wind nebulae, and AGN are rooted in complex, high-energy interactions, which remain one of the most formidable challenges in modern astrophysics. While spectroscopic and timing studies from previous space observatories have unveiled crucial insights, the fundamental nature of these emissions continues to elude definitive characterization. Polarimetry introduces a paradigm shift by adding two crucial dimensions, the degree and angle of polarization, transforming our ability to decipher the intricate physics governing these cosmic behemoths.

There is a persistent decadence in theoretical models of X-ray emission. Polarimetric and spectroscopic observations can be assimilated in order to resolve such degeneracy in theoretical models of X-ray emission. With this, we can unwind the complicated mechanisms which drive the high energy process in the universe. This mission signifies a monumental leap forward for India’s scientific community, empowering researchers to push the boundaries of astrophysical exploration and illuminating the hidden dynamics of the cosmos with unparalleled precision and depth.

3.1 POLIX Payload

The POLIX instrument investigates the polarization characteristics of X-ray photons within the medium energy band, specifically spanning from 8 keV to 30 keV. By analyzing these polarization signatures, the payload enables in-depth exploration of the magnetic field configurations and emission mechanisms associated with various cosmic sources. POLIX was developed by the RRI, Bangalore, in collaboration with the URSC, this pioneering instrument represents a groundbreaking advancement in space-based polarimetry. The instrument comprises three core components: a collimator, a scatterer, and four X-ray proportional counter detectors strategically positioned around the scatterer. The scatterer, constructed from a low atomic mass material, facilitates anisotropic Thomson scattering of incident polarized X-rays, a fundamental mechanism that enables precise polarization measurements. The collimator, with a 3°×3° field of view, ensures that observations are predominantly focused on a single bright X-ray source, minimizing background contamination and maximizing measurement fidelity. As the first-ever dedicated Polarimeter in the medium X-ray energy range, POLIX is poised to observe approximately 50 high-intensity astronomical sources spanning diverse astrophysical classes, including black holes, neutron stars, pulsars, and active galactic nuclei, over XPoSat's planned five-year operational lifespan. By capturing the polarization signatures of these extreme cosmic environments, POLIX will provide unparalleled insights into the fundamental emission mechanisms, magnetic field structures, and relativistic effects governing high-energy astrophysical phenomena, establishing a new frontier in X-ray astronomy.

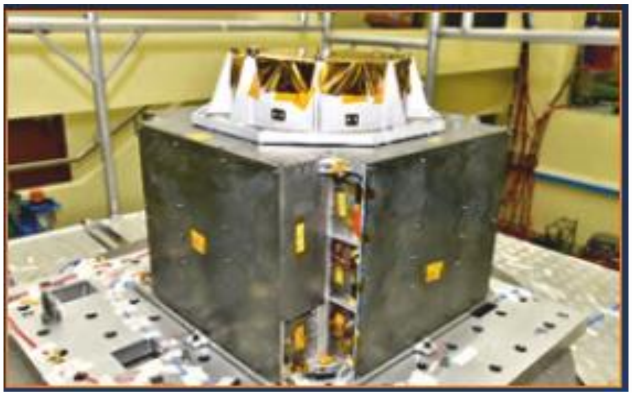


Fig.2POLIX Payload (Courtesy: ISRO Website)

3.2XSPECT Payload

Equipped on board XPoSat, the advanced XSPECT payload specializes in high-precision spectral measurements and rapid timing analysis within the soft X-ray domain, covering the 0.8–15 keV energy range. By utilizing the extended observation windows required by POLIX for polarimetric studies, XSPECT facilitates uninterrupted, long-duration tracking of both spectral and temporal fluctuations in celestial sources. This capability opens up a transformative perspective on the time-evolving behavior of high-energy astrophysical phenomena. This state-of-the-art instrument is built around an array of SCDs, offering an effective detection area exceeding 30 cm² at 6 keV and superior energy resolution (<200 eV at 6 keV). To enhance observational fidelity, passive collimators are incorporated, effectively constraining the field of view and minimizing background noise. This ensures high signal purity, allowing for precise characterization of spectral state transitions, continuum emission variations, and temporal evolution of X-ray sources. XSPECT is poised to conduct in-depth investigations of a diverse array of high-energy cosmic phenomena, including X-ray pulsars, black hole binaries, accreting neutron stars in LMXBs, AGNs, and Magnetars [1]. By capturing spectral line variations, flux modulations, and long-term soft X-ray emission trends, XSPECT will provide critical insights into accretion physics, relativistic dynamics, and magnetospheric interactions in extreme astrophysical environments, solidifying its role as a cornerstone in X-ray astronomy.

