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Generation-X: An X-ray observatory designed to observe first light objects

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Abstract

The new cosmological frontier will be the study of the very first stars, galaxies and black holes in the early Universe. These objects are invisible to the current generation of X-ray telescopes, such as Chandra. In response, the Generation-X (“Gen-X”) Vision Mission has been proposed as a future X-ray observatory which will be capable of detecting the earliest objects. X-ray imaging and spectroscopy of such faint objects demands a large collecting area and high angular resolution. The Gen-X mission plans $100\ \mathrm{m}^2$ collecting area at 1 keV (1000× that of Chandra), and with an angular resolution of $0.1''$. The Gen-X mission will operate at Sun–Earth L2, and might involve four 8 m diameter telescopes or even a single 20 m diameter telescope. To achieve the required effective area with reasonable mass, very lightweight grazing incidence X-ray optics must be developed, having an areal density 100× lower than in Chandra, with mirrors as thin as 0.1 mm requiring active on-orbit figure control. The suite of available detectors for Gen-X should include a large-area high resolution imager, a cryogenic imaging spectrometer, and a grating spectrometer. We discuss use of Gen-X to observe the birth of the first black holes, stars and galaxies, and trace their cosmic evolution.

Keywords: Gen-X; Vision Mission; X-ray astronomy; Active optics; Lightweight optics

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Contents

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1. Introduction

Astronomers are always in search of more photons, to study ever fainter objects in ever finer detail. In this way, they have pushed the frontiers of astrophysics back to the time when the Universe was only a small fraction of its present age. The new frontiers are to find the very first stars, black holes and galaxies to form in the universe. This requires ever larger telescopes, with ever finer angular resolution, throughout the electromagnetic spectrum. In the optical and infrared efforts are underway to build telescope mirrors up to 20, 30 or even 100 m in diameter, with active and adaptive optics control to achieve resolution near or at the diffraction limit. In the radio, the Square Kilometer Array interferometer is being planned. Similarly, a large X-ray telescope in space could observe the formation of the first galaxies and black holes in the Universe. To this end, the X-ray astronomical community conceived the large-area high-resolution Gen-X mission, which would succeed the Constellation-X (Con-X) mission, and outlined a baseline concept for Gen-X (Cameron et al., 2004) which was successfully proposed for a one year study as a NASA Vision Mission in 2004. We report the status of that study, which is developing and refining the science objectives for Gen-X, concepts for mission architecture, and the key technologies needed for the X-ray telescope and instruments. In the following sections, we discuss some of the far-reaching science goals, and then present our areas of study and outline some of the technical issues being addressed in each area.

2. Summary of science goals of Generation-X

Gen-X will be able to address a wide variety of key goals. The two goals most relevant for this Workshop are discussed briefly here.

2.1. Observe the birth of the first black holes, stars and galaxies

The exact sequence of structure formation after the CBR was released at $z \simeq 1100$ and before the highest known redshifts quasars and galaxies at $z \simeq 6$ is currently mostly a theoretical frontier. Since we know massive black holes (BHs) exist at $z \simeq 6$ (age $\simeq$ 1 Gyr), the first stars, galaxies, and BHs must have formed much earlier, and the BH-accretion must be rapid, releasing X-rays in the process. Recent cosmic background polarization results from WMAP (Spergel et al., 2003) put this first epoch of energy injection at $z \simeq 10$–20 (age $\simeq$ 0.5–0.2 Gyr). The first generation of stars are likely to be massive ($\gtrsim 100\,M_{\odot}$), and these stars will quickly burn their nuclear fuel collapsing to form the first BHs, perhaps in 'pair instability' supernova (SN) explosions 100× more powerful than SN today (Heger and Woosley, 2002). These SN may be visible as Gamma-ray bursts (GRBs; Loeb, 2005) detectable by other satellites simultaneously. Gen-X can obtain spectra of their X-ray afterglows, determining GRB distances and total energy output, and probing the high-redshift intergalactic medium (IGM).

