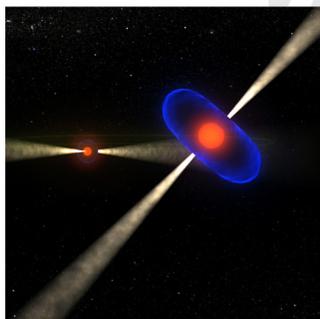
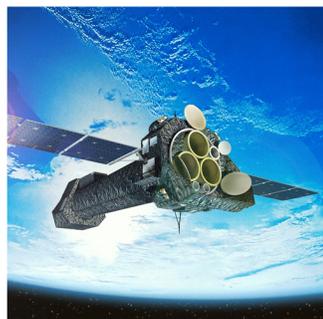
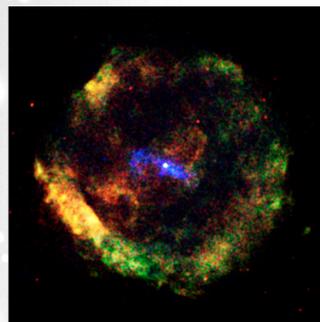
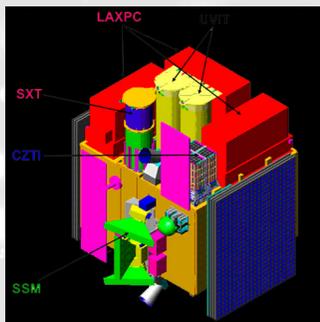
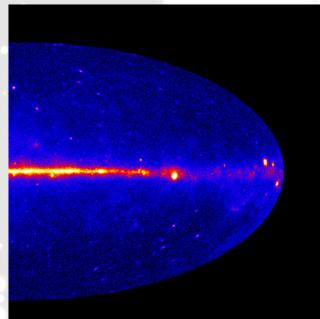
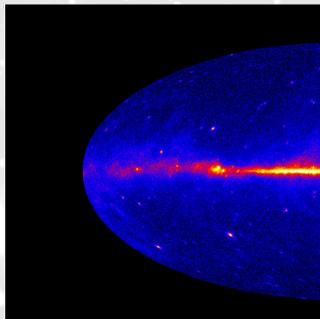
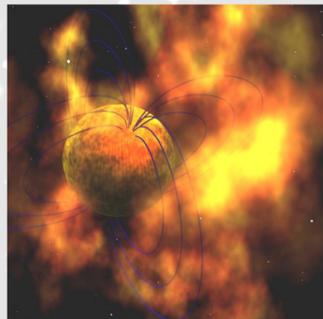
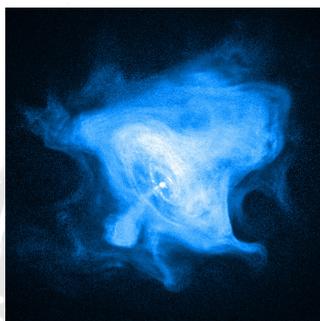
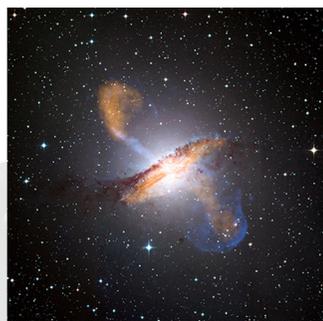


# Report of the Canadian Space Agency Discipline Working Group in



## HIGH ENERGY ASTROPHYSICS



March 2009

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**Report of the Canadian Space Agency  
2007–2009 Discipline Working Group  
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## EXECUTIVE SUMMARY

High Energy Astrophysics (HEA), broadly meaning X-ray and  $\gamma$ -ray astronomy, encompasses an extremely broad range of astrophysical science, with sources that include stars, black holes, neutron stars, white dwarfs, supernova remnants, the interstellar medium, galaxies, active galactic nuclei, galaxy clusters, gamma-ray bursters, all emitting via fundamental but extreme physical processes, including extremes of gravity, density, temperature and magnetic field. Many HEA phenomena are inaccessible at any other waveband.

In this report, we consider Canadian priorities for HEA, specifically focussing on astrophysics accessible primarily through X-ray and  $\gamma$ -ray observations. Importantly, most observations in the X-ray regime and in most of  $\gamma$ -ray regime can be done only from space; it is this space-based arena on which we focus here. We also briefly discuss some relevant particle-astrophysics (see §7).

This report is timely given that HEA is currently the fastest growing subfield of astronomy in Canada. Over one dozen astrophysics faculty hirings have been made in the past 10 years in HEA and related fields, 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 nearly 90 people. Thus the community is young, active and growing. While the last Long-Range Plan (LRP; 2000) for astrophysics in Canada made no mention of X-rays or  $\gamma$ -rays, the Mid-term Review of the LRP (2005) specifically noted the growth of Canadian HEA, identifying its potential “to lead the way to a new area of exciting space astronomy in Canada.”

We believe that significant Canadian involvement in one or more forefront HEA missions is essential for nurturing and retaining the vibrant expertise and talent of the Canadian HEA community. We therefore recommend that the CSA pursue involvement, both technical and scientific, in one or more of the following planned or envisioned international HEA missions (which are described in more detail in Appendix A):

- **Short-term (present–2014) Ordered Priorities:**

- Involvement in a focussing hard X-ray ( $E > 10$  keV) mission with excellent angular resolution ( $< 1'$ ) and spectral resolution, and ideally good ( $\sim 100 \mu\text{s}$ ) timing resolution. One particularly attractive opportunity is the upcoming JAXA/NASA *Astro-H* (formerly *NEXT*; PI T. Takahashi, JAXA) mission, with planned launch 2013. This has the advantage of also carrying a soft X-ray microcalorimeter, having modest sensitivity and excellent spatial resolution. An alternative for a focussing hard X-ray instrument is the ESA *Simbol-X* mission, with planned launch 2014.
- Involvement in a broad-band, modest sensitivity X-ray polarimeter operating anywhere in the 0.1-100 keV band. Focussing ability is a plus that would allow extragalactic work. Good ( $100 \mu\text{s} - 1$  ms) time resolution is also important. We note the Phase A development of the *GEMS* X-ray polarimetric mission as part of the 2008 NASA Small Explorer competition (PI J. Swank, NASA/GSFC).