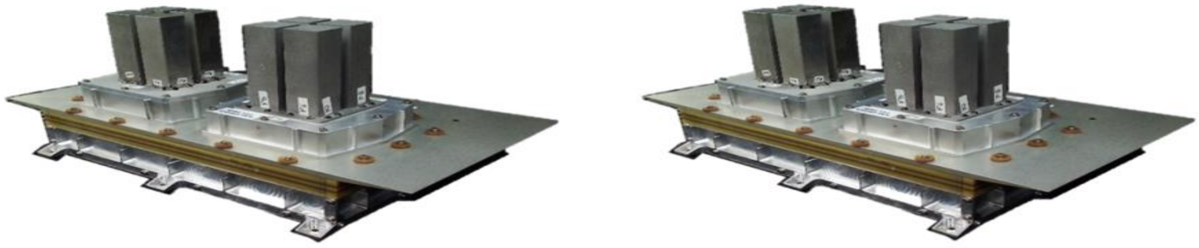


Fig.3 Detector packages of XSPECT payload. (Courtesy: ISRO Website)

3.3X-ray Sources Observed by XPoSat

Within its inaugural year, XPoSat has successfully captured observations of 13 distinguished high-energy astrophysical sources, affirming its outstanding capabilities in both X-ray polarimetry and spectroscopy. The observed targets span a wide astrophysical spectrum, including supernova remnants like Cassiopeia-A (Cas-A) and Tycho, the archetypal Crab Nebula, and an eclectic collection of compact objects. The observation catalogue encompasses a diverse range of celestial X-ray sources, including binary pulsars such as Centaurus X-3 [2] and GX-301.Additionally, several neutron star binary systems including Vela X-1, 4U 1700-37, Circinus X-1, GX 13+1, Hercules X-1, and Scorpius X-1 were studied, along with distinguished black hole binary candidates such as Cygnus X-1 and Aquila X-1. These pioneering observations are instrumental in deepening our understanding of extreme astrophysical regimes, offering valuable insights into magnetospheric dynamics, accretion behavior, and high-energy radiation processes across some of the cosmos' most enigmatic entities.

4. **First Light of XSPECT**

XSPECT emerges as a groundbreaking payload in high-energy astrophysics, uniquely designed to decode the spectral evolution of bright X-ray binaries and illuminate the dynamic processes shaping their high-energy emissions. It focuses on both continuum and discrete emissions and its variations over a long period of time. In addition, it provides information about the dynamics involved in the shape of the pulse and its period when observed from X-ray pulsars. With its exceptional count rate handling capability, XSPECT enables the exploration of luminous X-ray sources in the soft X-ray domain, a breakthrough previously unattainable with conventional imaging X-ray CCDs. This transformative capability positions XSPECT as an indispensable tool for unlocking the intricate emission mechanisms and extreme physical processes governing the universe's most enigmatic celestial bodies.

Primary Scientific Objectives of the XSPECT Payload are:

1. The primary objective of XSPECT is to trace the spectral evolution in X-ray binaries by examining long-term variations in their continuum X-ray spectra and spectral transitions. Focusing on black hole and neutron star X-ray binaries, this investigation will offer crucial insights into the underlying physics of accretion processes, as well as the fundamental emission mechanisms that govern these extreme astrophysical systems.
2. Unraveling Neutron Star Accretion Dynamics: By examining the spin period evolution, accretion torque history, and associated changes in X-ray flux, emission mechanisms, and pulse profiles, XSPECT will offer critical insights into the standard model of accretion onto magnetized neutron stars, refining our understanding of their complex interactions with in falling matter.
3. Constraining Black Hole Mass and Spin: Through precise modeling of the X-ray continuum and iron-line emissions, XSPECT will facilitate the determination of black hole mass and spin, key parameters in deciphering the nature of strong gravitational fields and relativistic effects near these enigmatic cosmic entities.

