

THE FUTURE OF X-RAY ASTRONOMY IN CANADA

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ABSTRACT

The X-ray community in Canada has experienced explosive growth since the last Long-Range Plan in 2000. Here we describe a variety of upcoming or foreseen X-ray missions of specific interest to the Canadian High-Energy Astrophysics community. At the top of our list, *Astro-H* and *IXO* are international X-ray missions that will launch in 2014 and 2021, respectively. Both will make tremendous advances in X-ray astronomy by offering capabilities in micro-calorimetry, high-energy X-ray ($E > 10$ keV) focussing, and polarimetry. Canadians are poised to contribute technically and scientifically to these missions, and benefit from the outcome. We also describe several other, generally smaller, proposed or planned X-ray emissions of significant interest to Canada.

Subject headings:

1. INTRODUCTION

X-ray astronomy encompasses an extremely broad range of astrophysical science including everything from planets and stars to black holes and gamma-ray bursts. The sources are all emitting via fundamental physical processes influenced by extreme gravity, density, temperature and magnetic fields. Many high-energy astrophysical phenomena are simply inaccessible at any other waveband. X-ray observations will answer crucial questions in all fields of contemporary astrophysics.

In 2007 the high-energy astrophysics (HEA) community in Canada came together to form a Canadian Space Agency (CSA) Discipline Working Group (DWG). The primary mandate of the HEA-DWG was to define the science priorities of the HEA community. The final DWG report (Kaspi et al. 2009; hereafter HEADWG) was presented to the CSA in 2009 and it is available from the Canadian HEA Research website¹.

The engagement of the HEA-DWG was particularly timely. Over the past decade the high-energy community has experienced explosive growth in Canada. Over one dozen astrophysics faculty hirings have been made in the past 10 years in high-energy astrophysics including five Canada Research Chairs. Considering the cadre of postdoctoral, graduate and undergraduate student researchers these faculty employ, the HEA community in Canada now includes approximately 90 researchers (HEADWG). In addition, Canada is also participating on a national level in the Indian-led (ISRO) multiwavelength facility *ASTROSAT*,² which will possess X-ray capabilities primarily suitable for monitoring and timing studies.

Though the Canadian HEA community is relatively young, it is extremely active and most of the members are recognized world leaders working at the forefront of their respective fields. To date, however, the success of this community, particularly in observational X-ray astronomy, has been dependent on open-door policies (e.g. via peer reviewed time allocation) of international space agencies elsewhere. Canada has never contributed to

the design and development of an X-ray facility, nor has it been in a position to guide the direction of international programs. In the case of *ASTROSAT*, for example, Canada gained partnership by developing the UV detectors for the Ultraviolet Imaging Telescope (UVIT). Consequently, the Canadian science programme will largely revolve around these instruments. Significant Canadian involvement in the design and implementation of cutting-edge HEA missions is critical if Canadian researchers are to fully realize their scientific and leadership potential.

In common with all other areas of astronomy, access and active involvement in observatories and instrument design are essential for the continued success of high-energy astrophysics in Canada. Input at an early stage will allow Canadian researchers to guide the specifications of future instrumentation (energy band, sensitivity, time resolution, spectral resolution) in a manner that best serves our collective goals and allows us to continue to pursue ambitious scientific initiatives over the coming decades.

Via sensitive X-ray observations of thermal emission from neutron stars, we will probe the nature (equation-of-state) of ultra-dense matter that cannot be addressed in terrestrial laboratories. By exploring supernova remnants (SNRs), we will study the life cycles of matter and energy: we will address the origin and dispersion of heavy elements in the Universe and probe the acceleration sites of cosmic rays to very high energies. We will study the nature of matter in the highest magnetic fields known in the Universe via observations of magnetars. We will investigate the strong and fast winds expelled by massive stars, the main drivers of the ecology of the Universe. We will examine the accretion flows nearest extremely compact objects to gain understanding of matter in extreme gravity. We will measure black hole spin; physically testing the theory of General Relativity. We will explore how supermassive black holes (SMBH) grow and evolve, and how they contribute to galaxy formation by detecting X-rays from significantly obscured and highly redshifted systems. We will examine the interplay between galaxy formation and feedback, which can be addressed by observing the physical and chemical properties, and kinematics of the intracluster medium. We will detect