- **Long-term (2014–2020) Ordered Priorities:**

- Involvement in a soft-band (0.1–10 keV) mission having excellent sensitivity (effective area  $> 10\times$  *XMM-Newton*) and excellent ( $R > 1000$ ) spectral resolution with good ( $< 5''$ ) angular resolution and good ( $100 \mu\text{s} - 1$  ms) time resolution, such as *IXO*, a joint ESA/NASA/JAXA mission (formerly ESA's *XEUS* and NASA's *Constellation-X*). Project scientists on this mission are A. Parmar (ESA), N. White (NASA), and H. Kunieda (JAXA).
- Involvement in a mission with excellent sensitivity (effective area  $> 10\times$  *XMM*) and excellent timing resolution ( $< 10 \mu\text{s}$ ), with modest angular resolution and spectral resolution, in the soft/hard (2–100 keV) band. Possible implementations are the envisioned wide field-of-view all-sky survey *EXIST* mission (PI J. Grindlay, Harvard), or the proposed *AXTAR* mission (PI D. Chakrabarty, MIT).

**Table 1: Document Terminology for X-ray Mission Attributes**

	“Modest”	“Good”	“Excellent”
Sensitivity (effective area*)	$< XMM$	$2-3 \times XMM$	$> 10 \times XMM$
Spectral Resolution ( $R \equiv \Delta E/E$ )	$< 50$	50-1000	$> 1000$
Timing Resolution ( $\Delta t$ )	$> 10$ ms	100 $\mu$ s–10 ms	$< 10$ $\mu$ s
Angular Resolution/soft ( $\Delta\theta$ , FWHM)	$> 20''$	$2''-20''$	$< 2''$
Angular Resolution/hard ( $\Delta\theta$ , FWHM)	$> 20'$	$2'-20'$	$< 2'$

\*The effective area of *XMM*'s PN instrument at 1 keV is  $\sim 2600$  cm<sup>2</sup>.

## 1 Introduction

This document represents the final report of the Canadian Space Agency (CSA) Discipline Working Group (DWG) in High-Energy Astrophysics (HEA). The membership of this DWG is listed in Appendix B. The DWG met in a series of face-to-face meetings and teleconferences in 2007-2009. A list of these meetings is in Appendix C.

This is the first time that Canadian HEA researchers have come together in a major effort to define our science priorities as a community. This engagement was particularly timely because, although there have always been a handful of high-energy astrophysicists in Canada, the last decade has seen explosive growth in the field, such that our DWG includes two-dozen Canadian faculty members of which roughly 3/4 were brought to Canada in the last decade. Seven among our group hold distinguished Chairs, including five Canada Research Chairs. Including postdocs, graduate students and undergraduates being supervised by DWG members in HEA research, there are at least 88 HEA researchers in Canada today, 72 excluding undergraduates. This is to be compared with the 420 members of CASCA living in Canada. The 24 HEA DWG members collectively published at least 78 HEA papers in refereed journals in 2008 alone. This is clearly a large, young and highly active group. A Canadian HEA website is currently under construction (see <http://physics.ubishops.ca/chea/>). Note that currently no HEA researcher, including any DWG member, has an active research program in HEA instrumentation. Thus Canadian HEA expertise is currently focussed on HEA science; practically all is funded by NSERC Discovery Grants, provincial science and technology agencies (e.g. FQRNT in Quebec), the Canada Research Chairs Program, the Canada Foundation for Innovation, or the Canadian Institute for Advanced Research.

Observatory access is obviously critical to the success of any astrophysical field, and HEA is no exception. Because of open-door policies of space agencies in the U.S., Europe, Japan and elsewhere, Canadian HEA researchers have generally enjoyed significant access to major HEA facilities, thanks to successes in peer-reviewed observing proposal competitions. However such a situation leaves Canadians in the awkward position of depending on the good graces of others, and, more importantly, generally silent on the future directions of the field. Without solid involvement in the design and development of future facilities, valuable Canadian expertise is at best briefly entertained, and at worst ignored, in planning for the future. This marginalization of Canadian talent ultimately weakens our researchers' stature on the international scene, regardless of our scientific output.

With this report, we aim to make a first step at improving the situation for the blossoming HEA field in Canada. In what follows, we consider the important science questions that should be addressed by the next generation of high-energy space missions, with a particular emphasis on topics on which there exists Canadian expertise. As this is the first such document ever written in Canada for HEA, we have elected to emphasize the tremendous breadth of Canadian HEA science.

In each section, the most pressing relevant HEA science issues are described, followed by a description (*italicized*) of the characteristics of a future HEA mission that would be of use in making progress. At the end of each section, recommendations are made for future mission prospects that are worth pursuing. We are aware that two HEA missions, ISRO's *Astrosat* (planned launch 2010) and NASA's *NuSTAR* (planned launch 2011), are currently under construction; we therefore do not include them in the discussion as decisions regarding instrumental contributions have long since been made.

In the course of preparing this document, clear common themes in desired mission capabilities emerged; these were then identified with envisioned international missions and opportunities for involvement were identified. Our prioritized list of recommendations for future mission involvement thus represents the conjunction of scientifically desirable capabilities and opportunities for involvement.

To be concrete in describing mission characteristics throughout this document, we have prepared Table 1, which summarizes our terminology for different instrument attributes. Throughout this document, “soft X-rays” refer to the energy range 0.1–10 keV, “hard X-rays” refer to the energy range 10-100 keV, “soft  $\gamma$ -rays” refers to 100 keV – 10 MeV, and “ $\gamma$ -rays” refers to  $> 10$  MeV. As our recommendations tend toward involvement in X-ray missions, the Table is applicable mainly for the soft- and hard-X-ray regimes. Note that angular resolution, in particular, is highly energy dependent. In the Table, we provide guidelines for both soft- and hard X-ray instruments. In the document, where our recommendations are for instruments at higher energies, or which do not fall into the simplified framework of Table 1, we provide specifics within the text.

A list of acronyms used in this report, as well as mission URLs, is provided in Appendix D.

