New Horizons in Time-Domain Astronomy
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Next-Generation X-Ray Astronomy

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Invited Talk

Abstract. This review of future timing capabilities in X-ray astronomy includes missions in implementation (ASTRO-H, GEMS, SRG and ASTROSAT), those under study (currently NICER, ATHENA and LOFT), and new technologies that may be the seeds for future missions, such as lobster-eye optics. Those missions and technologies will offer exciting new capabilities that will take X-ray Astronomy into a new generation of achievements.

Keywords. Telescopes, X-rays: general, Instrumentation: detectors

1. Introduction

X-ray astronomy missions planned over the coming 5 years will have new capabilities that are the result of technology investments made over the past 20 years. In addition to the planned missions, both ESA and NASA are studying a number of concepts that will bring further advances. In this review I will highlight those missions individually, emphasizing how each new capability will bring a new view of the Universe.

2. Missions in Development

2.1. *NuSTAR: Nuclear Spectroscopic Telescope Array*

The NuSTAR mission will for the first time bring focusing X-ray optics to the 6-79 keV hard X-ray band, resulting in a factor of 10–100 increased sensitivity over previous instruments (Harrison *et al.* 2010). This band is important for a number of studies. The extra-galactic X-ray sky is dominated by the X-ray background at 40 keV, so NuSTAR will be optimal for studying the evolution of massive black holes in active galactic nuclei through extra-galactic surveys. The band is also free from the effect of X-ray photo-electric absorption from the interstellar medium and other obscuring matter, which means that NuSTAR will be able to probe many obscured regions such as the population of compact objects and the nature of the massive black hole in the centre of the Milky Way. NuSTAR will image the Ti-44 isotopic line emission at 68 and 78 keV in young supernova remnants to study the birth of the elements and supernova dynamics. In combination with observatories at other wavelengths, NuSTAR will be optimal for probing particle acceleration in relativistic jets from active galactic nuclei.

The key NuSTAR technology is the use of depth-graded, multilayer-coated, grazing-incidence optics to increase X-ray reflectivity above 10 keV. The mission is part of NASA's small explorer (SMEX) program. The telescope requires a 10-metre focal length, which is achieved in the small launch volume of a Pegasus through on-orbit deployment of an extendable mast. The overall energy band of NuSTAR is 5–80 keV, with an angular resolution of $\sim 50''$ (Half Power Diameter). The field of view is $13'$. Each focal plane consists of four CdZnTe pixel sensors with a resolution of 1.0 keV at 60 keV (FWHM) and a time resolution of 0.1 msec. The planned orbit of 550 km × 600 km with a 6-degree inclination avoids the South Atlantic Anomoly in order to ensure a low background. The current planned launch date is 2012 February.

2.2. Astrosat

Astrosat is a multi-wavelength space observatory of the Indian Space Research Organisation (Agrawal *et al.* 2006). It is to be launched in late 2012, and will offer a multi-wavelength capability that allows simultaneous monitoring of targets from optical wavelengths to 100 KeV, with high timing precision. That will enable sky surveys in the hard X-ray and UV bands, broad-band spectroscopic studies of X-ray binaries, AGN, SNRs, clusters of galaxies and stellar coronæ, and studies of periodic and non-periodic variability of X-ray sources. The sky monitor will also be a trigger for Target Of Opportunity observations. The mission lifetime is planned to be least 5 years.

Astrosat will carry five instrument packages: (1) twin 40-cm Ultraviolet Imaging Telescopes (UVIT), (2) three Large Area Xenon Proportional Counters (LAXPC) covering medium X-rays from 3–80 keV with an effective area of 6,000 cm^2 at 10 keV, (3) a Soft X-ray Telescope (SXT) with conical foil mirrors and X-ray CCD detector, covering the energy range 0.3–8 keV ($\sim$200 cm^2 at 1 keV), (4) a Cadmium-Zinc-Telluride coded-mask imager (CZTI), covering hard X-rays from 10–150 keV, with $\sim 10°$ field of view and 1000 cm^2 effective area, and (5) a Scanning Sky Monitor (SSM) consisting of three one-dimensional position-sensitive proportional counters with coded masks on a rotating platform to scan the available sky once every six hours in order to locate transient X-ray sources.

