

REVIEW ARTICLE

Advancements and Challenges in X - ray Astronomy Based on Wolter - 1 Optics

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ABSTRACT: X-ray astronomy, a new discipline of study in astrophysics, has emerged because of the advancements in high-resolution X-ray telescopes. It was a challenging time faced by X-ray astronomers to invent space borne technologies from ground based existing technologies. Since X-ray get absorbed by the atmosphere of earth, a few rocket flights, and satellites, carrying X-ray telescopes, were launched in succession from 1960-70s. Further, to enhance our view of space, there was a challenge to design an X-ray telescope having a large collecting area as well as high angular resolution. The configuration development of the astronomical telescopes to the most adopted Wolter-1 type geometry (paraboloid+hyperboloid system) revolutionised X-ray astronomy. This continuous technological development in space-borne telescopes has led to an accurate and detailed study of X-ray stellar objects. This review aims to examine the developments in X-ray astronomy from the rockets carrying telescopes in the 1960s to the present space observatories. Further, to describe performance capabilities of X-ray telescopes used in various observatories, the orbital and physical parameters associated with them have also been highlighted. It also addresses technical challenges encountered during the journey. It will act as a basic structure and a reference to help in research dedicated to X-ray astronomy since inclusion of Wolter optics.

Keywords: Astronomy, X-ray telescope, Grazing incidence, Wolter type I.

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1. INTRODUCTION

The era of studying stellar objects emitting high-energy gamma and X-ray, commenced in the middle of the twentieth century around the 1960s. Before that scientist had recognized the sun as a powerful source within these wavebands but they had not detected any other stellar source carry in this energy region. Therefore, there was an emerging need for sending spacecraft which could

carry out scientific experiments for studying these rays [1]. This resulted in carrying X-ray telescopes in balloons or rockets positioned above the atmosphere [2]. Later, Satellites were the best option for X-ray detection in comparison to carriers because of their longer lifespan. W.C. Röntgen (1885), discovered X-ray and found difficulty in making optics for these rays, as they cannot be concentrated by lenses due to weak interaction of these rays with material [3, 4]. Enrico Fermi (1922) performed experiments on X-ray using pseudo-cylindrical mica optics based upon von Hamos configuration. He obtained successfully first-time converging X-ray using focusing methods employing grazing-incidence for reflection and Bragg diffraction from mica crystals [5]. In the same year, A. Compton achieved the total reflection using polished surfaces at grazing incidence angles of one degree or less for X-ray [6, 7]. Kirkpatrick-Baez (K-B) (1948) obtained a successful first-time X-ray image using double-reflection grazing incidence paraboloidal shaped in 1960,

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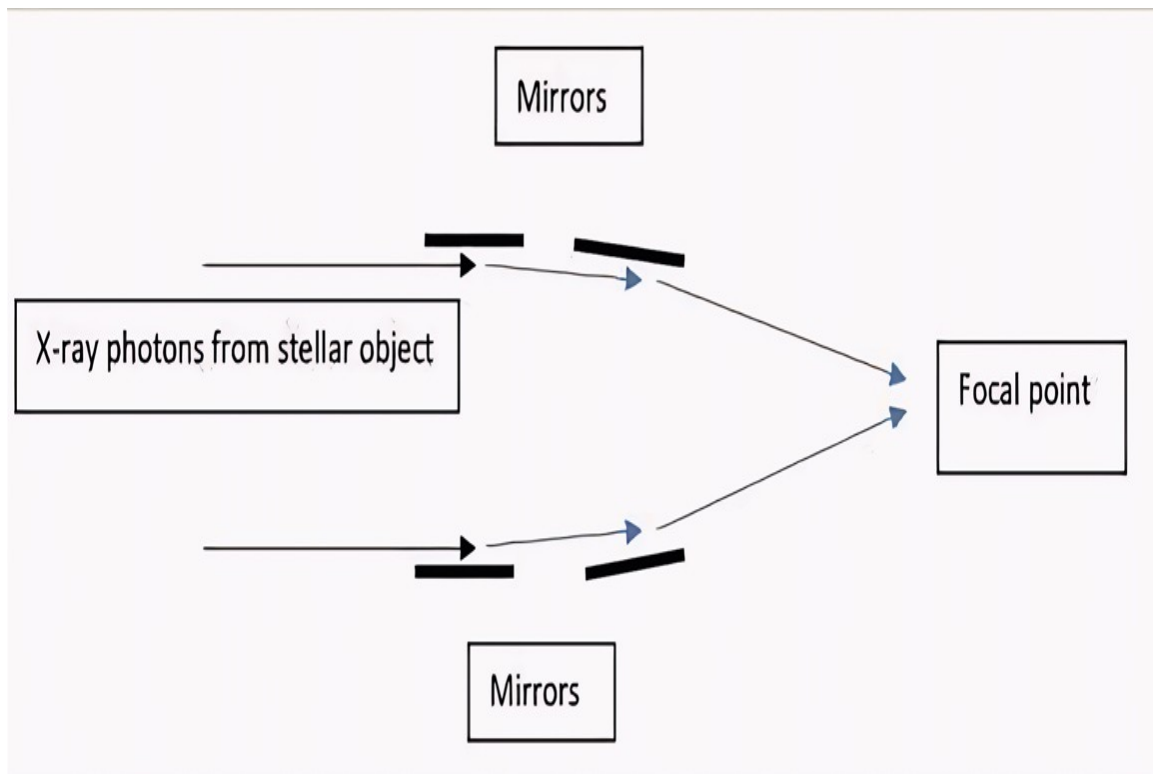


Fig. 1. Grazing incidence technique.

Giacconi and Rossi, mirrors in sequence, this optics is still used for X-ray microscopy applications [8, 9] proposed the usage of grazing-incidence concentrators for concentrating flux from low flux astronomical sources [10]. Furthermore, they proposed nesting of many confocal mirrors for increasing collecting area as well as usage of multiple mirrors' reflections to achieve "image-forming X-ray telescopes" [11]. Giacconi et al [12], were part of the AS&E team (American Science and Engineering) that conducted the first Aerobee 150 sounding rocket flight successfully in 1962 to find a first extra-solar X-ray stellar object [13, 14], Scorpius X-1, in the direction of the Scorpius constellation, which was identified as a pair of stars consisting of a neutron star (NS) with a low-mass companion star.

This finding ushered in a new branch "X-ray astronomy" [1, 12]. In the 1970s, satellites like Uhuru, SAS-3, Ariel5, HEAO-1 and OSO-8 were developed specifically for exploring X-ray astronomy followed by the HEAO series, ASCA, XMM-Newton, Swift, Suzaku, EXOSAT, Ginga, RXTE, ROSAT, Chandra and BeppoSAX (1980s to the early 2000), Nustar and Astro- sat (2012 and 2015) [1].

While telescopes carried up by satellites and rockets were utilised to capture soft X-ray and they captured hard X-ray with balloons only [13]. These telescopes must have a completely different design

from a traditional optical telescope. The highly energetic X-ray photons would easily penetrate the reflector's mirror, so if X-ray photons are to be collected, they must be reflected from a mirror at an extremely small angle called critical grazing incidence of highly dense optical coatings. Therefore, X-ray telescope mirrors are placed such that their surfaces are just off parallel with the incident X-ray [14, 15], typically using Wolter optics [11].