Early BHs (Wyithe and Loeb, 2003) of $\sim 500\,M_{\odot}$ at $z \simeq 15$ can be detected at their Eddington luminosity by Gen-X at a flux of 3×10^{-20} cgs, or 1000× fainter than Chandra can reach. The 0.1–10 keV Gen-X band is uniquely tailored to the detection of these first BHs. Chandra deep surveys (Alexander et al., 2003) find 10× more active galactic nuclei (AGN) per unit solid angle than other wave-bands. Most high energy radiation from quasars is emitted below 100 keV, which at $z \simeq 15$ will be seen below 7 keV. The 1.5 keV radiation can escape through the enshrouding dust and gas expected in these primordial objects, and will be redshifted to ∼0.1 keV. Gen-X will thus detect such BHs, and measure the accretion-powered luminosity of the high-redshift Universe.

Galaxy evolution has been most dramatic at $z \simeq 1$–3 (ages $\simeq$ 6–2 Gyr), causing the broad peak in the cosmic SFR during that epoch. These galaxies should have several young SN remnants (SNR) and "ultra-luminous X-ray sources" (ULXs; York et al., 2003), which might be intermediate mass BHs (several $1000\,M_{\odot}$). Gen-X can detect both at their expected flux of $\gtrsim 10^{-19}$ cgs. HST shows that at such redshifts galaxies are $\sim 0''.5$ across, requiring the low background rate specified in Table 1 for detection. Detecting SNRs, ULXs, and low luminosity AGN (super-massive black holes, SMBHs) against the unresolved X-ray binary (XRB) sources and the hot interstellar medium (ISM) in these objects requires an angular resolu-

Table 1
Key mission parameters for Gen-X

Parameter	Baseline	Study range
Effective area (m^2)	100	50–150
Resolution (HPD)	$0''.1$	$0''.1$–$1''.0$
Energy resolution	$E/\mathrm{d}E = 1000$	10^3–10^4@1 keV
Background (0.5–2.0 keV) (cts/ks/arcsec^2)	0.004	0.04–0.004
Energy range (keV)	0.1–10	0.05–10
Field of view	$5'$	5–$15'$
Time resolution (μs)	50	10–100
Count rate limit (cts/read)	0.05	0.05–0.5
Sky availability (%)	90	70–90
Calibration	3% absolute	3–10% absolute

tion $\sim 0''.1$. Efficient mapping requires a FOV of at least $5'$, which matches that of JWST.

Gen-X will explore galaxies from high redshift to the present, studying the X-ray evolution of their components with cosmic epoch. The cosmic star formation rate (SFR) was 10–100× higher at $z \simeq 1$–3 than at present. Since X-ray luminosities in 'normal' galaxies are well correlated with the SFR (Grimm et al., 2003), X-ray evolution with redshift is expected (White and Ghosh, 1998). This is confirmed crudely by the Chandra 'stacking' detection of the integrated emission of large samples of 'Lyman break' galaxies at $z \simeq 2$–3 (Brandt et al., 2001a,b; Nandra et al., 2002), which reveals higher X-ray luminosities at higher redshifts. Gen-X will study hundreds of these galaxies, obtaining $\sim$400 counts in 10^6 s for a $z \simeq 3$ galaxy (Fig. 1), spatially separate the integrated XRB emission from a nuclear BH, and spectrally separate the hard XRB emission from hot gas (e.g., Fabbiano, 1989; David et al., 1992), revealing the true SFR, even in dust enshrouded protogalaxies.