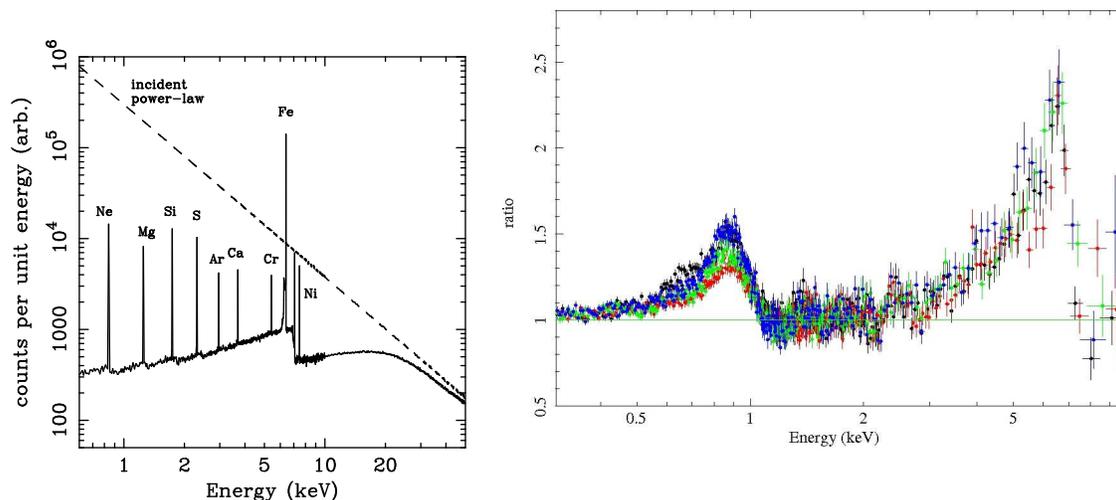


Figure 1: (Left) X-ray reflection from an illuminated slab. The dashed line shows the incident continuum and the solid line shows the reflected spectrum integrated over all angles (from Reynolds, 1999). (Right) The ratios of four colour-coded *XMM-Newton* spectra of the AGN 1H0707–495 to a continuum model. The two flux excesses above the continuum are consistent with relativistically broadened ionised Fe L and K emission lines (from Fabian et al., 2009).

## 2 Extragalactic Astronomy: From Supermassive Black Holes to Gamma-Ray Bursts

### 2.1 Introduction

Most baryons in the Universe exist not in the familiar form of stars and planets, but in reservoirs of diffuse gas at temperatures between  $10^5$  K and  $10^8$  K. These reservoirs are found in a wide range of cosmic environments, including the tendrils of the cosmic web, the deep gravitational potential wells of galaxies and great clusters of galaxies, and in the vicinity of supermassive black holes. Such gas is the raw material out of which luminous galaxies and supermassive black holes form, and at these temperatures, emits and absorbs radiation in the X-ray band. It is therefore best studied with Earth-orbiting X-ray observatories.

Over the past decade, observations made with the *Chandra* and *XMM-Newton* X-ray observatories have opened new vistas into the properties of these reservoirs and the physical processes that govern their evolution. Observations have revealed a strong coupling between hot, diffuse gas, the stars that form the luminous galaxies, and the supermassive black holes located in their nuclei. Central to this picture are the intense radiation fields and powerful outflows of particles launched from near the event horizons of supermassive black holes. The radiation and kinetic energy associated with these outflows appear to regulate the rate of heating and cooling of the gas surrounding them, which in turn governs the rate at which galaxies and their supermassive black holes grow over cosmic time. Understanding this process, which has been dubbed “feedback,” has become one of the most significant problems in astrophysics.

Recent advances in X-ray detector and mirror technology will increase the effective collecting area and spectral resolution of the next generation X-ray observatories by an order of magnitude. An X-ray observatory equipped with these capabilities promises a great leap forward in our understanding of feedback by tracing the velocities and chemical makeup of outflows over ten decades in size, from their launch near a black hole’s event horizon to their terminus in the large-scale flows seen in galaxies and clusters. Spectral line shapes and variability in the emission strength of the gas near the event horizon will probe the size and spin of the supermassive black holes launching these outflows, and could provide tests of General Relativity.

### 2.2 The Physics of Accretion around Supermassive Black Holes

The standard model of a rapidly accreting Active Galactic Nucleus (AGN) consists of a supermassive black hole and an optically thick, relatively cool ( $T \lesssim 10^5$  K) accretion disc surrounded by a corona of hot ( $T > 10^8$  K) electrons at small radii (within light hours to light days), often with an accretion disc wind at larger radii (from light days to light years). Ultraviolet photons emitted from the accretion disc gain energy from inverse Compton-scattering as they propagate through the hot corona (Haardt et al., 1994). The high-energy photons generated in the corona produce the power-law continuum that dominates much of the observable X-ray band (0.1–100 keV). While X-rays account for 2–20% of the power in a typical AGN, they are generated on the smallest scales and probe all of the material in the immediate vicinity of the accretion system (e.g., Gallagher et al., 2004).

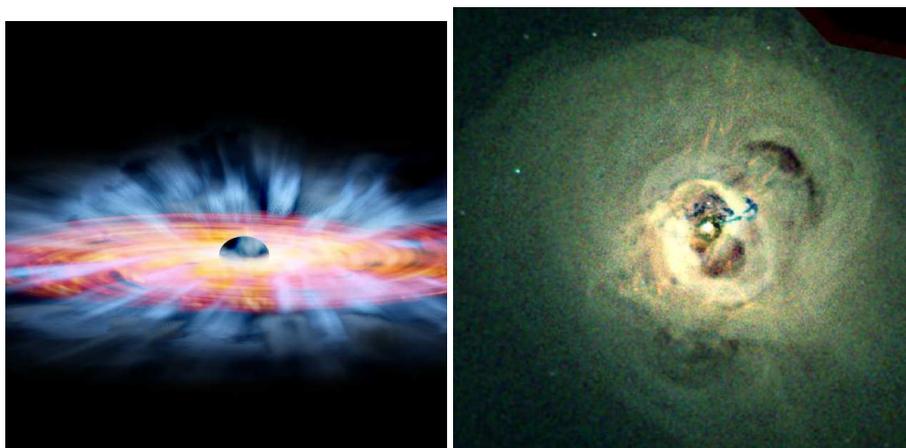


Figure 2: (Left) Artist's impression of an accretion disc and disc wind surrounding a black hole. Credit: NASA/CXC/M. Weiss. (Right) X-ray colour image of the Perseus cluster made from the 0.3–1.2 (red), 1.2–2.0 (green), and 2–7 keV (blue) bands. A  $10''$  smoothed image has been scaled to 80% of its intensity and then subtracted in order to bring out fainter features (from Fabian et al., 2006).