The article comprehensively summarises the advancements in space-borne X-ray observatories based upon Wolter optics. The purpose of the present review follows the evolution of X-ray telescopes since the 1960s. Further, the mission features and scientific advances made by several space-borne observatories are summarised. Furthermore, the orbital and physical aspects related with the X-ray telescopes deployed in these observatories to demonstrate their performance potential have also been highlighted. Apart from section 1 which introduces the need for the X-ray telescopes; section 2, accords a brief overview of grazing incidence and Wolter optics; section 3 deals with various performance parameters associated with space-borne telescopes; section 4 gives a comparative assessment based on performance parameters of various space observatories using X-ray telescopes; section 5 discusses challenges encountered faced in the designing of X-ray telescopes with higher resolution;

followed by the conclusions in section 6. The outcomes of this review article will act as a guide for further research in this domain.

2. X-RAY TELESCOPE

X-ray telescope (XRT) is a specially designed telescope, different from optical telescopes, as it is used to get an image of a stellar (generally faint) object by employing the grazing incidence technique. In this technique, mirror surfaces are placed nearly parallel to incoming X-ray photons and coated with a material which can reflect high energy (consequently small wavelength) X-ray photons at the grazing incidence angle. The telescope is oriented to capture these reflected photons at the focus point. Further, nested, and cylindrical mirrors are used to capture maximum X-rays [2]. The grazing incidence based astronomical systems require the minimum two reflecting surfaces to produce true imaging as single mirrors (such as grazing incidence parabolas) suffer with coma aberration [3, 16]. There are three different configurations using two reflecting surfaces operating at grazing-incidence techniques: Wolter, Kirkpatrick-baez and focusing collimator or 'lobster-eye'. The present study deals with only Wolter type geometry. For X-ray astronomy applications, grazing-incidence configuration exhibiting total reflective phenomenon, larger effective area and increased flux sensitivity are required.

2.1 Grazing Incidence Reflection Theory

There is difficulty in obtaining reflected and refracted X-ray due to its weak interaction with the matter. The reason for this is as the refractive index of a material is greater than one in visible light but becomes very close or less than one in X-ray. The X-ray refractive index, n , is given by [17]

$$n = 1 - \delta + i\beta \quad (1)$$

where δ ($\sim 10^{-4}$ - 10^{-5}) and β ($\sim 10^{-5}$ - 10^{-6}) are optical constants of the material, for the refraction effect and photoelectric absorption of X-ray, respectively [3].

Very small value of δ results in lower reflectivity from a mirror surface, as is evident from the Fresnel equations used for two polarizations—orthogonal to the plane of incidence (s) and parallel to the plane of incidence (p)—for reflection and refraction. [3].

$$r_s = \frac{n_1 \sin \theta_1 - n_2 \sin \theta_2}{n_1 \sin \theta_1 + n_2 \sin \theta_2} \quad (2)$$

$$r_p = \frac{n_1 \sin \theta_2 - n_2 \sin \theta_1}{n_1 \sin \theta_2 + n_2 \sin \theta_1} \quad (3)$$

where n_1 , n_2 , θ_1 , and θ_2 represent the refractive indices of two media, and the angles of incidence and refraction, respectively (Figure 2).

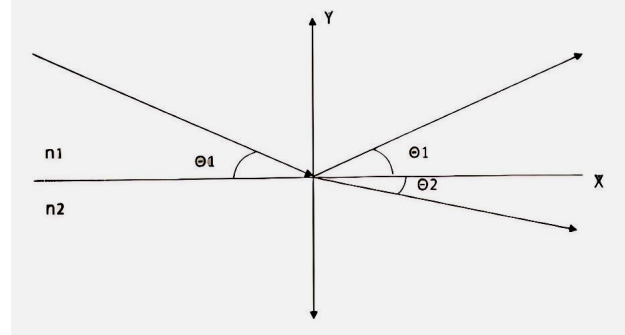


Fig. 2. Phenomenon of reflection and refraction at boundary of two media with refraction indices n_1 and n_2 ; for X-ray, $n_1 = 1$ (for vacuum), and $n_2 < 1$.

As the angle approaches zero, the reflectivity does not diverge to infinity but instead results in total reflection, and the above Fresnel equations become invalid. In particular, total external reflection may occur at a reasonably small grazing incidence angle.

The real part of Eq. (1), $n = 1 - \delta > 1$ for optical wavelengths, but it becomes $n = 1 - \delta < 1$ as the wavelength decreases. Snell's law cannot be satisfied for grazing incidence angles (critical angle) under total reflection. For small values of the incident angle, the ray is totally reflected, and the critical angle approximately becomes

$$\theta_c \approx (2\delta)^{1/2} \quad (4)$$

$$\theta_c \propto \frac{\sqrt{\rho}}{E} \quad (5)$$

The critical angle decreases with increasing X-ray energy (E). Therefore, keeping the incidence angle fixed, X-rays below E_c (cut-off value) can be totally reflected, whereas the use of single-layer X-ray optics is difficult for the determination of hard X-rays having energies > 10 keV. For grazing-incidence mirrors, multi-layer coatings typically consist of several hundred bi-layers that is, an alternating repetition of two different elements used in the mirror. For example, a graded Pt/C multilayer has layer thickness of 2.61 nm to 12.64 nm [18]. This increases the photon energy to approximately 100 keV [16]. Multilayer coatings on grazing incidence mirrors in X-ray telescopes

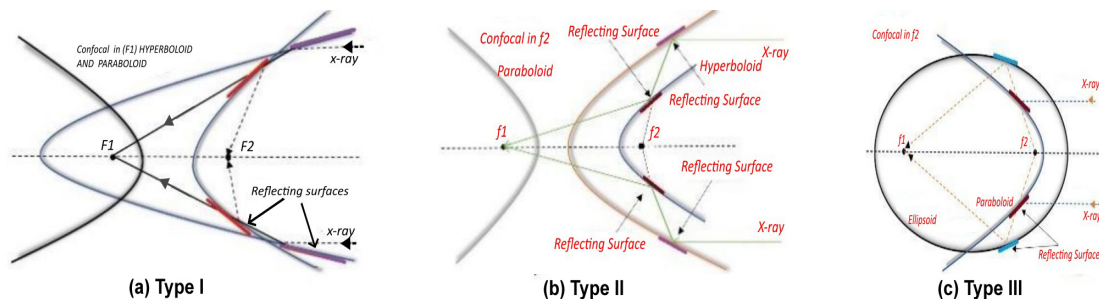


Fig. 3. Adopted Telescopes configurations based on Wolter optics.

Table 1. Presents a summary of the performance parameters of X-ray telescopes, comprising specific instrumentation details, energy ranges of operation, orbit regimes, apogee, perigee, period, payload, coating material, and focal length.