2.2. Trace the evolution of black holes, galaxies and the elements they produce from the earliest times to the present epoch

A recent surprise is the discovery that the mass of the SMBHs in the centers of nearby normal galaxies and the stellar velocity dispersion of their stars are tightly linked. This M_{BH}–σ_{v} relation (e.g., Gebhardt et al., 2000) suggests that SMBHs and galaxies evolve in a tightly coupled fashion. However, there is little or no information on the nature of this relation at higher redshifts. In protogalaxies the SMBH may well be proportionately larger (Wyithe and Loeb, 2003). At $z \simeq 10$, a young galaxy of mass $\sim 10^8 M_{\odot}$ could harbor a $10^6 M_{\odot}$ SMBH. Such an SMBH accreting at the Eddington limit will have an X-ray flux of 10^{-16} cgs, providing $\sim 10^4$ counts for spectral analysis in 10^6 s with Gen-X, plausibly yielding the galaxy redshift via the iron line (redshifted to $\sim$0.5 keV). To maintain the M_{BH}–σ_{v} relation, galaxy mergers must merge their BHs, triggering AGN activity (Hernquist and Springel, 2003) at almost all wavelengths. Gen-X is designed to observe all these objects in detail.

3. Generation-X mission concept

Table 1 lists the key parameters for Gen-X. The effective area of 100 m^2 at 1 keV allows detection of a distant black hole in 10^6 s. The angular resolution of $0''.1$ HPD results in negligible background in that time. Achieving both the large area and fine angular resolution will require breakthroughs in technology for X-ray telescopes. The baseline concept being studied consists of four identical telescopes, each having an 8 m diameter mirror assembly, attached to an instrument platform at a 50 m focal length. An alternative configuration consists of a single telescope, with a mirror assembly of about 20 m diameter having 100 m^2 effective area at 1 keV, and with focal lengths in the range 80–125 m. A detached, formation flying spacecraft would carry focal plane instruments. Table 2 compares the baseline Gen-X telescope parameters with those of previous or planned missions. In the four-telescope concept, each telescope would be separately launched on an expendable launch vehicle. Each telescope will be carried as six segments to fit in an existing large payload fairing, and with a deployable attachment to the focal plane assembly. Each telescope will have an instrument suite consisting of a grat-

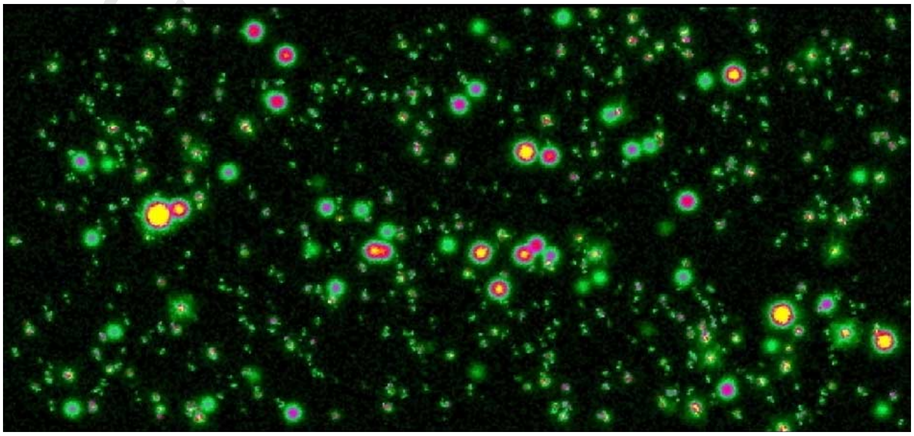

Fig. 1. Slice of a simulated 10^6 s Gen-X image of the Hubble deep field (HDF). Chandra saw 17 sources in the same exposure time (Brandt et al., 2001a,b). With realistic fluxes and sizes, most of the 3000 HDF galaxies will be detected with Gen-X, and over 800 will have $\gtrsim$400 counts.