- How Does Matter in an Accretion System Behave?** X-ray photons generated in the corona illuminate the accretion disc and surrounding material and create a reflection spectrum (see Fig. 1, Left). Its characteristic continuum ‘hump’ peaks between 20–40 keV; NASA’s upcoming *NuSTAR* mission will therefore make progress here. Spectral features, primarily of fluorescent Fe emitting from 6.4–7 keV, are sensitive to the ionisation and geometry of surrounding material. Both these properties are expected to vary with accretion rate and other physical parameters of the system. For example, at very low accretion rates the accretion disc can be supplanted by a radiatively inefficient accretion flow and the reflection component can weaken dramatically due to a scarcity of ultraviolet seed photons (e.g., Ptak et al., 2004). *Modest hard X-ray sensitivity to constrain the strength and shape of the reflection continuum and good to excellent spectral resolution around the Fe feature are necessary to infer physical properties of the AGN environment from reflection spectra. Modest sensitivity in the soft X-ray band with excellent spectral resolution would also be of use for studying the Fe emission.*
- How Fast do Black Holes Spin?** Very close to the supermassive black hole, the reflection and continuum spectra are produced under the influence of extreme gravity. The spin of the black hole governs how close matter can orbit the black hole before falling past the event horizon and, consequently, how significant the effects of gravity will be. Measuring black hole spin is important as it clarifies how supermassive black holes have accreted their mass – via discs (increasing spin), or via black hole mergers (usually decreasing spin). The influence of Doppler shifts, beaming, and General Relativity (e.g., gravitational redshifts, light-bending, and frame dragging; Miniutti & Fabian 2004) alter the shape of the spectra accordingly, in particular the shape of X-ray emission lines (see Fig. 1, Right). *Excellent sensitivity near the Fe feature (5–10 keV) and good to excellent spectral resolution (the latter even with modest sensitivity) are needed to investigate matter in this regime, and constrain the spins of black holes.*

### 2.3 Supermassive Black Hole Feedback on Galaxies and Galaxy Clusters

In the past decade, it has been recognized that every massive galaxy has a supermassive black hole at its centre. Moreover, the mass of the black hole correlates with the mass of the spheroid of the host galaxy, so some connection must exist between the formation of the two (e.g., Di Matteo et al., 2008). When a black hole accretes matter through an accretion disc, some of the matter is expelled in a disc wind (Fig. 2, Left), a radio jet, or both. This mass ejection can be comparable to or even exceed the radiant power of the AGN. An outflow with such kinetic power affects the host galaxy by triggering star formation (by shocking and compressing the interstellar medium), or perhaps by shutting it down (by clearing gas from the host). This ‘feedback’ affects individual galaxies and clusters of galaxies. In galaxy clusters, the feedback prevents all but a small fraction of the gas at the centres of clusters from cooling to form young stars (e.g., McNamara & Nulsen, 2007).

- How are Mass Accretion and Outflow Related, and What is the Kinetic Power of the Outflow?** The extent of the importance of outflows in galaxies and clusters depends heavily on the geometry, ionisation state, column density, and velocity of the ejected material. X-rays, originating in the heart of the accretion system, are penetrating probes of all of the material in the outflow (dusty through highly ionised) along the line of sight to the observer (e.g., Chartas et al., 2002). *This crucial information is accessible with excellent spectral resolution at  $E < 2$  keV (where many strong lines are found) coupled with good sensitivity.*

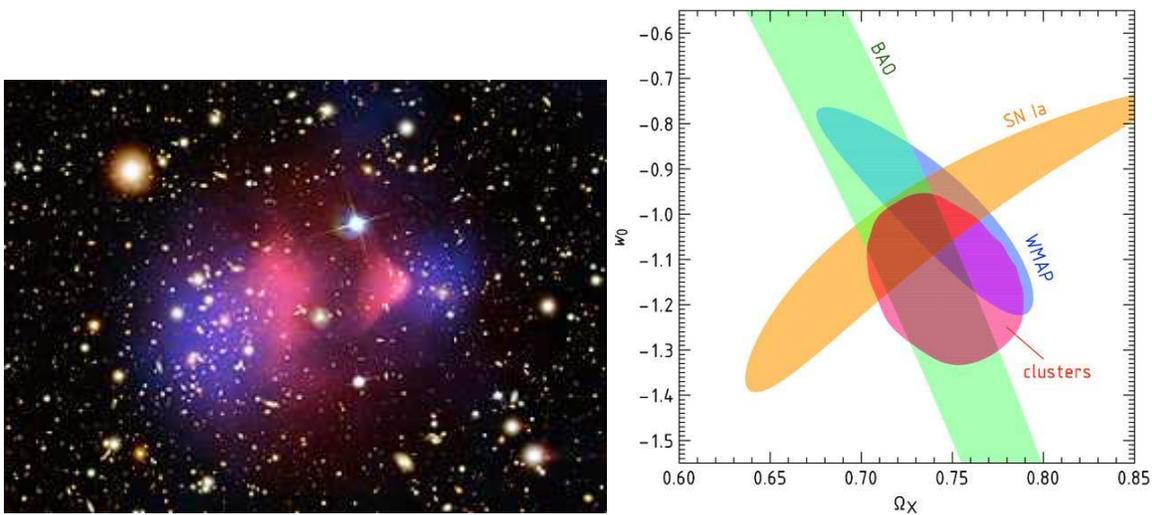


Figure 3: (Left) Composite *Chandra* X-ray image of the Bullet Cluster showing X-rays in pink and what is believed to be dark matter, as inferred from gravitational lensing, in blue. Orange and white are optical. Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al. (Right) Comparison on constraints of dark energy from X-ray clusters and other methods: Type I SNe, CMB (*WMAP*), and baryonic acoustic oscillations (BAO) (after Vikhlinin et al., 2009).