Satellite	Mass (Kgs)	Orbit Regime	Apogee (Km)	Perigee (Km)	Period (min.)	Energy Range (keV)	Payload (HRI/PC with effective area in cm ² @ keV) *	Coating Material	Focal Length (m)
Uhuru	141.5	Low Earth	560	520	96	2-20	2 PC-840@2-20	-	3.5
Einstein (HEAO ₂)	3130	Low Earth	476	465	94	0.2-20	PC-100@0.4-4.0, MPC-667@1.5-20, HRI-5-20@0.15-3	Gold	3.4
ROSAT	2421	Low Earth	580	580	96	0.1-2.5	2 PSPC-/240@1, HRI-80@1	Zerodur	2.4
RXTE	3200	Low Earth	409	409	92.6	2-250	PCA-6500@2-60, HEXTE-2x800@15-250	-	-
BeppoSAX	480	Low Earth	594	575	96.4	0.1-300	4 FTs HPGSPC-240@30	-	1.85
Chandra	4790	Highly Elliptic	134527.6	14307.9	3840	0.1-10	HRMA-800 and 400@0.25 and 5	Iridium	10
XMM-Newton	3234	Elliptic	112877.6	5662.7	2789.9	0.1-15	3 XRT-1500@1	Gold	7.5
Suzaku	1600	Low Earth	550	550	96	0.2-600	5 XRT	Gold	4.75
NuSTAR	171	Near Equator	612.6	596.6	96.8	3-79	DXRT-2 sets of 133 multilayer mirror shells	Pt/SiC and W/Si	10.14
Astrosat	1470	Near Equator	654.9	643.5	97.6	0.3-100	UVIT, LAXPC-8000@10 and SXRT-120@1	Gold Coated	2
XRISM	2300	Low Earth	550	550	96	0.4-13	Xtend(SXI) 420@1.5 and 310@6	Gold Coated	5.6

* ISS-International Space Station; FT - Focusing Telescope; DXRT - Dual XRT; MPC-Monitor PC, HEXTE-High Energy X-ray Timing Experiment, HPGSPC-High Pressure Gas Scintillator PC, PGC-Proportional Gas Counter, LAXPC-large Area Xenon PC, SXI-Soft X-Ray Imager.

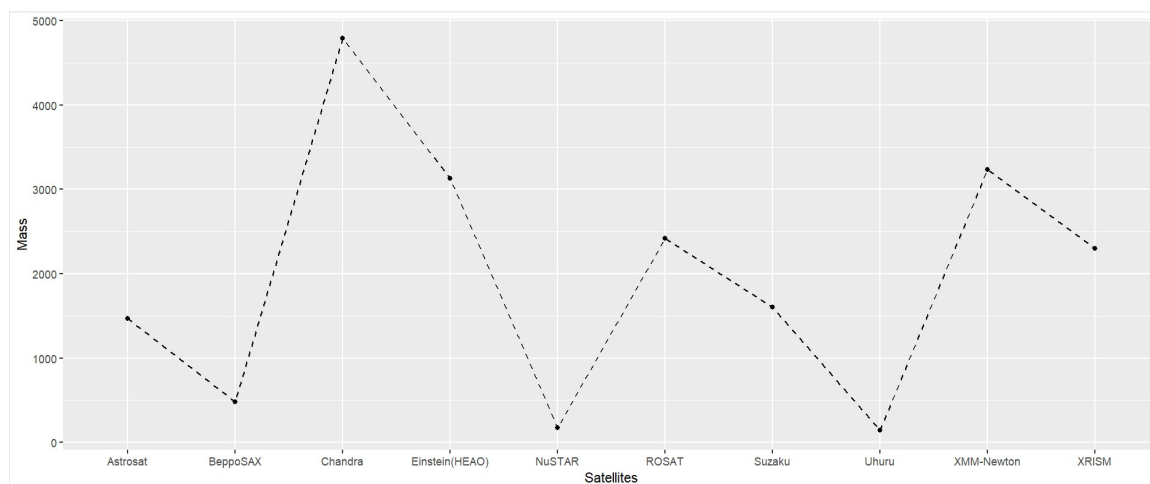


Fig. 4. Plot of Satellites Masses.

significantly enhance reflectivity at shallow angles by utilizing alternating layers of materials to create constructive interference, enabling optimized performance for specific X-ray energies, such as around 100 keV, while reducing sensitivity to surface roughness effects. Further, imaging parameters are adjusted normally by taking complete tracing of rays including reflectivity produced by material coating, which usually change significantly with energy. In XMM-Newton telescopes, all 58 Wolter type 1 mirror pairs were gold coated, resulting in energy dependence of the collecting area [16].

2.2 Grazing Incidence Telescopes

Hans Wolter developed three versions of Wolter imaging grazing-incidence telescopes in 1952, called Type I, Type II and Type III [19] (Figure 3). A hyperboloid and a paraboloid are used in Type I and Type II whereas an ellipsoidal mirror and a paraboloidal are used in type III, using two mirrors in confocal and coaxial arrangement in each type of telescope to focus and produce real image [16]. The differentiating parameter of these telescopes is the ratio calculated by taking the focal length to the total system length (physical length of telescope) [3].

In Type I, focal length is calculated from the intersection of the paraboloid/hyperboloid plane to the focus of the system such that the physical length of the system always comes out to be greater than the focal distance by the extent of the paraboloid. This telescope arrangement is preferred in space observatories due to its simple configuration, compactness and interface with mounting structure providing free space such that telescopes can be easily added outside and inside. The multiple components assisting telescopes known as nested systems, can increase collecting area substantially. Type II telescopes have larger focal lengths which further increase the length of the system and are useful for feeding spectrometers. Whereas Type III telescopes have the shortest focal length unsuitable for nested systems [3, 16].

Out of three types, nested systems of type I telescopes are used in solar X-ray study and in various space borne observatories such as Einstein [20, 21], ROSAT [22], Exosat [23], Suzaku [20], Chandra [24, 25] and Swift mission [26, 27]. The three X-ray telescopes onboard XMM-Newton [28] carried 58 nested paraboloid /hyperboloid Wolter type 1 mirror shell pairs.

3. X-RAY DETECTORS

The X-ray detectors used for detecting photons are

Proportional Counters, Charge- Coupled Devices, Microchannel Plates [29], Scintillators, CdZnTe detectors, Microcalorimeters [18].

Proportional Counters (PCs) are the primary detectors used to detect incoming X-ray. These detectors are still widely used whereas the latest PCs are enabled to detect location, arrival time, and energy of incoming photons. Naming a few examples of PCs flown on X-ray observatory are IPC (Imaging PC) the Einstein, PSPC (Position Sensitive PC) on ROSAT and PCA (PC Array) on the RXTE.

Further, Charge-Coupled Devices (CCDs) record images of incoming X-ray photons in the form of pixels when a photon collides with detector material. They are used like PCs to detect location, observe arrival time and energy of X-ray photons. Naming a few examples of usage of CCDs in ASCA as Solid-State Imaging Spectrograph, in Chandra as ACIS (Advanced CCD Imaging Spectrometer) and in XMM-Newton as EPIC (European Photon Imaging Camera).

Microchannel Plates (MCP) help to provide the finest spatial resolution for any kind of X-ray detector. It consists of innumerable exceptionally very narrow lead-oxide glass tubes, that are coated on the inside with photosensitive material. Naming a few examples of its usage, first time onboard Einstein was HRI (High Resolution Imager) and then in ROSAT, where they have the best spatial resolution in Chandra as HRC (High Resolution Camera) respectively. Solid-state detectors and scintillation detectors are also used in detection of X-ray [30].

Scintillators are used in the energy region above 50 KeV after which PCs are not effective enough as the incident X-ray cannot be absorbed by the gases. The name “scintillator” comes from the fact that the crystal used in this setup scintillates that is, it emits a photon in the visible range of Electromagnetic Spectrum when an X-ray is absorbed and then the photons are collected in the Photomultiplier Tubes (PMTs). Two crystals used and the combination of these crystals is called Phosphorus Sandwich or “Phoswich”. In RXTE, BeppoSAX, a combination of NaI(top) and CsI(bottom) was used [15, 31, 32]. The top crystal is used for detection and bottom one for the background rejection. In Suzaku, a combination of Ce-doped Gd₂SiO₅(top) and Bi₄Ge₃O₁₂(bottom) was used.