Table 2
Baseline Gen-X telescope parameters

Mission	Telesc. modules	Angular HPD (″)	Module effective area (m^2)	Module mass (kg)	Mirror technology
Chandra	1	0.5	0.1	1000	Zerodur shells
XMM-Newton	3	15	0.15	420	Replicated Ni shells
Astro-E 2	5	90	0.04	12	Replicated Al segments
Constellation-X	4	15 (Goal = 5)	0.75	700	Thermally formed or replicated segments
Generation-X	4	0.1	25	3000	Thin nested segments with active control

ing spectrometer, micro-calorimeter imaging spectrometer, and an active pixel large format imager. A single-telescope implementation of Gen-X would require multiple launches followed by in-flight assembly. A focal plane with the same three instruments would be launched as a separate vehicle.

4. Generation-X mission architecture

4.1. Architecture trades

We are carrying out mission architecture trades, associated with the different telescope configurations described above, to refine our concept for Gen-X. These trades include the amount of ground vs. on-orbit assembly of the optics, and separate or combined vehicles for the optics and focal plane detectors. The focal plane architecture must accommodate a variety of instruments. Furthermore, since the telescope will certainly remain state of the art for much longer than an instrument lifetime, Gen-X must provide for the replacement or refurbishment of instruments detectors at the L2 location. If multiple telescopes and spacecraft are utilized to achieve the full mirror area, the instruments might be arranged in a series of identical focal planes, or with unique instruments dedicated to individual telescopes. Several issues influence such decisions, including the payload mass and size capability of the launch vehicle, possibilities for astronaut-assisted or robotic on-orbit assembly which might be developed in the future, vehicle propulsion, and formation-flying capabilities.

4.1.1. Constellation definition

While the four-telescope configuration was the starting point of the study, we have identified promising single-telescope configurations. Several factors will influence the trade-off between different configurations. The key driver is the expected performance of the assembled optics, including manufacturing tolerances and diffraction effects (Reid et al., 2004).

4.1.2. Launch vehicle

Currently, Delta 4H and Atlas V vehicles could be used to launch Gen-X, but we anticipate advances in launch weight and propulsion technologies, as well as possible increases in payload size envelopes that future very large space telescopes may require. Gen-X must achieve about an order of magnitude improvement in effective area to weight ratio relative to Con-X. This is less than the improvement from Chandra to Con-X, and is a reasonable goal. For the four telescope option, we budget a baseline optic-module weight of 3000 kg per telescope.

4.1.3. Orbit

A pre-requisite to mission definition is orbit selection. For the large telescopes required by Gen-X, a low-disturbance orbit is needed, to minimize structural mass and/or station-keeping fuel or power, and thermal stresses. This eliminates low earth orbit (LEO) or even the highly elliptical Chandra or XMM type-orbits, and favors Sun–Earth L2. We might use astronauts and/or robotics to assist in telescope assembly and alignment at LEO or at the Earth–Moon L1, and then travel to the Sun–Earth L2. For Gen-X, we will draw on the demonstrated or planned capabilities of other upcoming missions such as Con-X, JWST, LISA, and TPF, to make such architecture and orbit decisions.

4.2. Spacecraft configuration

Gen-X presents significant challenges for the spacecraft platform for telescope(s) with such large mirror area, long focal length and high count rates. For telescopes with 50–200 m focal length, the optics and detector assemblies require either attachment via a deployed boom, or separate formation flying vehicles. The resulting position control tolerances between optics and detector are of order 0.1–0.3 mm in separation, and several mm in the plane perpendicular to the optical axis, which are modest compared to the expected formation flying capabilities. Our trade study is considering the thermal stability required to maintain telescope and instrument performance,including the possibility that low temperature operation might be needed to limit heater power requirements for the optics. Angular momentum management for pointing and slewing is also an issue.