The XPECT payload is equipped with sixteen Silicon Drift Detectors (SCDs), each functioning as a non-imaging CCD sensor with an active area of 4 cm^2. These detectors are configured with two distinct types of collimators to define their field of view (FOV): seven units are aligned with a 3° × 3° FOV, while eight are aligned with a narrower 2° × 2° FOV. This dual-FOV arrangement facilitates both the detection of cosmic X-ray background and the measurement of source-specific flux, thereby allowing independent background correction for each observation. To measure the charged particle background, one of the detectors is shielded by a tantalum sheet, effectively blocking X-rays.

As part of the PV phase, the XSPECT payload was directed toward Cassiopeia A, a well-established calibration standard in X-ray astronomy, renowned for instrument validation and spectral benchmarking. The first light of XSPECT was on 5th January 2024 with CAS-A SNR which is a rich reservoir of high-energy emission lines, prominently featuring elements such as Magnesium, Silicon, Sulfur, Argon, Calcium, and Iron. These spectral signatures provide a crucial window into the nucleosynthesis processes, shock dynamics, and elemental composition of supernova remnants, offering profound insights into the energetic feedback mechanisms shaping the interstellar medium.

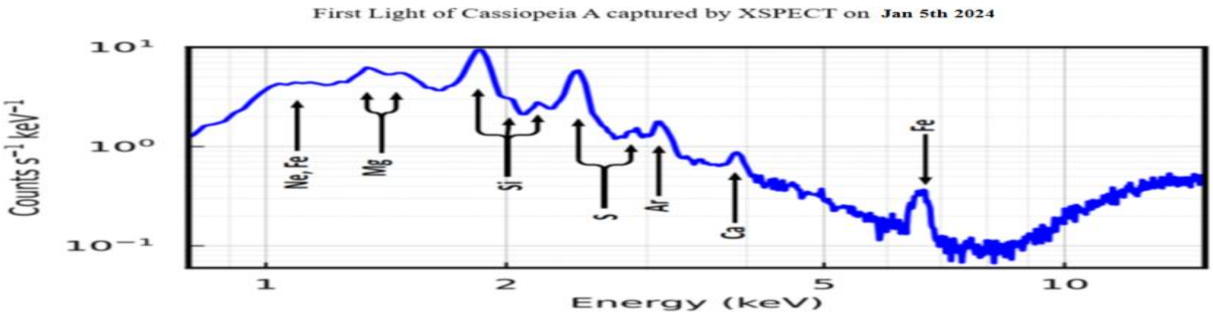
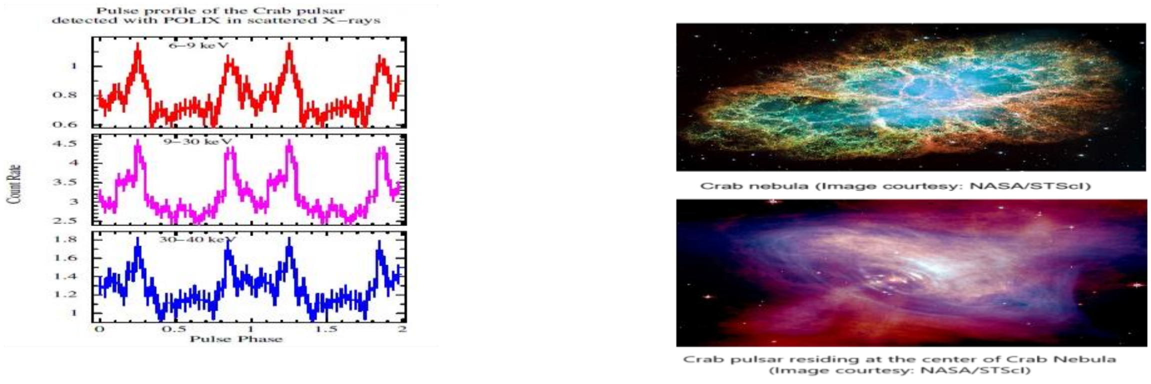