CdZnTe(CZT) detectors are used in the energy region of 10 keV for X-ray detection. Since its a semiconductor, its operations are similar to that of the CCDs. The reason, a CZT is used is because it is an improvement upon CCDs as it has higher cross section for detecting the absorption and hence higher

Quantum Efficiency(QE), that is, the probability that given we have a photon striking the detector and the event actually getting detected. In the range of 10-100 keV, a few percent of energy resolution are achievable. It is used in Swift, Nustar [33, 34].

Microcalorimeters come as an improvement over the CCDs and MCPs as they detect the incoming energies by measuring the change in temperature of a small block. This can be used to detect an energy resolution up to 6 keV. Suzaku had one microcalorimeter which showed an energy resolution up to 7 keV for the initial calibrations [35]. The difficulty with this system is that the change detected is very small (order of a few millikelvins) [36]. Hence it needs to be adjusted and made more thermally sensitive.

3.1 Performance Parameters

There are many important parameters such as collecting area, detector sensitivity and angular resolution [15] that impact an X-ray telescope's imaging performance. Further, the performance parameters determine the optical performance resulting in an increased sensitivity towards the detection of sources and their spectral flux. We are going to discuss a few of them and how these parameters affect the observational capabilities of X-ray satellites.

3.1.1 Total Effective Area (A_{eff})

The collective or total effective area of a group of X-ray telescopes, $A_{\text{eff}}(E)$, is energy-dependent and can be calculated as the summation of areas of individual mirror shells Eq. (1).

$$A_{\text{eff}}(E) = \sum_s A_{\text{eff},s}(E) \cong \sum_s A_{\text{ap},s} * R^2(E, \theta) \quad (6)$$

where $A_{\text{ap},s}$ is energy independent and is taken as the geometric area of the aperture of the mirror shell, whereas $R(E, \theta)$ is energy dependent and represents the reflectance at a grazing angle, which is the same as the axial slope θ_s of the primary mirror. The term $\sum_s A_{\text{eff},s}(E)$ represents the summation over different components or modules of the telescope array, where each part contributes its own effective area. It accounts for the combined capabilities of all individual telescopes in the array. The term 's' relates to aperture representing the area through which X-ray enter the telescope. A larger aperture area generally results in a larger effective area, which, in turn, enhances the telescope's sensitivity.

3.1.1 Angular Resolution

Angular Resolution is another important performance parameter, specified by HPD (half-power diameter) or HEW (half-energy width), and FWHM (Full Width at Half Maximum).

To understand angular resolution, we first define PSF (Point Spread Function). A PSF is simply an intensity distribution of the light source. A typical PSF that is used for the calculation of angular resolution for HPD/HEW and FWHM is the Gaussian distribution. The intensity distribution arises simply because the light source is generally not concentrated at one pixel or a few pixels when viewed. This can be due to the defects in the mirror surfaces, also called microroughness, misalignments during installation processes etc. which affect the resolution of the telescope detectors.

HPD refers to the angular diameter of the circle that contains half of the total power or intensity of a point source. If you imagine the point source of light as a spot on an image, the HPD is the diameter of the circle around that spot within which half of the total light or energy is contained. If you have an intensity distribution, HPD is the angle between two points on opposite sides of the peak where the intensity drops to half.

HEW is similar to HPD but is often used in the context of X-ray optics. It refers to the angular diameter of the circle that contains half of the total energy emitted by a point source. HEW provides a measure of the spatial resolution while taking into account the energy spread of the X-ray. Smaller HEW indicates better spatial resolution, considering the distribution of energy.

To understand HPD/HEW better, we can take the example of a 2-D Gaussian distribution function. This is an ideal case to demonstrate a basic calculation of the angular resolution parameter based on HPD/HEW and FWHM. For a more realistic calculation, extended power-law wings are used. The wings are simply an increased energy on the periphery of a point which if not taken into account can give us a poor approximation of the angular resolution parameter [37].

We can define a typical intensity distribution with peak intensity I_0 , Standard Deviation (width parameter) σ as

$$I(r) = I_0 \exp\left(-\frac{r^2}{2\sigma^2}\right) \quad (7)$$

We can find the value of I_0 by the normalization condition, in the polar coordinates as:

$$\int_0^{2\pi} \int_0^r I(r) r dr d\theta = 1 \quad (8)$$

So, we get:

$$I(r) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) \quad (9)$$

Where $I_0 = \frac{1}{2\pi\sigma^2}$. Now, we calculate the EEF (Energy Encircled Function), which is defined as the integral of $I(r)$ up to a particular radius $r = R$.

$$\int_0^{2\pi} \int_0^R I(r) r dr d\theta = 1 - \exp\left(-\frac{R^2}{2\sigma^2}\right) \quad (10)$$

For HPD, we know, the value should be at 50% the energy hence,

$$\frac{1}{2} = 1 - \exp\left(-\frac{R^2}{2\sigma^2}\right) \quad (11)$$

$$R = \sigma\sqrt{2\ln(2)} \quad (12)$$

Since HPD is a diameter,

$$D_{(\text{at } 50\% \text{ energy})} = 2\sigma\sqrt{2\ln(2)} \quad (13)$$

In case of FWHM, it would be the length across any two points where the intensity of the peak is at half its value. In our example, FWHM happens to have the same value as the HPD by the following calculation, due to the circular symmetry of the function. From (7) and the definition, we have:

$$I(r_{1/2}) = \frac{I_0}{2} \quad (14)$$

$$r_{1/2} = \sigma\sqrt{2\ln(2)} \quad (15)$$

$$2r_{1/2} = 2\sigma\sqrt{2\ln(2)} \quad (16)$$

The value of the angular resolution is typically given in arcseconds. We can think of angular resolution as the sharpness of the telescope. Its ability to distinguish fine details. For example, we have the value of angular resolution (HPD) of ROSAT satellite as $\sim 26''$. This is defined using more sophisticated PSFs [38].

HPD gives better results as compared to FWHM for image resolution. This is because the HPD accounts better for extended wings about a scattered point that we discussed earlier. FWHM's calculations do not take those effects into account which results in an error prone calibration value. The real-world images of course, do not exactly map as a perfect Gaussian distribution and hence the preference for HPD [39]. A benefit of higher angular resolution is the ability to detect and measure energy from weak unresolved sources. In the case of a high angular resolution, it is very unlikely for a background event to be associated with a non-X-ray source, resulting in reduced background detection.

3.1.3 X-Ray Reflectance

X-rays can show mirror-like reflection from a surface under two conditions: when the rays fall on the surface at grazing incidence, and when, due to the varying atomic number of the layers in a periodic manner, constructive interference takes place.

In the complex expression for the index of refraction, $n_r - ik$, we have $n_r < 1$ for wavelengths in the X-ray range. Thus, X-rays travelling through a vacuum encounter an interface with lower optical density. Using Fresnel's equations for a complex index of refraction, we can calculate the reflectance. The atomic scattering factors (forward), f_1 and f_2 , are used to determine the real and imaginary parts of the refractive index.

$$n_r = 1 - \delta = 1 - \frac{\rho}{W_m} A_0 r_e \lambda^2 f_1 \cdot \frac{1}{2\pi} \quad (17)$$

$$k = \frac{\rho}{W_m} A_0 r_e \lambda^2 f_2 \cdot \frac{1}{2\pi}$$

where A_0 is Avogadro's number, λ represents the wavelength of the incident X-rays, W_m is the molar weight of the reflecting material, r_e is the classical electron radius, and ρ is the density of the material. The quantity f_1 is the atomic scattering factor corresponding to the real part of the complex index of refraction; it represents the contribution of the scattering amplitude that is in phase with the incident wave. Similarly, f_2 is the atomic scattering factor corresponding to the imaginary part of the complex index of refraction; it represents the contribution to the scattering amplitude that is out of phase with the incident wave. The scattering factors depend on both wavelength and material properties. These factors can be computed in various ways, including from measurements of forward scattering amplitude and

by deriving them through measurements of X-ray reflectance [40].