2.3. *SRG: Spektrum Roentgen Gamma*

The Russian SRG mission will fly on a medium-class spacecraft platform (Navigator, Lavochkin Association, Russia). The launch from Bajkonur is currently planned for late 2013 using a Soyuz-2 rocket into an orbit around L2. There are two instruments: (1) eROSITA (extended Röntgen Survey with an Imaging Telescope Array) provided by Germany (Predehl *et al.* 2010) and (2) ART-XC (Astronomical Roentgen Telescope X-ray Concentrator) led by Russia (Pavlinsky *et al.* 2010). The primary eROSITA science goal is to detect 100,000 galaxy clusters up to redshift $\sim$1.3 in order to study the large scale structure in the Universe and test cosmological models, especially Dark Energy (Cappelluti *et al.* 2010). The results will provide complementary constraints on the Dark Energy parameters with a precision comparable to that of other Dark Energy experiments planned for later this decade. eROSITA will also detect 3 million active galactic nuclei (AGN) as well as many variable galactic objects (CVs, Novae, GRB afterglows, stellar flares, etc.).

The detection of 100,000 galaxy clusters drives the telescope design. The effective area of eROSITA is about twice that of one XMM-Newton telescope in the energy band below 2 keV, whereas it is three times less at higher energies, and is a consequence of the small f-ratio (focal length to aperture) of the eROSITA mirrors. The short focal length gives the larger field of view that is essential for the all-sky survey. The angular resolution averaged over the field of view is $\sim 28''$, which is sufficient to distinguish extended clusters from point sources. SRG will scan the entire sky for four years (compared to Rosat's 6 months), and will result in a final eROSITA sensitivity during this all-sky survey that is approximately 30 times deeper than Rosat in the soft X-ray band. The 0.5–2 keV flux limit for galaxy clusters will be, on average, of the order of 3×10^{-14} erg cm^{-2} s^{-1}. For point sources detected in the all-sky survey the typical flux limit is 10^{-14} erg cm^{-2} s^{-1} and 3×10^{-13} erg cm^{-2} s^{-1} in the 0.5–2 keV and 2–10 keV energy bands, respectively.

The latter is ∼100 times more sensitive than the Heao-1 survey in the same 2–10-keV X-ray band.

2.4. Gems: *Gravity and Extreme Magnetism SMEX*

Gems will perform the first sensitive X-ray polarization survey of several classes of X-ray emitting sources characterized by strong gravitational or magnetic fields (Jahoda *et al.* 2010). These sources are expected to have intrinsic asymmetries with respect to a distant observer and are therefore likely to have emission with a net polarization. Polarization measurements are routinely made in other bands, providing important probes of astrophysical objects which are not available via imaging, spectroscopic, or timing observations. With this new capability Gems promises to determine (a) how fast black holes spin, and where the energy is released in black-hole systems including disks, coronæ, and jets, (b) the location of the energy release in neutron-star systems powered by rotation, accretion, and the magnetar phenomenon and the physical mechanism responsible for magnetar emission, (c) whether the magnetic fields of shell supernova remnant shocks are tangled or aligned, and—if aligned—the direction, and (d) the field direction and regularity of pulsar-wind nebulæ.

As a result of photoionization in a proportional counter, a photoelectron is emitted preferentially in the direction of the absorbed photon's electric field. The distribution of emission angle gives an unambiguous determination of the polarization: micro-pattern gas detectors determine the photoelectron emission angle by forming images in the plane containing the ionization trail left by the photoelectron. With a pixel size (∼100 microns) that is small compared to the path length (∼1 mm) of the photoelectron, the emission angle can be determined with high accuracy (Costa *et al.* 2001). Gems has two X-ray polarimeter instruments, each at the focus of an X-ray telescope with $\sim 1'.7$ angular resolution. The mirrors will be deployed at the end of a coilable boom to reach their 4.5-m focal length. The two polarimeters will be mounted at different angles with respect to each other so that, if the detectors are identical, false modulations common to all detectors will cancel. The entire spacecraft will rotate around the science axis so that each detector angle is mapped with uniform exposure onto all sky angles. The nominal rotation period is 10 minutes, which is relatively rapid with respect to orbital changes and is not an integral multiple of the orbit period. Typical observations are greater than 10^5 sec and will thus include more than 100 spacecraft rotations. The spacecraft will be launched in 2014 into a circular orbit of 575 km altitude and $28^\circ.5$ inclination.

2.5. Astro-H

The joint JAXA/NASA Astro-H mission will be the sixth in a series of highly successful X-ray missions initiated by the Institute of Space and Astronautical Science (ISAS) in Japan (Takahashi *et al.* 2010). Astro-H will also be the next major observatory-class mission in X-ray astronomy. The launch date is currently planned for the summer of 2014. The science focus will be dedicated to investigating the physics of the high-energy universe by performing high-resolution, high-throughput spectroscopy with moderate angular resolution over a very wide energy range (from 0.3 keV–600 keV). Astro-H brings several new innovations that will represent a major advance over current capabilities, including the long-awaited X-ray micro-calorimeter array for high-resolution X-ray spectroscopy (∼7 eV resolution) and hard X-ray imaging in the 5–80 keV band provided by multilayer coatings on grazing incidence optics. The mission will also carry an X-ray CCD camera as a focal plane detector for a soft X-ray telescope (0.4–12 keV) and a non-focusing soft gamma-ray detector (40–600 keV). Owing to limited space this review will concentrate on the next-generation capabilities of the X-ray micro-calorimeter.