Fig. 4: XSPECT captures an observation of Cassiopeia-A (CAS-A) SNR. The displayed spectrum, as recorded by the payload, incorporates contributions from both the Galactic Cosmic Ray (GCR) background and the Cosmic X-ray Background (CXB). The flux observed above 8 keV is predominantly attributed to a combination of CXB and GCR influences. This spectrum has an integration time of 20 ksec and XSPECT had been operated over many orbits by the XPoSat Mission Operations Team at ISTRAC. (Courtesy: SAG, URSC)

5. POLIX observation on Crab Nebula

POLIX captured an observation from Crab Pulsar during third week of January 2024 [4]. Crab Pulsar is in the center of Crab Nebula and completes thirty rotations in 1 second. Crab pulsar is also a neutron star. This plot represents a pioneering dataset in this energy range (8–30 keV), capturing the time window of X-rays scattered by the Beryllium scatterer inside POLIX, originally emitted from the Crab pulsar. Missions from various other space agencies have obtained data on the same source, but outside POLIX's energy range, underscoring the uniqueness of this dataset. The X-axis of the plot marks the temporal span of two consecutive pulses, covering approximately 67 milliseconds in total. In addition, the plot captures the timing characteristics of the non-pulsed emission components arising from the Pulsar Wind Nebula enveloping the pulsar. This temporal window is instrumental in distinguishing X-rays emitted directly by the pulsar from those emanating from the wind nebula. There will be an asymmetry of X-ray scattering in POLIX whenever it receives a polarised emission. The extent of asymmetry is directly proportional to the incoming polarised emission received by POLIX. The first observation of POLIX was Crab Nebula on 10th January 2024. The dataset collected during January 15–18, 2024, has undergone rigorous validation by RRI team and the dataset aligns precisely with theoretical expectations.

This initial observation marks a significant milestone for POLIX, demonstrating its functionality and readiness for in-depth investigations of pulsars, black holes, and other high energy astrophysical sources. Since POLIX is the only payload currently operating in this energy band, it is uniquely positioned to provide unparalleled insights into the fundamental physical processes governing astronomical X-ray sources, further solidifying its role in advancing X-ray polarimetry and astrophysical research.



Crab nebula (Image courtesy: NASA/STScI)

Crab pulsar residing at the center of Crab Nebula (Image courtesy: NASA/STScI)

Fig.5. This figure presents the pulse profile of the Crab Pulsar, as captured by POLIX in scattered X-rays (Courtesy: Raman Research Institute, Bangalore, India), alongside a composite X-ray and optical image of the Crab Nebula. The dataset was meticulously collected by the ISTRAC XPoSat Mission Operations Team. (Courtesy: NASA/STScI, Space Telescope Science Institute).

6. **Challenges in Mission Operations**

A comprehensive overview of XPoSat's mission operations is essential for understanding the challenges involved. One of the most critical phases is the Payload Operations Phase (POP), during which the scientific payloads are actively operated—making it the core of mission execution. In XPoSat, payloads are operated during every orbital eclipse, except for one orbit per day, which is dedicated to downlinking all recorded data from the previous day. On-board, each payload operation is classified as a session comprising 15 critical events necessary for successful execution. These events include payload power activation, spacecraft attitude adjustments for precise source pointing, quaternions required for accurate alignment, and essential safety protocols. Each of these events is continuously monitored from the ground to ensure operational integrity. Once source pointing is complete, the spacecraft exits the orbital eclipse and reorients towards the Sun, ensuring uninterrupted power generation throughout the sunlit portion of the orbit. The entire sequence—from payload activation to solar pointing—is meticulously tracked by the mission operations team. Similarly, payload calibration operations are conducted periodically, following a structured approach. The on-board payload events during calibration are analogous to regular operations, with the addition of roll and yaw scanning to refine calibration accuracy. For calibration, CAS-A serves as the primary reference source due to its well-characterized and stable emission. Despite its gradual intensity decline of ~0.6% per year at 1 GHz, this decay is thoroughly documented, ensuring precise calibration adjustments. CAS-A's high brightness in both radio and X-ray wavelengths, coupled with its uniform structure, makes it an ideal target for evaluating resolution and imaging capabilities. Furthermore, its historical use in previous missions provides a reliable benchmark for comparing new observational data.