X-ray reflectance is crucial in the design and optimization of X-ray optics. X-ray telescopes, for example, use mirrors coated with special materials that reflect X-rays. Understanding X-ray reflectance is essential for constructing mirrors that can efficiently focus and direct X-rays onto detectors, enabling detailed observations of celestial objects in the X-ray region of the electromagnetic spectrum.

Telescopes such as the Chandra X-ray Observatory use finely polished mirrors coated with materials capable of efficiently reflecting X-rays. This allows astronomers to observe high-energy astrophysical phenomena such as supernova remnants, black holes, and active galactic nuclei.

3.1.4 Detector Sensitivity

The detection sensitivity of an X-ray telescope refers to its ability to detect X-ray photons, especially those coming from celestial sources. It is actually the total observational capability of the telescope, which is the apparent effect of all the above given factors and many more factors that are not mentioned here. Paul B Reid gave a more detailed explanation on detection parameters and designing of X-ray telescopes in Encyclopaedia of Astronomy and Astrophysics [40].

Detection sensitivity can be enhanced with larger collecting area as well as with a high angular resolution which reduces the noise due to background charged particles or an imagined X-ray. A larger collecting area allows more photons (light particles) to be gathered from celestial objects. This increased signal improves the signal-to-noise ratio in the observations. The signal is the desired astrophysical information, while noise is the unwanted background or random fluctuations. With more signals and less noise, the quality of the observed data improves. The resolution of a telescope, its ability to distinguish between closely spaced objects, is influenced by its collecting area. Larger telescopes can achieve higher resolution, allowing astronomers to study finer details in the observed objects. This is important for resolving features such as structures in galaxies, planetary surfaces, or the dynamics of stellar systems. Several of the issues can be resolved by either increasing the collecting area (exposure) for better imaging or fine-tuning the angular frequency [15].

4. ADVANCEMENTS IN X-RAY OBSERVATORIES

Various X-ray observatories were launched into space by different agencies such as NASA (National Aeronautics and Space Administration, United State of America), RFSA (Russian Federal Space Agency, earlier known as Soviet Space Program), ISRO (Indian Space Research Organisation, India), CNSA (China National Space Administration), ESA (European Space Agency), ISAS (Japanese Institute of Space and Astronautical Science) and ASI (Italian Space Agency).

The advancing imaging competency of X-ray telescopes for X-ray astronomy has been used to study and provide important information about various X-ray sources and activities in the stellar objects, including formation and life cycles of stars.

Uhuru was the first satellite, commonly referred to as SAS-1 (Small Astronomical Satellite1) in this direction. Uhuru was launched from Kenya's San Marco platform on December 12, 1970, by NASA, revolutionising X-ray astronomy [41]. The project continued for two years before coming to an end in March 1972 [42]. It provided complete data (4U catalogue) regarding the intensity and positions of 339 discrete X-ray sources, comprising identified stellar objects like Supernovas (SNs), binary stellar systems, clusters, and a new class of superclusters of galaxies, and Seyfert galaxies [43, 44], also observed the first X-ray pulsar Cen X-3 in 1971, in the Centaurus constellation [12].

Uhuru was the first satellite specifically designed for X-ray observations. Before Uhuru, astronomers could only observe celestial objects in visible light or other non-X-ray wavelengths. Uhuru's X-ray observations opened a new window to the universe, allowing scientists to study high-energy processes and objects. Uhuru conducted the first comprehensive survey of the entire X-ray sky, providing astronomers with a map of X-ray sources. This survey laid the groundwork for subsequent X-ray observatories and missions, guiding astronomers in selecting targets for further study.

Uhuru's success demonstrated the feasibility of X-ray astronomy from space. This boosted the research and development of advanced X-ray observatories and telescopes, such as the Chandra X-ray Observatory and XMM-Newton, which became the modern-day advanced devices that enabled us to see further in the X-ray works and contributed to our understanding of high-energy astrophysical processes.

Einstein (HEAO 2) (Einstein observatory), launched from Florida (Cape Canaveral), on November 13, 1978 was the first X-ray telescope, with full imaging capability, to be placed into orbit. It was a critical X-ray mission to examine sky with low angular resolution (few arc-seconds), FOV (Field

of View) -10 arc minutes, with very high sensitivity having effective area $\sim 400 \text{ cm}^2$ at 1keV and the obtained results replaced the perspective of the X-ray. It was successful in detecting X-ray and aligned radio jets from M87 and Cen A and resolution of innumerable X-ray stellar sources in Magellanic clouds and the Andromeda galaxy [3, 17, 45].

ROSAT (Röntgen Satellite), launched on June 1, 1990, functioned over nine years. The mission's first six months were focused on an all-sky survey, succeeded by the pointed phase. ROSAT, with an imaging telescope, having X-ray sensitivity 1000 times greater than Uhuru, was able to complete the first sky survey of XUV and X-ray. ROSAT conducted the first systematic all-sky survey in the soft X-ray band. The ROSAT All-Sky Survey (RASS), completed in 1991, provided a comprehensive map of the entire X-ray sky, detecting and cataloguing numerous X-ray sources. The survey identified over 100,000 X-ray sources, including many new and previously unknown objects.

ROSAT completed in-depth observations of a range of objects during the pointed phase. It was equipped with 2 PSPCs and two detectors for both pointed and survey phases. It has a FOV of $38 \times 38 \text{ arcmin}^2$ and spatial resolution of spatial resolution on the order of arcminutes. Specifically, the HPD for ROSAT was approximately 25 arcseconds. The main objective of the survey was to study bright LMXRBs (Low Mass X-ray Binaries) which have soft X-ray bands (0.1 to 2.4 keV) [46]. It has provided the morphology of detected SNs and galaxy clusters in detail and reported X-ray emissions from comets and molecular clouds [37–47].

ROSAT was used for the identification and further observation of X-ray emission from active galactic nuclei and quasars. These are highly energetic phenomena that are caused by the supermassive black holes at the centres of galaxies.

The spatial resolution of ROSAT was selectively chosen to fulfil certain goals, including the survey of the entire X-ray sky during the ROSAT All-Sky Survey (RASS). Even though not as advanced as some later X-ray telescopes with angular resolution, ROSAT's contributions to X-ray astronomy were substantial due to its wide field of view and ability to systematically scan the entire sky, identifying and cataloguing a large number of X-ray sources.

RXTE (Rossi X-ray Timing Explorer) launched on December 30, 1995, from Florida and positioned it in low-Earth orbit. It was in operation for exactly sixteen years and was terminated in January 2012. Three X-ray equipment were aboard, including HEXTE (High-Energy X-ray Timing Experiment), a set of five PCA with very good time resolution

($\approx 1 \mu\text{s}$) useful in studying the fast timing and continuum energy spectrum and ASM (All-Sky Monitor) consisting of three PCs with low sensitivity and large FOV for ASM. The satellite's major science goal was to investigate very short (μs) to long time scale (several years) variabilities in various short (μs) to long time scale (several years) variabilities in various astronomical stellar sources like magnetars, pulsars, X-ray binary systems, quasars and AGNs (Active Galactic Nuclei). RXTE led to the revelation of kilohertz QPO's and spin periods in LMXRBs. Further afterglows of X-ray were observed after Gamma Ray Bursts (GRB) [48, 49]. BeppoSAX, in 1996, (Satellite for X-ray astronomy under Italian-Dutch partnership) was critical in determining the origin of GRBs. Its key distinguishing feature among previous and future missions was its extremely broad spectral coverage, including good performance in low-medium and medium-high energy bands with the energy ~ 0.1 to 10 keV and 10-200 keV respectively. There were five science instruments in this satellite, in which four NFI (Narrow Field Instruments) took observations over the energy 0.1- 300 keV, and WFC (Wide Field Camera 2 - 30 keV) consisting of 2 coded aperture cameras with coverage of a region of 20×20 degrees (FWHM) on the sky [42]. To handle GRBs over the energy band 60 to 600 keV, lateral shields of PDS were used. BeppoSAX-NFI observed the MCG-6-30-15's spectrum in Seyfert 1 galaxy, in 40,000 seconds, including all the features and spectral components found by previous satellites [43, 50].