¹ http://physics.bishops.ca/cheat/report_csa.pdf

² <http://meghnad.iucaa.ernet.in/~astrosat/home.html>

emission from galaxy clusters, the largest virialised systems, whose majority of baryons are only visible in X-rays. Accurate measurement of the mass of these baryons places constraints on the distribution of dark matter and the dark energy equation-of-state. The details on some of these science topics are covered in various LRP white papers (e.g. McNamara et al. 2010 (M10): AGN; Stairs et al. 2010 (S10): neutron stars; Heinke et al. 2010 (H10): accreting compact objects; Yee et al. 2010 (Y10): galaxy evolution and clustering) and in HEADWG.

To make advancements in these fields the community requires telescopes and instruments that provide large collecting area, high spatial resolution, high spectral resolution, and timing capabilities. After detailed consideration of Canadian needs, as a community we have unanimously ranked two missions as top priorities for Canada: *Astro-H*³ and the International X-ray Observatory⁴ (*IXO*). The Canadian community is in a position to contribute to these missions and benefit scientifically from participation. Additionally, we have identified several other missions of considerable interest to the community. These are all described below.

2. ASTRO-H

Astro-H is a Japanese-led (JAXA) international X-ray observatory that will be launched in 2014. The mission will include four telescopes (two hard X-ray telescopes [HXT; $E = 10 - 80$ keV] and two soft X-ray telescopes [SXT; $E = 0.2 - 10$ keV]) with arcminute angular resolution, and a variety of instruments effectively collecting data between $0.2 - 600$ keV (Fig. 1).

The HXTs have a 12 m focal length. In order to launch compactly, the HXT detector platform is mounted on an extending mast that will deploy in orbit (Fig. 1). The HXTs will focus high-energy X-rays enabling imaging above 10 keV. The focussing of hard X-rays is challenging, but doing so reduces the background level and improves the signal-to-noise to levels compatible with those below 10 keV (Fig. 2 left panel). Among the many potential science goals that will be realised, high-energy imaging will permit us to map the spatial extent of the X-ray emission from diffuse sources such as SNRs, thereby tracing the sites of astrophysical particle acceleration. Imaging capabilities at high X-ray energies will revolutionize our understanding of HEA processes and open doors to new research areas.

One of the SXTs will focus $0.3 - 12$ keV X-rays on to a micro-calorimeter spectrometer array (Soft X-ray Spectrometer; SXS) with exquisite energy resolution (7 eV at 7 keV) providing a tremendous improvement in sensitivity and energy range over current X-ray grating spectrometers (Fig. 2 middle and right panels). Unlike grating spectrometers, the SXS is non-dispersive so it will provide spectroscopy of diffuse (e.g. SNRs and galaxy clusters) as well as point sources. This will permit, for example, high-resolution line diagnostic in clusters of galaxies that will enable the determination of velocity fields in baryonic material, deviations from thermal equilibrium, and determination of accurate temperatures (e.g. Fig. 3). The second SXT will focus light on a large area CCD covering 35 square arcminutes on the sky. The wide field is

ideal for X-ray imaging and complements the small field-of-view (FOV) of the SXS.

Astro-H will also host a non-focussing Soft Gamma-ray Detector (SGD), sensitive between $10 - 600$ keV. It will have enhanced background rejection capabilities making it $10\times$ more sensitive than the currently operating hard X-ray detector on *Suzaku*.

While each instrument on its own has high scientific merit, the most significant impact of *Astro-H* will be that all instruments operate simultaneously providing a high degree of synergy between broadband X-ray imaging and spectroscopy.