- **How is the Intracluster Medium Affected by AGN Activity?** Feedback from AGN creates dramatic bubbles, ripples and other gas flows within the X-ray emitting gas in a cluster (see Fig. 2, Right), but the true effect is measured by studying the velocity structure of the gas. *Spatially resolving and constraining the dynamics of the gas requires good angular resolution and excellent spectral resolution near 6 keV where 10 MK gas has strong Fe emission lines.*

## 2.4 Galaxy Clusters and Cosmology

Hot gas in the deep potential wells of galaxy clusters is gravitationally heated to temperatures approaching  $10^8$ K. At these temperatures, the main cooling mechanism is thermal bremsstrahlung radiation at X-ray wavelengths. Most of the baryons in galaxy clusters are in this intracluster medium, in approximate hydrostatic equilibrium with the gravitational potential. Studies of individual galaxy clusters and of the evolution of the population of galaxy clusters provide detailed information on plasma physics, chemical evolution, and the expansion history of the Universe.

X-ray observations of galaxy clusters provide detailed measurements of the gas density, temperature (Pratt et al., 2007), and metallicity distribution (Leccardi & Molendi, 2008) within galaxy clusters; these can be used to reconstruct the gravitational potential, entropy distribution and chemical enrichment history. This is directly coupled to the star formation history and feedback from AGNs, and also allows precise tests of the predictions of the cold dark matter model for the dark matter distribution (which sets the potential).

In addition, high-resolution X-ray spectroscopy can provide measurements of the turbulent velocities within galaxy clusters. This is a direct probe of the degree of thermalization of the intracluster medium. Galaxy clusters are observed to have a high rate of merging events, where relatively large subclumps of mass fall in and mix over several dynamical times. The “Bullet Cluster” (Fig. 3, Left) is an extreme example, where studies of the merger in the X-ray combined with optical imaging have provided direct evidence for collisionless dark matter (Clowe et al., 2006). On a more modest scale, however, the process by which subclumps are absorbed and thermalized is not well understood.

Radio observations have identified diffuse radio sources, indicative of electron acceleration in cluster mergers and/or AGN activity. Combining radio observations of synchrotron emission, and observations of nonthermal hard X-rays produced by inverse Compton scattering, provides the ability to measure the densities of relativistic electrons and magnetic field strengths in clusters (e.g. Arnaud 2008). Hard X-ray measurements will thus constrain the nonthermal intracluster-medium pressure – a key source of systematic error in cosmological cluster studies. To date, the poor angular resolution of hard X-ray imaging techniques has not permitted unambiguous detection of nonthermal X-rays from clusters of galaxies; this will be rectified with the new generation of focussing hard X-ray telescopes, starting with NASA’s pathfinder *NuSTAR* mission.

Galaxy clusters are the largest bound systems in the universe today, and they last formed rapidly during the epoch when the expansion of the universe began to accelerate; therefore, the evolution of their X-ray properties, among others, as a function of time is one of the most sensitive probes of the equation-of-state of the Universe, once variations between clusters are controlled for. Competitive measurements of the dark energy equation-of-state have been obtained in two separate ways: the apparent angular size of galaxy clusters as a function of redshift as measured

using X-ray observations of the gas fraction (Allen et al., 2008) and the evolution of the number density of X-ray bright clusters (Vikhlinin et al., 2009). This is highly complementary to studies of the cosmic microwave background (CMB; see Fig. 3, Right), which measure nearly the same objects through Compton scattering of microwave photons in the intracluster medium. As the redshift of a typical galaxy cluster increases, its X-ray flux decreases and becomes slightly softer, while its angular size will remain more or less constant.

*Progress requires improvements in soft X-ray sensitivity and spectral resolution, and hard X-ray focussing studies with good angular resolution. Improved soft X-ray sensitivity with good angular resolution will allow studies of many more galaxy clusters, improving the cosmological constraints. Measuring turbulent velocities (requiring excellent spectral resolution) and cluster magnetic fields (hard X-ray studies with good angular resolution), and thus the variation in cluster pressure from that of ideal gases, will address the major systematic uncertainties in the use of clusters as cosmological probes.*

## 2.5 The Cosmic X-ray Background and Active Galactic Nuclei

A faint glow of X-rays is seen across the sky, peaking at energies  $>10$  keV. These X-rays are produced by accretion onto black holes in galaxies throughout the history of the Universe. Studying the population of individual sources comprising the background therefore constrains supermassive black hole growth from the early Universe until today.

- **What is the History of Obscured Black Hole Growth in the Universe?** Deep X-ray surveys have resolved some 90% of the cosmic X-ray background at energies below 2 keV, but only 50% of the background at  $E > 7$  keV (Worsley et al., 2004) where its energy output peaks. The missing population of X-ray background sources likely consists of obscured AGN. Low-energy X-rays can be absorbed by gas and dust relatively easily, but high-energy X-rays are less affected; therefore heavily obscured AGN may only be detectable at hard X-ray energies. This missing population of obscured AGN – at least half the total population – provides an important contribution to understanding the co-evolution of galaxies and supermassive black holes, as every black hole may pass through an obscured accretion phase. *NuSTAR* will begin to make progress on this topic. *A focussing hard X-ray mission with excellent angular resolution will measure the luminosity function of obscured AGN, shedding light on AGN accretion history and its effects on the formation of structure.*

## 2.6 Gamma-Ray Bursts

Gamma-Ray Bursts are among the most energetic events in the Universe, with as much energy as a supernova emits over several weeks being emitted in  $\gamma$ -rays within just a few minutes. They are thought to occur when neutron stars and black holes are born or merge. In such catastrophic events, a narrow jet of particles moving at near light speed is created, along with a jet of  $\gamma$ -ray photons bright enough to be seen across the Universe. It is generally thought that long, low-energy bursts arise in the death throes of massive stars, when a rapidly spinning neutron star or black hole is born, and that most short, high-energy bursts arise from the inspiral of two neutron stars, or a neutron star with a black hole. Some short bursts may be produced by magnetars (see §4.3) in nearby external galaxies undergoing giant flares, such as are occasionally seen in our Galaxy.