The soft X-ray Spectrometer (SXS) is being developed by an international collaboration led by JAXA and NASA (Mitsuda *et al.* 2010). SXS is an integral-field spectrometer with 36 pixels and has an energy resolution of $\sim$7 eV between 0.3–12 keV. The array is cooled to 50 mK and makes precise measurements of the heat generated by the absorption of an X-ray photon. The array has a $3' \times 3'$ field of view. The effective area of SXS at 6 keV is 210 cm^2, with an angular resolution of $1'.7$, HPD (half-power diameter) with a goal of $\sim 1'$. The cooling system has redundancy that will protect the instrument against a single point failure.

The SXS will open a new era in X-ray spectroscopy. At $E > 2$ keV it will be both more sensitive and have higher resolution than current spectrometers. The Fe K emission region around 6 keV is particularly important, and will reveal conditions in plasmas with temperatures between 10^7 and 10^8 K, which are typical values for stellar accretion disks, SNRs, clusters of galaxies and many stellar coronæ. In cooler plasmas Si, S, and Fe fluorescence and recombination occurs when an X-ray source illuminates nearby neutral material. Fe emission lines provide powerful diagnostics of non-equilibrium ionization due to inner shell K-shell transitions from Fe XVII–XXIV. For example, Astro-H will observe clusters of galaxies—the largest bound structures in the Universe—to reveal the interplay between the thermal energy of the intra-cluster medium, the kinetic energy of sub-clusters from which clusters form, measure the non-thermal energy content and trace directly the dynamic evolution of clusters of galaxies.

3. Missions Under Study

3.1. Nicer*: Neutron star Interior Composition ExploreR* Sextant*: Station Explorer for X-ray Timing and Navigation*

Nicer was selected in 2011 October for a 11-month phase A study by NASA as part of the Explorer program. The Principal Investigator is Keith Gendreau of the Goddard Space Flight Center. Nicer offers order-of-magnitude improvements in time-coherent sensitivity and timing resolution beyond the capabilities of current X-ray observatories. The mission is optimized for addressing the following science goals: (1) to reveal the nature of matter at extreme densities through neutron star mass and radius measurements, (2) to establish the sites and mechanisms of radiation in their extreme magnetospheres, and (3) to measure definitively the stability of neutron stars as clocks, with implications for gravitational-wave detection and time-keeping.

Over the past year the NASA Office of the Chief Technologist has been studying how the capability provided by Nicer can prove the concept of using pulsars as a deep-space navigation tool under the name Station Explorer for X-ray Timing and Navigation using X-ray timing (Sextant). Sextant is a technology demonstrator to validate space navigation using X-ray observations of milli-second pulsars. Pulsars provide a natural infrastructure for a GPS-like navigation solution that works throughout the Solar system. Navigation accuracies of 500 m in a day can be achieved, with 100 m in a few days for interplanetary spacecraft.

Nicer/Sextant will achieve its goals by deploying a high-heritage X-ray timing instrument as a payload on the International Space Station (ISS), to be attached in the summer of 2016. The high collecting area is achieved with a collection of 56 X-ray concentrator/detector pairs that are simplified derivatives of the thin foil mirrors made by GSFC over the past 3 decades for Asca and Suzaku (Serlemitsos 2010). The telescopes together provide more than 2200 cm^2 of effective area with a $\sim 10' \times 10'$ field of view focusing onto Silicon Drift Detectors (SDD) from MIT Lincoln Labs. The SDD provide an energy resolution comparable to that of X-ray CCD detectors, with an absolute timing resolution better than 200 ns. The telescope array is pointed by using a 2-axis gimbal on a Zenith pointing Express Logistics Carrier (ELC) on board the ISS. The ISS offers nearly continuous contact with the instrument, and Target-Of-Opportunity observations will be possible within minutes.

3.2. Athena: *Advanced Telescope for High ENergy Astrophysics*

Athena is an observatory-class mission that will address key science challenges across astrophysics. It is designed to (a) map the innermost flows around black holes, measure their spins, and determine the equation of state of ultradense matter in the cores of neutron stars, (b) measure the energy flows giving rise to cosmic feedback, quantify the growth of supermassive black holes and the evolution of their obscuration over cosmic time and determine velocity and metallicity flows due to star-burst superwinds, (c) determine the evolution of the intracluster medium through temperature, metallicity and turbulent velocity changes with redshift, constrain dark energy as a function of redshift using clusters of galaxies and reveal the missing baryons at low redshift locked in the warm and hot intergalactic medium, and in addition it will (d) determine the physical conditions in hot plasmas covering a wide range of objects and phenomena, with profound impacts on astrophysics, from stars and planets, through supernovæ and the Galactic Centre.