3. THE INTERNATIONAL X-RAY OBSERVATORY (IXO)

IXO is a joint ESA-JAXA-NASA mission planned for launch to an L2 orbit in 2021. The mission boasts the largest collecting area of any X-ray observatory to date (Fig. 5), and will achieve $5''$ angular resolution below ~ 10 keV. With *IXO* we will reach sensitivities in the X-ray that are comparable to SKA, ALMA, JWST, and TMT. The synergy between these missions is necessary to effectively probe multiwavelength problems such as galaxy evolution.

The flight mirror assembly will provide a collecting area of 3 m^2 at 1.25 keV, 0.65 m^2 at 6 keV and 150 cm^2 at 30 keV. To satisfy launch specifications the mirror must be light-weight and two technologies⁵ are being developed and tested concurrently. Like *Astro-H*, *IXO* will launch compactly and extend to a 20 m focal length. The *IXO* configuration and quick reference guide from Bookbinder (2010) is included in Fig. 4.

Four instruments: (i) X-ray Micro-calorimeter Spectrometer (XMS); (ii) the Wide Field and Hard X-ray Imager (WFI/HXI); (iii) the High Time Resolution Spectrometer (HTRS); and the (iv) X-ray Polarimeter (XPOL); are mounted on a movable instrument platform (MIP). One instrument can be placed in the mirror focus at a given time.

The XMS is an array of micro-calorimeters and will provide high spectral resolution between $0.3 - 7$ keV (2.5 eV in the central region of the array, 10 eV along the edges). In conjunction with the large collecting area of the *IXO* mirrors XMS spectra will reveal how gas flows in galactic superwinds and how the environment around galaxies is enriched (Fig. 6; Strickland et al. 2009).

The WFI has a large 18 square arcminute FOV, provides moderate spectral resolution (< 150 eV) between $0.1 - 15$ keV, and will be important in determining the luminosity function of supermassive black holes at high redshift (Nandra et al. 2009; Fig. 7). The HXI is a Cadmium Telluride detector mounted below the WFI and operates simultaneously with the WFI. Together, the WFI/HXI provides simultaneous energy coverage between $0.1 - 40$ keV. The high energy capabilities will mean that sources compromised by high levels of absorption can be revealed, thereby providing a complete census of accretion powered systems (AGN) in the Universe.

The XPOL uses a gas-pixel detector for imaging polarimetry. The polarisation sensitivity is 1 per cent for a 1 mCrab source ($2 - 6$ keV). The HTRS will perform high timing measurements of bright X-ray sources while

³ <http://astro-h.isas.jaxa.jp>

⁴ <http://ixo.gsfc.nasa.gov/index.html>

⁵ These technologies are the slumped glass and silicon pore optics.

achieving moderate spectral resolution below 10 keV.

A fraction of the X-ray light will be diverted to an X-ray Grating Spectrometer (XGS; see Fig. 4). The XGS will provide high resolution dispersive spectroscopy between 0.3 – 1 keV. The XGS will function simultaneously with the operating MIP instrument.

4. OTHER FUTURE MISSIONS OF CANADIAN INTEREST

Astro-H and *IXO* are large, multi-purpose missions that have the potential to satisfy needs of a broad range of Canadian HEA aspirations. However smaller missions, targeting more specific science goals, are also considered of high value for Canadians and outlined in various LRP white papers.

4.1. *The Gravity and Extreme Magnetism SMEX (GEMS)*

GEMS (Swank et al. 2009) will measure the polarization of X-rays emitted from compact objects (see WPs H10 and S10) and will do so with an order of magnitude greater sensitivity over the only previous mission to have had sensitivity to the polarization state of X-rays (the 1970's *OSO-8*). The X-ray Polarimeter Instrument (XPI) on *GEMS* will measure linear polarization in the energy range 2 – 10 keV down to minimum detectable polarizations on the order of 1%. Incoming X-rays photoionise the gas atoms, ejecting the electron in a preferred direction that produces an ionisation track as it de-excites. Measurement of this track reveals the polarisation angle of the initial flux. Currently only one object (the Crab Nebula, also the brightest non-solar X-ray source in the sky) has been detected with polarized X-rays, so there is significant potential for breakthrough with *GEMS*, particularly in our understanding of neutron stars, AGN, black holes and SNRs.