- **What Underlies the Different Gamma-Ray Burst Populations?** Our understanding of the physics of these extreme events is rudimentary, and observations of many more bursts in many different energy ranges are needed to test and improve gamma-ray burst models (e.g., Willingale et al., 2007). Improved sensitivity to hard X-ray GRB emission will allow identification of extragalactic magnetar giant flares, through detecting their post-flash pulsations, and further study of the delayed emission ( $>1000$  s) in some GRBs (e.g. Villasenor et al. 2005), the nature of which is unclear. *A survey mission with excellent hard X-ray sensitivity, wide field-of-view, and the ability to give accurate positions rapidly for multiwavelength follow-up, will dramatically increase the numbers of detected gamma-ray bursts, our information about each, and our understanding of these events. Also, a Compton telescope observing the 1–100 MeV energy range could be used to study the high-energy tail of emission from gamma-ray bursts, particularly in conjunction with other orbiting  $\gamma$ -ray missions such as Fermi, and other all-sky sky monitors like Swift.*

## 2.7 Summary and Recommendations

HEA plays a pivotal role in many branches of extragalactic astronomy, ranging from the physics of AGN and supermassive black holes, to cosmology. Our overall recommendations for involvement in future missions are:

- excellent sensitivity in the soft X-ray band with excellent spectral resolution and good angular as in *IXO*
- modest sensitivity and excellent spectral resolution in the soft band as in the microcalorimeter on *Astro-H*
- modest sensitivity focussing hard X-ray telescope such as *Astro-H* or *Symbol-X*
- modest sensitivity for soft X-rays with excellent spectral resolution as in the micro-calorimeter on *Astro-H*
- excellent sensitivity, time resolution, and wide field-of-view in the hard X-ray band, with modest angular and spectral resolution, such as *EXIST*

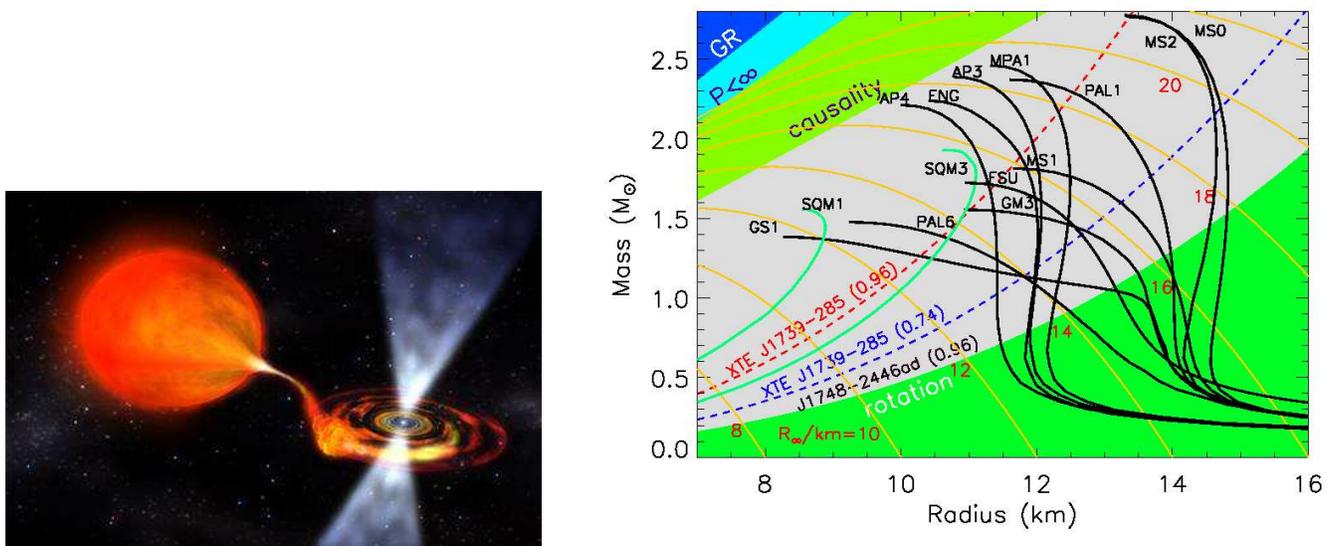


Figure 4: (Left) Artist’s concept of an X-ray binary (XRB) with an accreting neutron star (NASA/D. Berry). (Right) Neutron star mass-radius relationships for different equations-of-state (EOSs). The blue region is excluded by General Relativity, the lime-green (top left) region by requiring the sound speed be less than  $c$ , and the grass-green region (bottom right) by the observed rotation rate of the millisecond radio pulsar PSR J1748–2446ad (Hessels et al., 2006). Suggested constraints on the basis of two XRBs are also indicated. After Lattimer & Prakash (2004).

### 3 Accretion-Powered Compact Objects

#### 3.1 Introduction

In this section we consider accretion-powered compact objects, with a strong emphasis on neutron stars, an area of Canadian strength (see also §4).

Accreting neutron stars (NS) are in binary systems, with orbits small enough that matter from the companion star can make its way down to the surface of the neutron star (see Fig. 4, Left). There are two main ways this can happen: either the companion star has a significant stellar wind which blows past the neutron star and part of the wind is captured gravitationally (“Bondi-Hoyle” accretion); or the companion star is large enough that the stellar atmosphere directly gravitates onto the neutron star (“Roche-lobe overflow” accretion). In the latter case generically, and possibly in the former as well in some situations, the angular momentum of the accreted gas results in formation of an accretion disc in which the gas slowly flows toward the neutron star, with angular momentum transfer caused by viscosity. The inner edge of the disc can reach down to the surface of the neutron star for low magnetic field ( $\lesssim 10^{10}$  G) neutron stars, which reside in many low-mass X-ray binaries or LMXBs (the low-mass refers to the mass of the companion star). For high magnetic field ( $\gtrsim 10^{11}$  G) neutron stars (which reside in many high-mass X-ray binaries or HMXBs), the disc reaches down to the magnetosphere, inside which magnetic pressure dominates gas pressure and gas is forced to follow magnetic field lines to the magnetic poles.

Accreting neutron stars exist in a wide variety of binary systems, with a range of accretion disc sizes and mass transfer rates. The primary interests in studying accreting neutron stars are: deducing the fundamental properties of neutron stars; understanding the effects of mass transfer on the neutron star (including nuclear burning) and on the companion (stellar evolution, with varying mass with time); understanding the nature of physics in high magnetic field magnetospheres; and understanding the nature of the mass transfer process. Many of these same questions apply to accreting black hole binaries as well. Of interest as well are the Ultra-Luminous X-ray sources (ULXs) which have surprisingly high luminosities (Fabbiano, 1989). Whether these are an extension of binary X-ray sources containing neutron stars and stellar-mass black holes or a new class of objects containing intermediate-mass black holes with masses between  $\sim 10^2 - 10^4 M_{\odot}$  is unclear. If the latter, this would be the first evidence for the existence of objects that bridge the gap between stellar-mass and supermassive black holes (e.g. Madhusudhan et al. 2008).