XPoSat's mission operations must overcome several critical challenges to ensure optimal performance. While no specific CAMs have been designated for the mission so far, they will be implemented if required. The mission faces seven key challenges: the SAA regions, where elevated radiation levels can affect instrumentation; geomagnetic storms that pose potential risks to satellite electronics; lunar and solar eclipses impacting power availability and operational schedules; unexpected deviations in satellite subsystem performance requiring adaptive responses; ground station non-availability due to cyclones, leading to communication disruptions; unforeseen failures in communication links affecting data transmission; and the necessity of disaster management through ASCCs to ensure operational continuity during crises. By systematically addressing these challenges, XPoSat's mission operations are designed to maximize the scientific output of this ground breaking X-ray polarimetry mission.

6.1 South Atlantic Anomaly Regions

The SAA is dangerous for satellites in orbit because it is a region where Earth's inner Van Allen radiation belt comes closest to the surface, exposing satellites to intense radiation. As satellites pass through the SAA, they encounter high-energy charged particles, primarily protons and electrons, which can cause various issues, including damage to onboard electronics, increased noise in sensors, and data corruption. This radiation exposure can lead to SEUs, where high-energy particles alter bits in electronic circuits, potentially causing malfunctions or system failures. Additionally, prolonged exposure can degrade solar panels and other critical components, reducing a satellite's operational lifespan. To mitigate these risks, satellites are often designed with radiation-hardened components, and mission planners schedule sensitive operations outside of the SAA region whenever possible. In XPoSat, SAA region identification is calculated at onboard and onboard issues XSPECT payload OFF command whenever the mission is passing over this region and XSPECT payload ON command will also be issued by onboard when the mission comes out from this region. Mission operations team will be monitoring all the parameters of the health critically when the mission is passing through SAA region.

6.2 Geomagnetic storms

Geomagnetic storms affect satellites in orbit by exposing them to increased radiation, disrupting onboard electronics, and altering their trajectories. These storms, caused by solar wind disturbances such as CMEs or solar flares, intensify charged particle flows, leading to several critical issues. High-energy particles penetrate satellite shielding, damaging electronic components, degrading solar panels, and reducing battery life. They can also cause SEUs, where bit flips in memory or processors lead to data corruption, system malfunctions, or even complete failures. Communication disruptions occur as radio signals used for satellite operations and GPS navigation degrade, resulting in signal loss and increased errors. Additionally, geomagnetic storms heat Earth's upper atmosphere, causing it to expand and increase drag on LEO satellites, leading to unplanned orbital decay that requires corrective maneuvers. Electrostatic charging from high-energy particles can also lead to sudden discharges, damaging circuits and disrupting operations. To mitigate these effects, XPoSat mission is designed with radiation shielding, error-correcting memory, and redundant systems, while operators monitor space weather forecasts to adjust satellite operations during strong geomagnetic storms. In XPoSat, payload operations are not carried out as a precautionary measure.