Chandra X-ray Observatory is the largest X-ray satellite, launched from the payload bay of space shuttle Columbia by NASA on July 23, 1999, studied stellar objects including quasars, Black Hole (BHs), SNs, which could never be visualised through the naked eye. It is orbiting around Earth, having a range of 14,307.9 to 134,527.6 km. Chandra can observe its target for up to fifty-two hours before losing sight of it. It has four curved mirrors which are embedded inside each other. It consists of a high-resolution camera, transmission gratings, CCDs, and an X-ray telescope. It was equipped with HRMA (High-Resolution Mirror Assembly), having hyperboloid and paraboloid mirrors. It took images of X-ray in sub-arcsecond (0.5 arcsec). It has sixty-four hours of highly eccentric Earth orbits and spatial resolution of less than 1 arcsec with the ability to detect and study thin spectral lines also [13, 51, 52].

Chandra boasts its exceptional angular resolution and its ability to focus X-ray allows it to produce detailed images of X-ray sources with exceptional clarity. Its high angular resolution is used in studying

the fine structure of X-ray-emitting objects, such as the hot gas in galaxy clusters and the surroundings of black holes.

Chandra has played an important part in studying the remnants of exploded stars, known as supernova remnants. A supernova remnant (SNR) is the leftover from a supernova explosion. SNRs play a crucial role in grasping the dynamics of our galaxy. They speed up cosmic rays, warm up the interstellar medium, and disperse heavy elements throughout the galaxy. By observing the X-ray emissions from these remnants, scientists can learn about the processes involved in supernova explosions and the distribution of elements in the universe [53].

Chandra observational prowess has been instrumental in understanding galaxy clusters, the largest gravitationally bound structures in the universe. The X-ray emissions from hot gas within these clusters helps astronomers to investigate the distribution of dark matter and learn more about the large-scale structure of the cosmos.

XMM-Newton (X-ray Multi-Mirror Mission)-Newton (December 10, 1999) was the first satellite carrying an optical monitor besides being equipped with high-precision X-ray telescopes. Highly sensitive observations were made possible due to its wide collecting field and capability for long and undisturbed exposures. High-resolution Reflection Grating Spectrometers (RGS), X-ray telescopes and CCDs were the components of XMM-Newton. Consequently, this satellite was an excellent imager and suitable for spectral analysis, as it functioned in the range of 0.2 to 12 keV [46, 54]. It was equipped with three Wolter Type I telescopes, having an FWHM spatial resolution of 6" with 1500 cm² as an effective area at 1 keV. A wide collecting area and simultaneous observations of X-ray and other optical observations were its special features[47, 48]. The 3XMM catalogue (3XMM-DR5) consisted of 396910 unique X-ray sources out of 565962 X-ray detections, spectra, and light curves for 133000 bright sources, with details about locations on sky and X-ray variability as well as counts and fluxes rates in seven Energy bands and four hardness ratios respectively [13, 54].

Suzaku is the Uchinoura Space Centre (USC) in Japan successfully launched Suzaku (initially named Astro-E2) on July 10, 2005, designed at ISAS in partnership with the United States and was the fifth X-ray astronomy project launched by Japan. The X-ray micro-calorimeter, a novel type of X-ray spectrometer, was carried out for the first time by satellite. It finished its scientific observations in 2015 after ten years of operation [55]. It has produced significant scientific findings by showcasing remarkable observational

abilities, such as achieving the highest level of sensitivity. It detected Aquila X-1, NS LMXB, seven times in 2007[56]. It contained equipment with very wide energy bands (0.3-600keV) and high spectroscopic resolution in the detection of gamma rays and soft X-ray signals. It was equipped with five nested gold-coated grazing incident conical tin-foil X-ray telescopes. The satellite has a broad effective area, lighter particle background and high energy resolution which helped to understand the high-energy astrophysical mechanisms including BHs, galaxy clusters and interstellar medium (ISM) thermodynamics [43, 55, 57].

NuSTAR (Nuclear Spectroscopic Telescope Array) is an X-ray mission having the first focusing optics for hard X-ray (above 10 keV). It was NASA's Science Mission carried out by Caltech and managed by JPL. It was launched from a location close to Kwajalein Atoll using a Pegasus XL rocket on June 13, 2012. It was originally sent for a two-year mission, but it is still collecting data. The mission consisted of two X-ray telescopes, that are used to focus X-ray on two Focal Plane Module Detectors. Further, It has 4 hybrid X-ray detectors consisting of CdZnTe (Cadmium-Zinc-Telluride) sensors at the focal plane. Its sky survey consisted of BHs, NSs, and white dwarf star remnants, monitoring the growth mechanisms of BHs, and mapping of novae, supernovae remnants [58, 59].

Astrosat is the first astronomy mission from India, Astrosat, launched on September 28, 2015, from Sriharikota is devoted to study ultraviolet, optical and X-ray spectral bands. The five payloads consisted of (a) SXRT (Soft XRT) (b) LAXPCs (c) CZTI (Cadmium Zinc-Telluride Imager) (d) UVIT (Ultraviolet Imaging Telescope) and (e) SSM (Scanning Sky Monitor). Further, the electromagnetic spectrum was covered by these payloads in the visible region, near and far ultraviolet region, and hard and soft X-ray regions. Its main missions also included UV band and hard X-ray sky surveys, study of variations in the intensity of AGNs and X-ray Transients [60, 61].

Astrosat is equipped with instruments that can observe celestial objects in different wavelengths, including ultraviolet, optical, and X-ray. The multi-wavelength capability of Astrosat helps it to detect X-ray sources from a wide range of objects and helps astronomers to comprehend complex astrophysical phenomena. Astrosat's Soft X-ray Telescope (SXT) is sensitive to high-energy phenomena such as the emission from hot gases in galactic nuclei that are active, remnants of supernova and X-ray binaries.

The X-ray observations from Astrosat's SXT have been used to study the high-energy processes in

the universe. X-ray are emitted by extremely hot and energetic objects, such as accreting black holes, supernova remnants, and active galactic nuclei. By analysing the X-ray spectra and light curves, scientists gain information about the temperature, density, and composition of the emitting material. This enables us to comprehend the extreme environments around compact objects. Astrosat's X-ray observations contribute to the global efforts in understanding these phenomena.

Astrosat complemented the observations of other X-ray observatories like Chandra and XMM-Newton. Combining the data of each observatory, with all these unique capabilities, allows for a more comprehensive understanding of astrophysical sources. Complementary observations in different wavelengths help cross-validate findings. For instance, optical and X-ray observations together can provide a more complete picture of the emission processes in a given source.