5. Generation-X mission technology

5.1. Telescopes and optics

Efficient X-ray reflection in the broad energy range of Gen-X requires grazing incidence optics. The baseline optics for Gen-X uses the Wolter I geometry, consisting of concentric nested mirror shell paraboloid and hyperboloid pairs. Table 3 shows a representative Wolter I configuration for a four telescope and for a single-telescope

Table 3
Representative Wolter optics configurations

Mission configuration	Outer mirror diameter (m)	Inner mirror diameter (m)	Focal length (m)	Mirror shell length (m)	Number of mirror pairs	Field of view (arcmin)	Effective area @ 1 keV (m^2)
Four telescope	8.0	1.6	50	1.0	260	4.0	25
Four telescope	17.0	4.0	80	1.0	400	4.0	100

implementation. Fig. 2 shows the effective area of those optics configurations, assuming gold reflecting surfaces. In addition to Wolter optics, which provides optimal on-axis resolution, we have considered polynomial shaped optics, which provide better off-axis resolution at the cost of degraded on-axis resolution. The field of view for Gen-X must compromise between the need to fully cover nearby extended astronomical targets and match other observatories such as the planned JWST deep surveys for First Light objects (see Windhorst et al., this volume), and the practical limitations for X-ray detectors having focal plate-scales of about 2″/mm.

The theoretical angular resolution of our configurations easily meets the 0″.1 requirement for Gen-X, so that diffraction effects and manufacturing tolerances dominate the achievable angular resolution (Reid et al., 2004). In general, larger diameter optics have larger grazing angles, and tighter mirror figure control is needed to achieve maximum encircled energy within the desired angular resolution. The two reflections in the Wolter I optical geometry means that figure requirements for each optic scale as the square root of the system performance. Gen-X thus requires an improvement factor of 7× over the Con-X goals, and 3× better than achieved for Chandra.

Although the effective area is 30× larger than of Con-X, the weight cannot be more than a few times larger. The hundreds of mirror pairs shown in Table 3 imply that each must be extremely thin. We therefore consider an entirely new approach for grazing incidence X-ray telescopes: adjusting the mirror alignment and figure on-orbit. To derive the technology to be applied, we have considered the following issues: What materials should be used, what level of precision can be attained by manufacturing tolerances and material stability, what amount of adjustability must be provided, how are on-orbit adjustments made, and what metrology, calibration techniques, and algorithms are used in flight to evaluate and correct the mirrors? We have been performing finite element mechanical analyses to evaluate requirements for initial on-orbit alignment and for on-orbit adjustment methods.

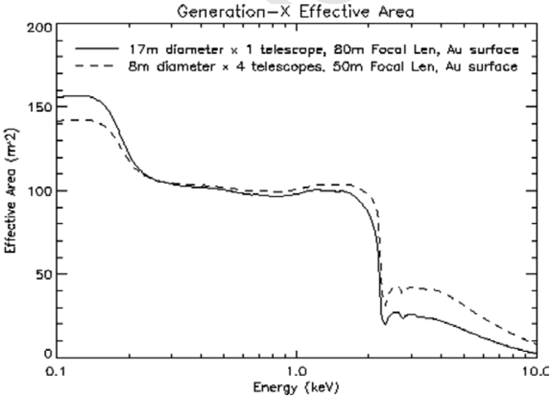

Fig. 2. Effective area for two candidate designs for Gen-X.

5.2. Configuration

Achieving high angular resolution with a very large area is the key feature of the Gen-X mission. One could list many approaches, ranging from building the complete optics on the ground to the final accuracy and mounting them so as to preserve the mirror figure through the injection into final orbit, to providing for both alignment and adjustment of individual mirror element shapes on-orbit. We are considering the latter approach, since it is the most general, and it mitigates a number of manufacturing, spacecraft, and environmental issues.

5.3. Materials and fabrication

To achieve high efficiency X-ray reflection requires grazing angles of order 1/2°. Therefore to achieve 100 m^2 of effective area requires more than 10^4 m^2 of optic surface area. To minimize the weight of such a large area constrains us to use thin-walled mirrors, ~0.1 mm thick, which are nested to build up the large area. Our study concept envisions thermal forming of smooth and thin glass sheets onto precision figured mandrels. The glass is intrinsically smooth at high spatial frequencies. The low spatial-frequency figure errors and the coating stress induced deformations are to be removed by on-orbit control.