4.2. *The Energetic X-ray Imaging Survey Telescope (EXIST)*

EXIST is a high-energy, deep, all-sky survey (Grindley & Natalucci 2010) with proposed launch in 2017. During the mission lifetime (nominally 5 years) *EXIST* will operate in a scanning (first two years) and pointed phase. GRB follow-up will be performed continuously. The payload consists of three telescopes: the High-Energy Telescope (HET), the Optical IR Telescope (IRT), and the Soft X-ray Imager (SXI). The HET is a wide-field imager ($\sim 70 \times 90$ degree FOV), capable of $2'$ resolution and sensitive between 5 – 600 keV. The wide-field permits imaging of the entire sky every few hours enabling variability studies of X-ray sources on time scales of minutes to years. The current design of the SXI is similar to that of *Swift* XRT and extends the mission X-ray sensitivity down to 0.3 keV. The science goals of the mission are to: detect and monitor X-ray transients of all types (see WPs H10 and S10); study SMBH to constrain the accretion luminosities in the Universe by detecting luminous, but obscured AGN (see WP M10); and study GRBs in order to learn about the first stars and development of structure in the Universe.

4.3. *The Wide Field X-ray Telescope (WFXT)*

WFXT (Murray et al. 2008) is a proposed medium-class soft X-ray (0.1 – 7 keV) survey mission comprising

three co-aligned telescopes. *WFXT* will have a 1 m^2 ($10 \times$ Chandra) collecting area and nearly constant angular resolution ($< 10''$) across a 1 deg^2 FOV ($> 10 \times$ Chandra). During five years of operation *WFXT* will conduct three extragalactic surveys: the Wide Survey will cover $\sim 20,000 \text{ deg}^2$ at 100 – 1000 times the sensitivity, and twenty times better angular resolution of *ROSAT*; the Medium Survey will map approximately 3000 deg^2 to deep Chandra or XMM sensitivity; and the Deep Survey will probe $\sim 100 \text{ deg}^2$, or roughly $1000 \times$ the area of the Chandra Deep Fields, to the deepest Chandra sensitivity. These surveys will generate a legacy dataset of $> 5 \times 10^5$ galaxy clusters to $z \approx 2$, a significant fraction with sufficiently high quality data to enable a detailed analysis of the intracluster gas. It will also generate a sample of $> 10^7$ AGN to $z > 6$, many with X-ray spectra able to distinguish obscured and unobscured quasars. These surveys will address key questions of how supermassive black holes grow and influence the evolution of the host galaxy and how clusters form and evolve, as well as providing large samples of massive clusters that can be used in cosmological studies (see WP Y10).

4.4. *The Advanced X-ray Timing Array (AXTAR)*

AXTAR is a mission concept (Chakrabarty et al. 2008) for an X-ray timing instrument that will be an order of magnitude more sensitive than *RXTE* and *ASTROSAT*. It is designed for sub-millisecond timing of bright Galactic X-ray sources necessary to study natural time scales at the surfaces of neutron stars and near black hole event horizons (see WPs H10 and S10). The mission design includes two instruments, the Large Area Timing Array (LATA) and the Sky Monitor (SM). The primary instrument, LATA, will have a large collecting area (4 m^2) and timing resolution of $1 \mu\text{s}$. LATA will operate in the energy range between 2 – 50 keV. The SM cameras provide a wide FOV and will be used to trigger pointed LATA observations.

5. CANADIAN INVOLVEMENT

Astro-H and *IXO* were unanimously agreed on by the HEA-DWG as the top short- and long-term recommendations for Canadian involvement in high-energy activities (HEADWG). Gaining participation via technology development is challenging since the Canadian X-ray community at the moment is exclusively science driven. However, there exist industrial programmes in Canada that have great relevance for possible contribution to high-energy missions. One such example of specific relevance to *Astro-H* and *IXO* is the need for a metrology system that will measure alignment of the extended optical bench (e.g. Gallo et al. 2010).