X-ray binaries and gamma-ray bursts are transient events that release significant amounts of X-ray radiation and Astrosat's ability to observe in the X-ray band is used for monitoring and studying these phenomena. The advanced technological capabilities as well as the high sensitivity and quick response mechanisms of Astrosat allow astronomers to capture crucial data during the brief episodes of X-ray emission associated with transient events. Astrosat marked India's entry into the field of space-based astronomy. It enables Indian scientists and researchers to actively participate in cutting-edge astronomical research. The mission has been instrumental in collaborating space based research with other international space organizations and boosted the growth of international X-ray astronomical research.

XRISM (X-Ray Imaging and Spectroscopy Mission) was launched on 7th September, 2023. It is a JAXA led mission with a joint collaboration from NASA and ESA. Some of the key objectives of the mission are - 1) To Understand the evolution and formation of big structures of cosmic scales. Galaxy clusters are of key importance with measurements focused on temperatures, velocities and hot X-ray emitting plasmas. 2) To try and sketch a history of baryonic matter circulating in space by studying the mass and chemical compositions, especially of supernova remnants, plasmas and other sources. 3) To understand the evolution of the galaxies and their supermassive blackholes. 4) To achieve major discovery using extremely high resolution X-ray Spectroscopy. The features of fine spectral can be used to understand the plasma ionization history. The high resolution of the telescope can enable it to detect gravitational redshifts [62].

XRISM has two types of instruments. It has Xtend which is its soft X-ray imaging telescope, working together with Resolve (XRISM component) to achieve high resolution spectroscopy imaging. Xtend consists of the Soft X-Ray Imager (SXI) (an X-ray CCD camera) and an X-ray Mirror Assembly (XMA) with a focal length of 5.6m. Xtend gives a 38' x 38' (FOV) Field of View, which at the same time covers the 3' x 3' FOV of Resolve. It operates in the energy range of 0.4 - 13 KeV, but remains a bit sensitive beyond this band. SXI utilizes four P-channel types of back illuminated CCDs with a 200 μm . It is in a 2x2 grid with temperature below -110°C. Xtend has a sharp point-spread function with FWHM 10'' and a mirror HPD of about 1.3', allowing it to resolve spatial structures and detect point sources. The in-orbit energy resolution is ~ 180 eV (FWHM) at 5.9 keV, which satisfies the mission requirement of 200 eV at the beginning of life. Xtend has strong sensitivity in the 5–10 keV band, with an effective area about 350 cm^2 at 6 keV, making it particularly good for studying Fe-group emission lines. Xtend has a low, stable, and clean non-X-ray background (NXB) with no strong instrumental lines overlapping major astrophysical lines. All in-orbit performances (FoV, HPD, effective area, energy resolution, background, contamination) are consistent with ground calibration results and meet mission requirements [63].

XRISM's observations are of massive significance. Its Resolve instrument measured that the Si and S emission lines are relatively narrow but the Fe emission lines are very broad (~ 1670 km/s), showing that hot shocked ejecta are expanding at high speeds and differ from the swept-up interstellar gas. The Fe Ly α line is redshifted by 890 km/s, which is much larger than the surrounding interstellar medium's speed, meaning the Fe ejecta are moving differently from their environment [64]. XRISM detected two weak spectral features at 2.41 keV and 2.63 keV that significantly improve fits when modelled as charge-exchange emission, implying interactions between hot ions and neutral gas. The charge-exchange contribution is constrained to be $\leq \sim 4\%$ of the total X-ray flux in the 1.7–3.0 keV band, showing that charge exchange is present but a minor component in this remnant's X-ray emission [65]. XRISM Resolve spectra of SN 1987A show the X-ray emission is well described by a single shock model with temperature ~ 2.84 keV, and the metal abundances match the Large Magellanic Cloud, indicating the X-rays arise from shock-heated ejecta that are not metal-rich. The Doppler broadening of the Si, S, and Fe emission lines corresponds to expansion velocities of about 1500–1700 km s^{-1} , showing that the observed line widths are

primarily caused by the large-scale bulk motion of the ejecta, rather than by thermal motion of the ions. For the first time, XRISM/Resolve found that the Fe $K\alpha$ fluorescence line's radial velocity varies with orbital phase in the X-ray binary Centaurus X-3, showing sinusoidal modulation. The velocity amplitude (~ 248 km/s) is smaller than expected if the fluorescence came from the neutron star surface, implying that the Fe $K\alpha$ emission likely originates from material far from the neutron star, such as the companion's surface or wind [66]. The era of X-ray astronomy started with Uhuru, which led the first mission to orbit the earth. Uhuru (1970-72), was able to provide the first survey (all sky) having 10-3 times Crab intensity as the sensitivity and indicated that most of galactic X-ray sources were not "transient", having outbursts due to changes in accretion rate.

Later, Einstein was equipped with an X-ray telescope having full imaging capabilities. Einstein (1978-1981), with Wolter type 1 incidence and high-resolution spectroscopy, was the first to perform deep and medium X-ray surveys. Einstein was able to observe for the first-time diffuse emission, extended objects, and identify faded sources. Sky survey with ROSAT (1990-1999), reported more than 150000 objects for the first time with the usage of a highly sensitive imaging telescope. RXTE (1995-2012) was associated with a soft X-Ray monitor (all sky) having resolution (1995-2012) was associated with a soft X-Ray monitor (all Sky) having resolution ($\approx 1\mu$ s) and a large collecting area.

BeppoSAX (1996-2003) was associated with energy coverage in broad-band and remarkable accuracy in defining the locations of X-ray sources emitting GRBs. XMM-Newton (1999) could take optical and X-ray observations concurrently because of the large collecting area. Also, NuSTAR (2012-) has broad area coverage on hard X-ray focusing on higher X-ray energies. Suzaku (2005-2015) was the very first satellite, to be equipped with a X-ray microcalorimeter, that offers remarkable energy resolution in comparison to non-dispersive equipment.

Under the active mission, Chandra (1999-) acted as the best and unique imager due to its small angular resolution in sub-arcseconds with gratings among all the X-ray instruments. It studied black matter at the centre of the Milky way galaxy and during collisions of galaxies.

5. CHALLENGES

Since the Earth's atmosphere absorbs X-ray, astronomers and scientists had to overcome

significant obstacles to adapt and advance technology employed in ground-based equipment and create new technologies that could be operated in space.

Further the Instruments, because of launch vehicle constraints, had to be small and light Furthermore, to endure vibrations and temperature changes, they needed to be robust and extremely sensitive since few photons reach the detectors from the cosmic X-ray sources since manual modification and change of equipment were not possible after launch, the equipment therefore had to be highly reliable to give stable output and compatible with distant telemetry networks [67]. The detectors used in satellites must have greater efficiency across vast areas, be operational at ambient temperatures, and highly durable for long duration missions.

X-ray telescope's imaging performance is identified by two key parameters: collecting area and angular resolution. Further because of envelope and mass constraints, it is difficult to enhance both parameters at the same time. As reduced mass decreases stiffness, resulting in degradation of the obtained image [14]. This requires co-aligned heavily nested grazing incidence imaging X-ray telescopes. It is a challenge to design an X-ray telescope having a large collecting area as well as high angular resolution. Further, this can be addressed using adaptive X-ray optics by concentrating flux on a very small detection area, resulting in a substantial decrease in the background leading to an increase in sensitivity improvement [43]. The next-generation missions are to be developed to meet the challenge of having a very large collecting area and very fine angular resolution in the same telescope. The follow-up Chandra mission, Lynx, seems to be transformed due to its extremely high sensitivity, FOV, absolute spectrum resolution and survey speed [43].