Note that recent *INTEGRAL* hard X-ray surveys of the Galactic Centre region have revealed a large population of likely XRBs whose nature is unknown (e.g. Revnivtsev et al., 2008). This represents an important population to examine in doing population synthesis studies of XRBs in general. Focussing hard X-ray missions, starting with the pathfinder *NuSTAR*, will be of great use in localizing these objects and helping to identify their nature.

#### 3.2 What is the Equation-of-State of Dense Matter?

A major question in physics is the behaviour of matter at super-nuclear density (the “equation-of-state” (EOS) of dense matter). By measuring the mass and radius of neutron stars, one can put strong constraints on allowable

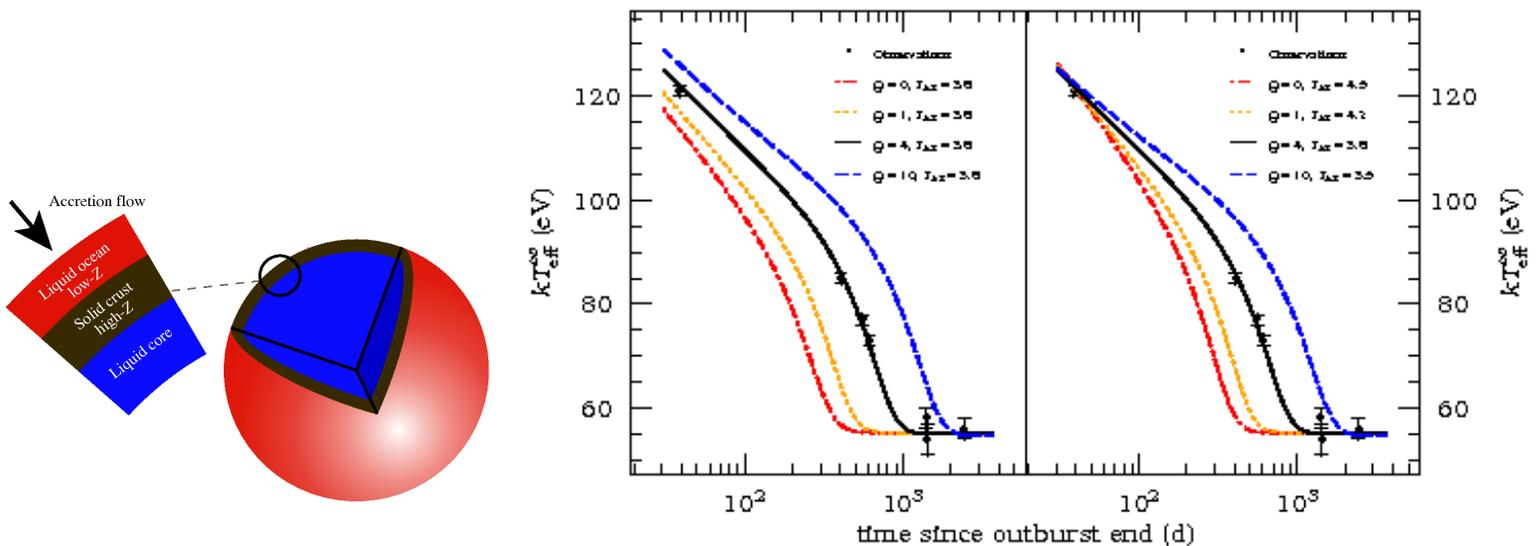


Figure 5: (Left) Compression of matter to high densities by accretion drives nuclear transformations that heat the neutron star crust. Courtesy E. Brown (MSU). (Right) Lightcurves of XRB MXB 1659–29 post-burst, for different choices of the impurity parameter  $Q_{\text{imp}}$  in the neutron-star crust. In both cases, the best-fit model is shown with a solid line. The other solutions have  $Q_{\text{imp}} = 0$  (dot-dashed line), 1 (dotted line), and 10 (dashed line). The left panel shows the case for which all other parameters are held constant; in the right panel the temperature at a column  $y_{\text{top}} = 10^{12} \text{ g cm}^{-3}$  was adjusted so that all solutions matched the first data point (after Brown & Cumming 2009).

equations of state at high density (see Fig. 4, right). As an example, General Relativistic calculations for an ideal gas of neutrons give an upper limit for the mass of a neutron star of  $0.7 M_{\odot}$ , much less than the observed masses of neutron stars in binary radio pulsars (Thorsett & Chakrabarty, 1999), ruling out an ideal gas EOS. Since the mass-radius relation is sensitive to the EOS, if we can measure the mass and radius of several neutron stars (or even one) with small ( $<10\%$ ) errors, strong constraints on the EOS can be placed (e.g. Lattimer & Prakash 2001, 2004).

- Using Thermal Emission to Constrain the EOS:** One efficient method of constraining the mass and radius of several neutron stars is to obtain high-quality X-ray spectra of LMXBs during periods of quiescence, when they are not actively accreting. In quiescence, NS LMXBs have relatively simple X-ray spectra, often dominated by the blackbody-like radiation of heat from the NS surface. Measuring the temperature of these NSs, along with the flux, gives  $R_{\infty}/D$  (where  $R_{\infty} = R \times (1+z)$ , where  $R$  is the stellar radius,  $R_{\infty}$  is that measured by an observer at large distance  $D$ , and where  $z \equiv GM/Rc^2$  is the gravitational redshift). For NSs in globular clusters, where the distance can be accurately determined, high-quality X-ray spectra can in principle strongly constrain the NS mass and radius, and thus NS interior structure (Brown et al. 1998, Rutledge et al. 2002a). Observations with *Chandra* and *XMM-Newton* are now providing interesting constraints (Heinke et al. 2006, Webb & Barret 2007). *Excellent sensitivity soft X-ray missions with good spectral resolution are needed for progress.*
- Constraining the EOS and Crust Properties using X-ray Bursts:** Many low-magnetic-field neutron stars exhibit seconds-long X-ray bursts, often reaching the Eddington luminosity limit. Most bursts are produced when the layers of accreted matter are hot and dense enough to ignite nuclear burning in the accreted material. These bursts can be studied by applying nuclear reaction networks and hydrodynamic equations, leading to better understanding of the thermal and physical state of accreted matter, and of the thermal state of the underlying neutron star (see Fig. 5, Left). In particular, the cooling of the neutron star during a quiescent period after a period of accretion and bursting gives information about the interior structure and EOS of the neutron star (Rutledge et al. 2002b, Cackett et al. 2006, Cumming et al. 2006, Heinke et al. 2007, Brown & Cumming 2009), including, among other things, impurity fraction in the crust (see Fig. 5, Right). Studies of the bursts themselves can identify the spin rate of the neutron star through burst oscillations (Chakrabarty et al. 2003), give clues to the star’s compactness by detailed modelling of the effects of gravitational light bending on those pulsations (as for the accreting millisecond pulsars; see §3.3), and possibly yield the redshift of the neutron star surface through identification of spectral lines (Cottam et al. 2002). *Studies of burst oscillations require excellent sensitivity and time resolution, while studies of lines require excellent sensitivity and good to excellent spectral resolution. Only modest angular resolution is required. An all-sky monitor is also important to identify opportunities for such observations.*