Canadian industry has recognised strengths in the development of such technology. The CSA has realised and embraced this Canadian niche, being well aware that precise metrology will be fundamental to the success of many other future mission (including astronomical ones such as *Darwin/TPF*, *LISA*, etc.). In 2010, CSA issued a number of awards for *Astro-H* metrology concept studies. Such technical contributions to missions will bolster Canada's international status in the X-ray community, along with providing Canadian astronomer access to the highest quality X-ray data, and enhancing the cooperation between Canadian industry and academia.

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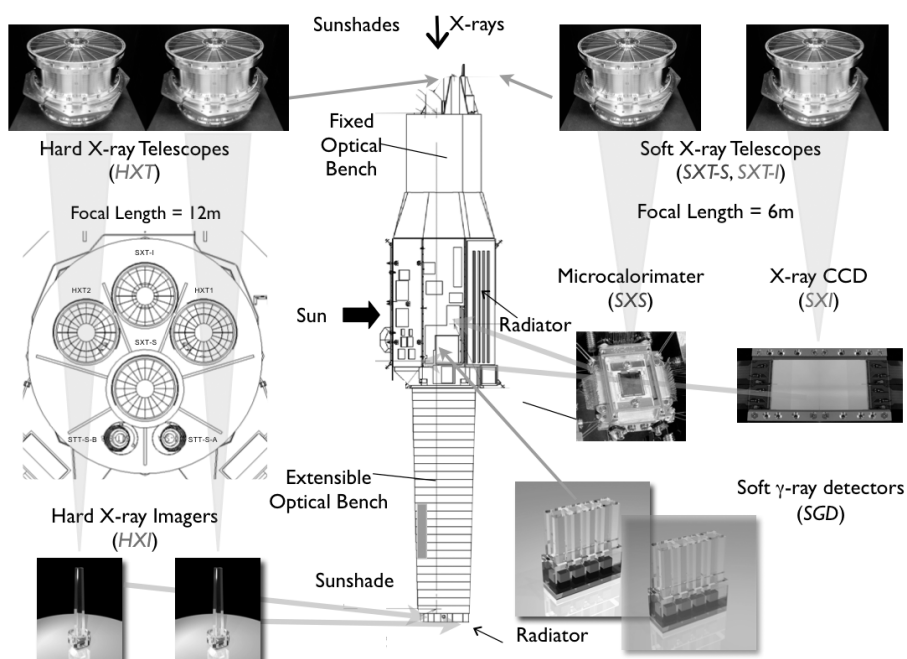


FIG. 1.— Configuration of the *Astro-H* satellite outlining the positions of the various telescopes and detectors. Figure taken from Takahashi et al. (2009).