6.3 Lunar and Solar Eclipses

Lunar and solar eclipses can significantly affect the power generation of orbiting satellites by temporarily blocking sunlight from reaching their solar panels, reducing or completely cutting off power supply. During a lunar eclipse, Earth blocks sunlight from reaching the Moon, but this does not directly impact satellites in Earth's orbit. However, during a solar eclipse, when the Moon casts a shadow on Earth, satellites in LEO passing through the shadow experience extended periods of darkness, leading to reduced or zero power generation. Satellites in LEO also encounter frequent but shorter eclipses during each orbit, requiring efficient power management. Prolonged eclipses can strain battery life, causing reduced efficiency or failures if the batteries are not adequately charged beforehand. To mitigate these effects, XPoSat mission are equipped with 50 Ah Li-Ion rechargeable batteries to store power during sunlight exposure and supply energy during eclipse periods. Mission team from URSC and Mission Operations team at ISTRAC optimize satellite orientation and power consumption strategies to ensure critical systems remain operational during extended shadow periods. In addition, payloads are not operated during such occasions.

6.4 Satellite Subsystem Performance Deviations

Satellite subsystem deviations can jeopardize mission success, causing inefficiencies, failures, or total loss. Power anomalies like solar panel degradation or battery failures disrupt operations, while propulsion issues lead to inaccurate orbits and wasted fuel. Communication failures from signal degradation or antenna misalignment result in data loss and command delays. Thermal control malfunctions cause extreme temperature shifts, damaging vital components. Attitude control errors from gyroscope or reaction wheel faults impair precision, affecting imaging and communication. To mitigate these risks, satellites rely on redundancy, autonomous fault detection, and real-time monitoring for resilience and longevity. For XPoSat, FDIR has been incorporated at onboard for some subsystems which will assist the mission operations team to handle the recovery of these subsystems in case of any functional deviations.

6.5 Unexpected non-availability of Ground Stations Due to Cyclones

The unexpected non-availability of ground stations due to cyclones can critically disrupt satellite mission operations by causing communication blackouts, data loss, and delays in critical commands. Ground stations provide TTC support for complete mission operations. ISTRAC Network is having ground stations at Indonesia and Mauritius. When a cyclone renders, these groundstations become inoperative through power failures, infrastructure damage, or network disruptions. Satellites may miss essential commands for orbital corrections, attitude adjustments, or emergency maneuvers. This can lead to positioning errors, degraded imaging accuracy, and potential mission risks. To mitigate these risks, XPoSat Mission operations team uses other ground stations of ISTRAC network and rearrange the mission operations accordingly till the affected ground stations are restored.

6.6 Unexpected non-availability of Communication Links

The unexpected non-availability of communication links in the ground network can severely disrupt satellite mission operations by causing data loss, command delays, and reduced operational control. Ground networks are essential for transmitting telemetry, issuing commands, and receiving mission-critical data from satellites. When communication links fail due to fiber optic cuts, network outages, cyber-attacks, or extreme weather satellites may miss essential commands for orbital corrections, attitude adjustments, or payload operations, leading to positioning errors and degraded performance. Extended outages can also impact satellite health monitoring, increasing the risk of undetected anomalies or system failures. To mitigate these risks, ISTRAC uses redundant communication paths, alternative ground stations, inter-satellite links, and autonomous onboard systems to maintain mission continuity until ground links are restored.

6.7 Disaster Management Using Alternate Satellite Control Centers(ASCCs)

An alternate control center for satellite operations plays a crucial role in disaster management by ensuring uninterrupted mission control when the primary facility is compromised due to natural disasters such as cyclones, earthquakes, or floods. It acts as a redundant command hub, allowing continued communication with satellites for critical functions like telemetry reception, command execution, and data transmission. This prevents operational blackouts, ensuring real-time monitoring of disaster zones, continued support for navigation, weather forecasting, and emergency response services. The backup center helps mitigate risks associated with ground station failures, network outages, and power disruptions, ensuring that earth observation satellites, communication relays, and search-and-rescue operations remain active. By maintaining seamless satellite control, an alternate control center strengthens disaster response efforts, facilitates timely information for relief operations, and enhances the overall resilience of space-based infrastructure during crises. ISTRAC is maintaining ASCCs towards disaster management.