6. CURRENT DEVELOPMENTS IN X-RAY ASTRONOMY

Scientists and space agencies around the globe are constantly in search of new ways to improve the current technology and to introduce new technologies in the field of X-ray astronomy. These conquests include hatching of plans for newer and advanced observatories, improved collaboration with global space agencies, improving detector technologies, advances in X-ray optics and upgrading the existing observatories with advanced technologies.

6.1 Next-Generation X-Ray Observatories

Scientists and space agencies are exploring the possibility of developing next-generation X-ray observatories with improved capabilities. These concepts often involve advanced technologies to enhance sensitivity, resolution, and versatility in observing different types of X-ray sources. For this purpose, various missions are being undertaken by space agencies to establish new and advanced observatories. A few of them are discussed below.

6.1.1 Lynx X-Ray Observatory

Lynx is a concept for a large X-ray observatory being studied by NASA in collaboration with other space agencies. It is designed to be a successor to the Chandra X-ray Observatory, with improved capabilities for high-resolution imaging and spectroscopy. Lynx aims to address a wide range of scientific questions, including the study of the early universe, galaxy formation, and the physics of black holes and neutron stars.

6.1.2 Athena (Advanced Telescope For High-Energy Astrophysics)

ATHENA is an X-ray telescope mission led by the European Space Agency (ESA). It is designed to investigate the hot and energetic universe, including the study of galaxy clusters, active galactic nuclei, and the effects of accretion around black holes. ATHENA is equipped with advanced X-ray optics and detectors for high-resolution spectroscopy.

6.1.3 eROSITA (Extended Roentgen Survey With An Imaging Telescope Array))

While eROSITA is already operational, it is worth mentioning because it is a German-Russian X-ray telescope designed to conduct an all-sky survey in the X-ray band. eROSITA is a part of the Russian-German "Spectrum-Roentgen-Gamma" (SRG) mission and aims to discover and study a large number of X-ray sources, including galaxy clusters and active galactic nuclei.

6.1.4 The High Energy X-Ray Probe))

The High Energy X-ray Probe represents a proposed NASA probe-class venture that merges high angular resolution with an extensive X-ray bandpass to deliver the crucial advancement in capabilities required to tackle the significant astrophysical inquiries of the upcoming decade. HEX-P attains revolutionary performance through the integration of technologies cultivated by proficient international collaborators.

HEX-P is scheduled for launch to L1 to optimize observing capabilities. To achieve the scientific objectives, the payload comprises a set of X-ray telescopes aligned together to cover the 0.2–80 keV bandpass. The High Energy Telescope (HET) has an effective bandpass spanning 2–80 keV, while the Low Energy Telescope (LET) covers 0.2–20 keV effectively [68]. The integration of bandpass and high observation effectiveness provides a robust framework for diverse scientific research to benefit a broad audience. The initial mission duration spans five years, with 70% of the observation period allocated to a General Observer (GO) program and 30% to the Principal Investigator (PI)-led initiative [68].

6.2 Advancements In X-Ray Optics

6.2.1 Silicon Pore Optics))

Silicon pore optics (SPO) technologies have been extensively studied and developed to be incorporated in the ESA's future ATHENA observatory, aiming to achieve a large collecting area while being lightweight enough to be launched and a target of ~ 9 arcsec HEW at 1KeV [69]. SPOs are manufactured using 300 mm monocrystalline silicon wafers, which are manufactured with high intrinsic surface quality. They are first grooved, wedged, and then elastically bent and stacked to form rigid mirror modules. This stacking process creates thousands of narrow rectangular pores functioning as grazing-incidence reflection channels that approximate Wolter-I geometry, hence called SPO [70]. This modular architecture enables the production of mirrors with a large effective collecting area and low mass without compromising structural integrity. This scalability, reproducibility, and favorable area-to-mass ratio of SPOs represent a breakthrough in X-ray mirror manufacturing.

6.2.2 Silicone Meta-Shell Optics))

Silicon meta-shell X-Ray Optics (SMO) is a modular approach to fabricate and integrate X-ray satellite mirror assembly and has been primarily developed in the context of NASA's future Lynx observatory, to meet its stringent sub-arcsecond angular resolution and collecting area requirements: however, the technology is mission-agnostic and is considered generally as a candidate for next-generation X-Ray observatories. SMO utilizes radially stacked, thin monocrystalline silicon shells with a thickness of 0.5 mm. Commercially available Si blocks are round and polished to a Wolter-conical contour, then sliced and polished to thin shells, which are subsequently

coated with stress-compensated films and aligned radially using kinematic spacers to form a mirror segment. This process allows for lower mass while retaining high stiffness and thermal stability. In X-ray tests, early SMO modules (paired shells on a stiff mid plate) produced $\approx 1.3''$ HPD images at 4.5keV and showed measured effective area within $\sim 2\%$ of the modelled value [71]. Due to the high throughput and repeatability of the manufacturing process, SMO remains one of the most promising technological breakthroughs in x-ray optics.

6.2.4 Slumped Glass Mirror Segments))

Alongside SPO and SMO which are mostly used for soft X-rays, slumped glass mirror segments remain a major technological route for hard X-ray optics. The process uses thin glass foils (0.4mm to 0.5 mm thick), which are first heated and slumped into a cylindrical shape. These cylindrical foils are stacked on top of an integration mould that has a Wolter-1 type profile. Glass spacers are glued between the glass layers and as the stack gets built, the spacers press the shells into the mould and effectively make them adopt the shape of the mould. Once everything is set, the glue hardens and spacers, which are referred to as ribs, endow the structure with high stiffness [72]. Since the hot slumping process compromised the intrinsic strength of the glass shells, simulations were done to use chemically tempered Corning Gorilla Glass to improve mechanical survivability. Early Schott AF-22 prototypes achieved 22 arcsec HEW on full illumination X-ray tests. On adopting the new chemically tempered gorilla glass technology, the expected angular resolution of 5.8-8.2 arcsec HEW was obtained after tempering. Tempering also restored and enhanced mechanical strength, which went down from 117-82 MPa on slumping, to strength >800 MPa, satisfying the minimum launch survivability criteria [72–88]. Thus, slumped glass mirror technology with the latest chemically tempered adaptation remains one of the strongest candidates for future hard X-ray astronomy missions. A summary of the various performance parameters of X-ray telescopes, in satellites is highlighted in Table 1.

7. CONCLUSION

A brief history of space borne observatories has been reviewed in this article, with an emphasis on their technical specifications, particularly various performance parameters of X-ray telescopes. Further,

the special features and outstanding scientific accomplishments of various missions by global space agencies have also been emphasised. A brief review on the challenges faced by modern X-ray astronomy and steps taken to overcome those challenges have also been discussed. X-ray astronomy got revolutionised after the introduction of grazing-incidence X-ray optics, which increased the database from the first All sky X-ray source catalogue of few hundred sources in 1972 to the presently available Chandra deep field data of more than 10000 X-ray sources/square degree, overcoming all the technological challenges successfully during journey. It is now possible to study high energy universe phenomena such as X-ray binary systems, X-ray transients, isolated and accreting NSs, PWNs, SNRs, BHs, GRBs, dark energy and dark matter, because of the technical advancements since 1970. Information from such observatories continues to help us in understanding the characteristics and processes that release x- rays in outer space. Although some of the satellites covered in this study are not operational at present, the knowledge they contributed is important for X-ray astronomy studies. Grazing incidence-based X-ray astronomy appears to be one of the most promising branches of science today and will continue to help mankind in exploring the universe.

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DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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