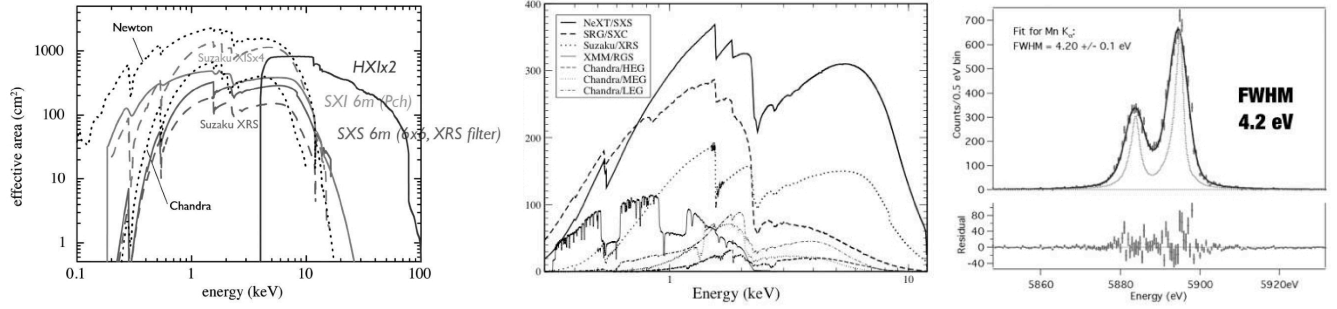


FIG. 2.— Left panel: The effective area of the *Astro-H* XRT telescope in comparison with current instruments. The effective area of *Astro-H* between 10 – 80 keV will be comparable to that of *XMM-Newton* and *Suzaku* below 10 keV. Middle panel: The effective area of the SXS compared to that of current grating spectrometers on *XMM-Newton* and *Chandra* demonstrating superiority above 1 keV. Right panel: The type of energy resolution that will be attainable with the SXS. Figures taken from Takahashi et al. (2009).

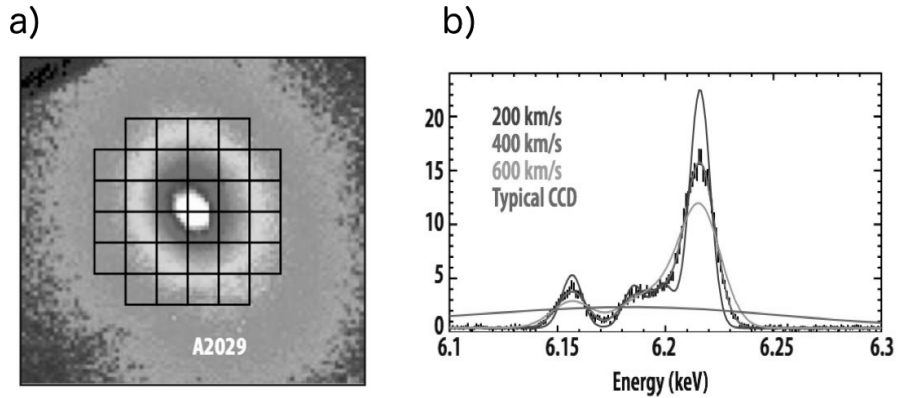


FIG. 3.— A portion of a simulated spectrum (100 ks) of the galaxy cluster A2029 assuming 400 km s^{-1} turbulence compared to models assuming velocities of 200, 400, and 600 km s^{-1} (right panel). The SXS will be capable of measuring cluster dynamics. The panel on the right shows A2029 along with an overlay of the SXS detector. Figure and caption taken from Takahashi et al. (2009).