5.4. Alignment and figure control

On the ground, the mirror elements will be nested and mounted in modules. On-orbit, either automated deployment or active on-orbit assembly will align these modules to a fraction of the resolution requirement, using a combination of mechanical tolerances and six-degree of freedom actuators. Then the figure errors, launch deformations, and thermal deformations are removed iteratively with alignment adjustment after extension of the optical bench. We anticipate infrequent optic figure adjustment throughout the mission, as necessitated by long term thermal drifts or radiation damage to the glass. For the precise figure adjustment, we are considering the use of actuators such

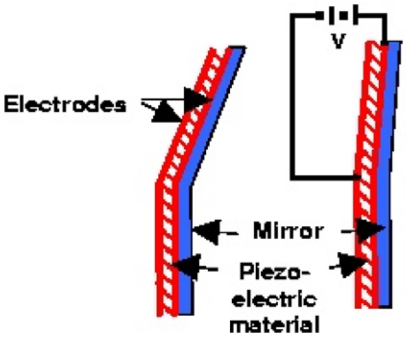

Fig. 3. Piezo-electric mirror figure control. Under an applied voltage *V*, the piezo material imparts a local force to the mirror (other strips would work in an orthogonal direction).

as micro-electro-mechanical (MEM) systems or thin film piezo-electric devices mounted on the back surface of the mirrors (Fig. 3).

6. Instruments

Gen-X requires X-ray detector capabilities significantly beyond those achieved to date. We need developments for high detection efficiency down to 100 eV, spectral resolution of 10^3–10^4 for point and extended sources, high count-rate capability, large detector areas to provide a substantial FOV, and non-X-ray background per unit detector area 10× lower than Chandra. Gen-X, like Chandra, will utilize a suite of complementary science instruments, with one chosen for any specific observation.

6.1. *A cryogenic imaging spectrometer*

A cryogenic imaging spectrometer will be a key instrument. It provides near perfect detection efficiency above 1 keV, and provides better energy resolution than gratings over the upper range of the Gen-X energy band. Current performance is 2.4 eV resolution at 1.49 keV, so Gen-X requires only a factor of $\sim$3 improvement to achieve the minimum spectral resolution at 1 keV. Improved energy resolution is expected from the on-going development of transition edge sensors, super-conducting tunnel junction, or metallic magnetic or kinetic inductance devices. Position resolution of 250 μm has been demonstrated in the laboratory and is baselined for Con-X. This scales to 1″ for Gen-X with a 50 m focal length. This device will not be required to achieve the ultimate imaging capability.

6.2. *A grating spectrometer*

A grating spectrometer will be required to provide energy resolution in the range 10^3–10^4, especially below 1 keV. Gratings are being considered in either a transmission or reflection configuration, which can draw directly upon either Chandra and XMM or Con-X experience, respectively. Gratings will provide the highest resolution spectroscopy for point sources at large redshifts.

6.3. *Imager*

To exploit the 0.1″ imaging, Gen-X requires a camera with a large field of view, broad energy response, moderate energy resolution, spatial resolution better than 0″.1, and high count rate throughput.We are considering Si devices with active pixel readout (Holl et al., 2003; Strueder and Lechner, 2003), or fully depleted pn frame-store arrays. To date such devices have been built with 75 μm pixels and 5 e^- readout noise. Since active pixel sensors do not involve charge transfer, CTI is not relevant and they are much less susceptible to radiation damage. They can be read in less than 1 ms, so that dark current does not build up even at relatively warm temperatures. The rapid readout also means that much less attenuation of external visible light is required, so that they can be operated without optical blocking filters and thus achieve high quantum efficiency down to 100 eV. High time resolution allows use of anti-coincidence to reduce charged particle background. We would mosaic these detectors to provide a $15' \times 15'$ FOV.

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