7. Conclusion

XPoSat marks a historic milestone in India's space exploration journey, pioneering the study of X-ray polarimetry and unlocking the secrets of some of the most enigmatic celestial phenomena. As India's first dedicated X-ray Polarimeter mission, and only the second globally, its outstanding success in the inaugural year reflects the unparalleled dedication, technical brilliance, and relentless effort of the XPoSat Mission Operations Team at ISTRAC, ISRO. Central to the success of this groundbreaking mission is the unmatched dedication and proficiency of the XPoSat Mission Operations Team at ISTRAC, ISRO. Their vigilant monitoring and timely, effective decision-making have been crucial in maintaining the spacecraft's continuous performance amidst the challenging and unpredictable conditions of space. Their indomitable perseverance in overcoming operational challenges ranging from navigating the perilous SAA regions and mitigating geomagnetic storms to ensuring resilience against communication disruptions and natural disasters has been nothing short of exemplary. As XPoSat progresses beyond its first year, the unparalleled expertise, innovative strategies, and relentless dedication of the XPoSat Mission Operations Team at ISTRAC, ISRO will continue to play a crucial role in driving its discoveries, ensuring that India remains at the forefront of advancing astrophysics and cosmic exploration. With its uncompromising operational excellence and transformative scientific contributions, XPoSat not only unravels the deepest mysteries of the universe but also heralds a future where India leads the global quest for cosmic understanding. By planning payload operations and payload calibrations well in advance and by being proactive in the execution of collision avoidance maneuvers as and when it is called for, the XPoSat Mission Operations Team at ISTRAC, ISRO has not only safeguarded the mission's scientific ambitions but also set an elevated benchmark for mission execution and operational strategy. Their unwavering dedication to excellence has enabled POLIX and XSPECT to deliver groundbreaking insights into the polarization and spectral characteristics of X-ray sources, revolutionizing our understanding of high-energy astrophysics. The remarkable success of XPoSat stands as a strong testament to India's expanding space capabilities, with its mission operations playing a crucial role in establishing this significant milestone.

Acknowledgements

With profound respect, we convey our deepest gratitude to the distinguished Chairman of ISRO, Dr. V. Narayanan,whose unwavering support and guidance have been instrumental in advancing research and innovation, contributing significantly to the successful execution of XPoSat mission operations at ISTRAC, ISRO. We wholeheartedly recognize the exceptional dedication, skill, and resilience of the entire XPoSat Mission Operations Team at ISTRAC. Their unwavering pursuit of operational excellence and precision has been key to the flawless execution of this groundbreaking mission during its first year in orbit. Our sincere appreciation to Dr. K. V. Madhu, Mission Director, XPoSat, whose steadfast guidance have been pivotal in navigating the complexities of this groundbreaking endeavor. We also extend our sincere gratitude to the Mission Team URSC for their unwavering support, technical brilliance, and ingenuity, which have been the backbone of XPoSat's operational success, overcoming the formidable challenges of space. Additionally, we acknowledge the vital contributions of scientists, engineers, and support personnel from ISRO's diverse centers. Their combined expertise and collaborative efforts are

key drivers in advancing India's progress in space science and astrophysics. This mission stands as a reflection of their unwavering dedication to discovery, a celebration of human curiosity, and a pivotal step in unlocking the secrets of the cosmos that define the very fabric of our universe.

References

[1]Taverna, R., Turolla, R., Muleri, F., Heyl, J., & Zane, S. (2022). Polarized X-rays from a Magnetar.Science, 378(6620), 646-650.

[2] Ehlert, S. R., Ferrazzoli, R., Marinucci, A., Marshall, H. L., & Middei, R. (2022). Limits on X-Ray Polarization at the Core of Centaurus A as Observed with the Imaging X-Ray Polarimetry Explorer.The Astrophysical Journal, 935(1), 1-8.

[3] Negro, M., Di Lalla, N., Omodei, N., Veres, P., & Silvestri, S. (2023). The IXPE View of GRB 221009A.The Astrophysical Journal Letters, 945(1), L1-L6.

[4] Vadawale, S. V., Chattopadhyay, T., Mithun, N. P. S., Rao, A. R., & Bhattacharya, D. (2018). Phase-resolved X-ray Polarimetry of the Crab Pulsar with the AstroSat CZT Imager. Nature Astronomy, 2(1), 50-55.