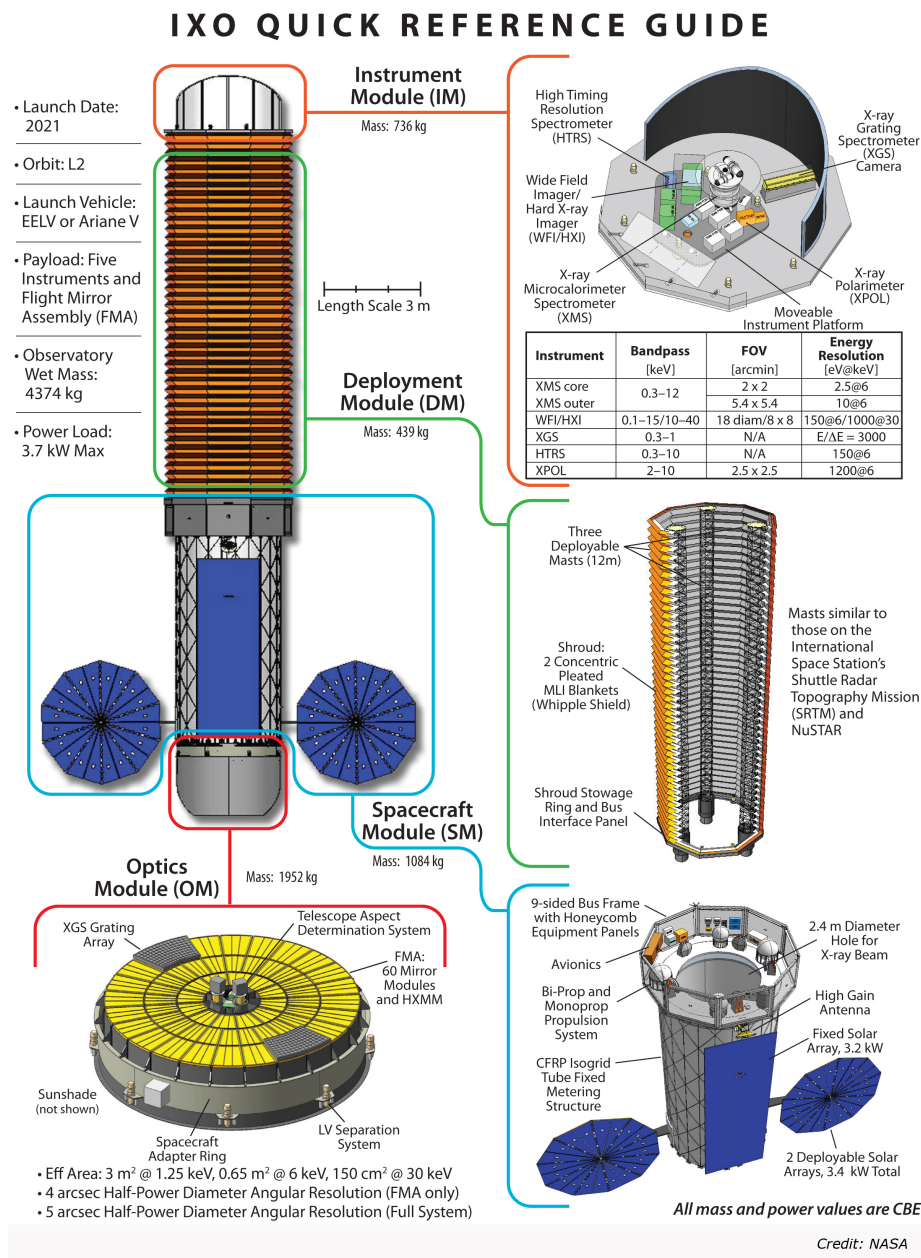


FIG. 4.— A quick reference guide for the IXO satellite. Image taken from Bookbinder (2010).

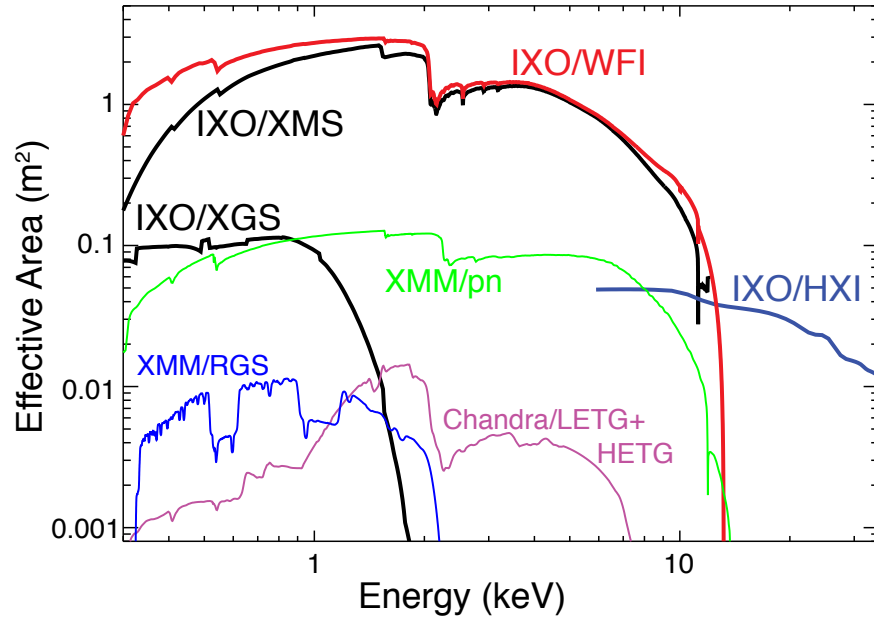


FIG. 5.— The *IXO* effective area compared to current missions. *IXO* will provide an order of magnitude greater effective area than current X-ray missions over several decades of energy. Figure taken from White et al. (2010).