Achieving those ambitious goals requires a major leap forward in high-energy observational capabilities. The X-ray optical system will utilise the innovative silicon pore optics technology pioneered in Europe to achieve the required 1 m^2 effective collecting area with $10''$ angular resolution (with a goal of $5''$). An assembly of two 12-m focal length telescopes will feed two instruments operating simultaneously. One of those is a next generation X-ray microcalorimeter spectrometer which provides integral field spectroscopy over a $2'$ field of view (using a 32×32 array) with 3-eV resolution. A Wide Field Imager is an active pixel sensor camera covering the full field of view given by the Athena flight mirror, providing wide-field survey capabilities and a high time-resolution capability and $\sim$100 eV energy resolution. If selected, Athena will be placed in orbit at L2, which provides uninterrupted viewing. The design assumes a 5-year mission lifetime, but has consumables for at least 10 years.

athena is a simplified version of the International X-Ray Observatory (IXO) (Bookbinder 2010) that can be implemented by ESA alone while still addressing the highest priority goals of the IXO science case. JAXA and NASA participation is limited to instrument contributions. ESA will decide in 2012 whether to select Athena for a definition phase with a launch in $\sim$2022. In parallel to the ESA Athena study, NASA has made a call for ideas to implement the 2010 Decadal Survey priorities for X-ray astronomy in a more affordable cost profile to drive technology investments over the rest of the decade.

3.3. Loft: *Large Observatory for X-ray Timing*

Loft (Feroci *et al.* 2010) was one of four missions selected in 2011 February for a competitive study by ESA as part of its call for the third M-class mission to be launched in the 2023 time-frame. The key science goal is the use of high-time-resolution X-ray observations of compact objects to provide direct access to strong-field gravity, to the equation of state of ultradense matter, and to black-hole masses and spins. Those science goals require an order-of-magnitude increase in collecting area to 10 m^2 and an energy resolution of $\sim$260 eV over the 2–30 keV band. That extremely large collecting area will be achieved with an array of monolithic silicon drift detectors deployed in orbit like solar array panels, so that the detector array can fit within a launcher shroud. Since Loft is observing the brightest galactic and extragalactic sources, an angular resolution of $\sim 1^\circ$ is sufficient and can be provided by simple collimators.

4. Next Generation All Sky Monitors: Lobster Eye Optics

Angel (1979) proposed a wide field-of-view X-ray optic that mimics the way a lobster's eye works, and uses a curved array of square channels. Lobster-eye optics gives an order-of-magnitude or more improvement in point-source sensitivity over current all-sky monitors and offers a new capability for studying the variable X-ray sky in detail, including stellar capture events in galactic nuclei, super-flares from solar-type stars, gamma-ray bursts, supernova break-outs, thermonuclear bursts on accreting neutron stars, electromagnetic counterparts to gravitational-wave and cosmic neutrino sources, surveys of active and variable stars (dMe-dKes, Algols, RS CVns, CVs, etc.), magnetar outbursts, and AGN variability and blazar flares. There is also considerable scope for the discovery of unexpected high-energy time-variable phenomena. It is hoped that in the near future a mission will be selected to fly that technology and realize those science goals.

Lobster-eye optics work by reflecting incoming X-rays on two orthogonal walls into a central focus with arc-minute angular resolution. This gives an instantaneous grasp (collecting area field-of-view solid angle) that is much larger than Wolter-1 X-ray telescopes. Square pore (20-micron) glass micro-channel plate (MCP) arrays provide a practical means to implement a lobster-eye optic with fields of view of 10° or more. Test MCP arrays have been measured at Leicester University (G. Fraser, private communication) with a PSF of $\sim 2'$ (FWHM). So far there are no missions planned or being studied which make use of these optics for Astrophysics, but they are being incorporated in the Mercury Imaging X-ray Spectrometer (MIXS) on ESAs BepiColombo mission, due for launch in 2014, so is it hoped that an astrophysics application will follow soon.

5. Conclusions

The next 5 years in X-ray astronomy will bring exciting new missions that will open new vistas on the X-ray sky. For the 2015–2025 era several missions are being studied that build upon these new capabilities and will, it is hoped, bring other new technologies to bear. Those concepts will surely evolve over the coming years, but whatever missions finally emerge the new capabilities being developed promise spectacular advances.

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