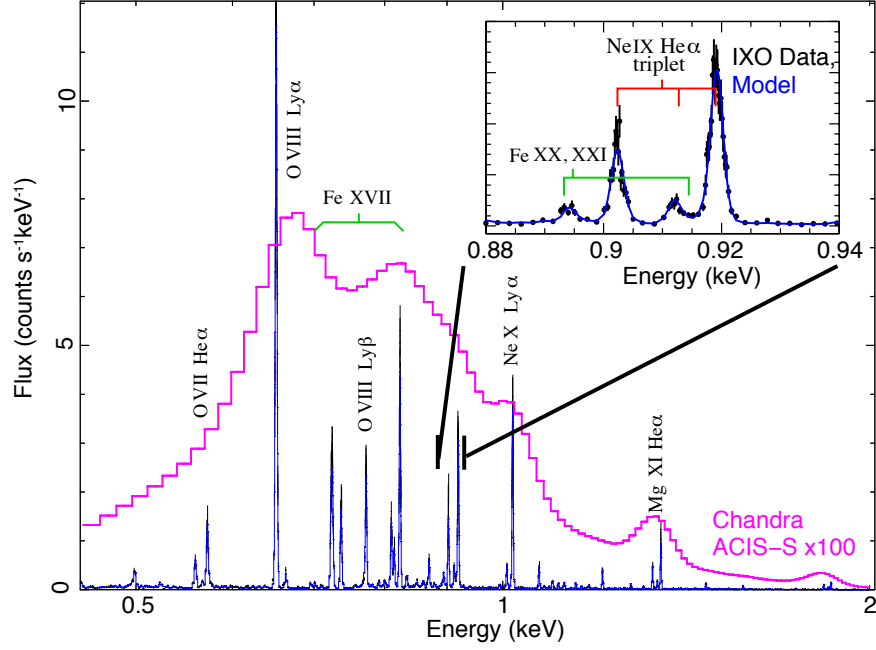


FIG. 6.— The *IXO* XMS spectrum of a 1 square arcminute region within a typical nearby starburst superwind, showing the relative strength of the line to continuum emission. Figure and caption taken from White et al. (2010).

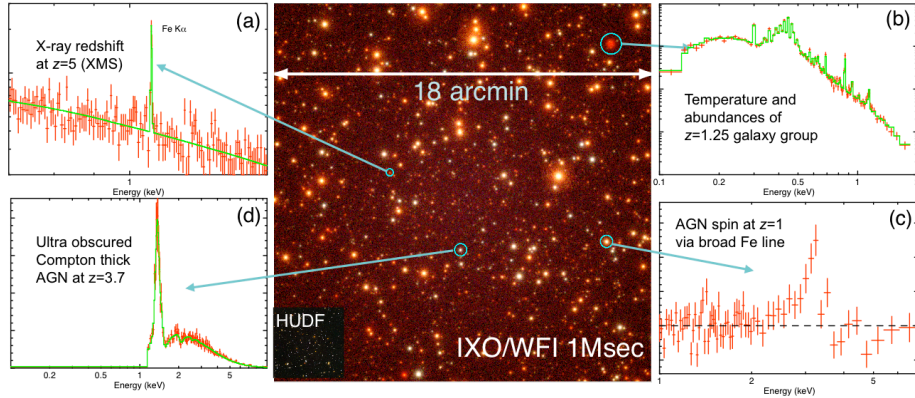


FIG. 7.— WFI simulation of the Chandra Deep Field South with the Hubble Ultra Deep Field (HUDF) in the inset. Simulated spectra of various sources are shown illustrating the ability of *IXO* to: (a) determine redshift autonomously in the X-ray band, (b) determine temperature and abundances even for low luminosity groups to $z > 1$, (c) make spin measurements of AGN to a similar redshift, and (d) uncover the most heavily obscured, Compton-thick AGN. Figure and caption taken from White et al. (2010).