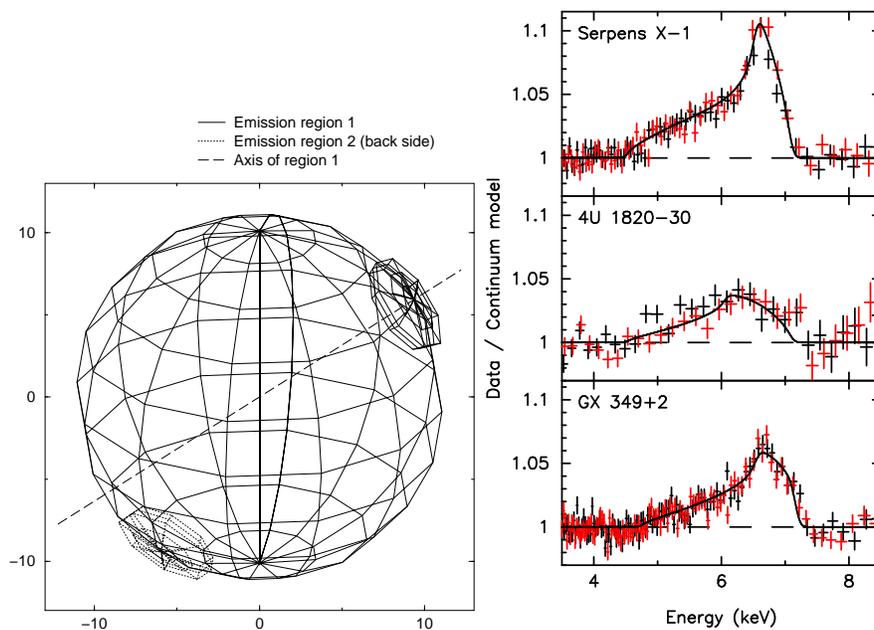


Figure 6: (Left) Wireframe of neutron star and accretion column model relevant to modelling of Her X-1 emission. (Right) Relativistic iron emission lines measured in the *Suzaku* spectra of X-ray binaries Serpens X-1, 4U 1820-30 and GX 349+2. After Cackett et al. (2008).

### 3.3 Understanding the Accretion Process

- What is the Origin of QPOs in XRBs?** Many LMXBs (with either neutron stars or black holes), where the magnetic field is weak and the mass transfer rate is high, exhibit a poorly understood phenomenon called Quasi-Periodic Oscillations (QPOs). Low frequency QPOs ( $\lesssim 50$  Hz) are thought to be associated with oscillation frequencies of the accretion disc and can be studied to determine their possible origin and relation to disc accretion physics. High frequency kHz QPOs around neutron stars may be produced by interactions between the stellar spin period and orbital period in the inner disc (the beat-frequency models). In the cases where a neutron star spin period and QPO period are measured (e.g. Chakrabarty et al., 2003), the QPO period is generally close to either the spin period or one-half the spin period, suggesting a connection. Alternative QPO drivers include relativistic precession models or relativistic resonance models (see van der Klis 2006). Both the relativistic precession models, and the beat-frequency models, predict the masses of the accreting object. Thus proving one of the models correct could give us a powerful tool for measuring fundamental properties of compact objects. The upcoming *Astrosat* mission will make some progress on these topics. *Identifying the nature of QPOs will require excellent sensitivity in the soft and hard X-ray bands, with high timing precision, but only modest angular resolution. An all-sky monitor is important for such work as well.*
- What are the Geometry and Physics of the Accretion Flow?** The process of gas accretion onto a neutron star is not well understood. This includes the interaction between the accretion disc and magnetic field of the neutron star, and interactions between the X-ray radiation and the surface of the accretion disc (which affects the shape of the disc). It also includes the structure of the accretion column and standoff shock near the neutron star surface, where the kinetic energy of infalling matter is thermalized and converted into outgoing radiation. Pulse shape modeling can be used to obtain the geometry of the emission region and obtain information on the mass and radius of the underlying neutron star. Accretion columns are known to exist for some  $10^{12}$  G slowly rotating neutron stars, from modelling such as Her X-1 (e.g. Leahy 2004; see Fig. 6, Left). X-ray polarimetry of such emission, however, has the potential to unambiguously test geometric models (e.g. pencil versus fan beams) for the emission. On the other hand, surface hot spots appear to be adequate to describe the X-ray pulse shapes for millisecond radio pulsars (see §4.2). These objects, because of their high rotation speeds have strong Doppler effects and have pulse shapes which are sensitive to radius (e.g. Cadeau et al. 2007; Bogdanov et al. 2008). Thus in principle one can obtain good constraints on mass and radius (e.g. Leahy et al. 2008). By comparing spectra and pulse shapes, or modeling simultaneously the pulse shapes at different energies, one can determine the radiation spectra of different components of the accretion column. The X-ray spectrum of an accreting neutron star is determined by radiation transfer in strong magnetic fields and can be modeled to give the physical conditions in the accretion column or hot spot. *Missions with excellent sensitivity to soft X-rays and excellent timing resolution, and modest angular resolution, can test these models. X-ray polarimetry would also allow major progress in this area. Excellent sensitivity and timing resolution in the soft to hard X-ray band, with only modest angular and spectral resolution, would also be of great use.*

### 3.4 X-ray Timing of Accreting Pulsars

X-ray pulse timing measurements yield pulse time delays and thus the relative neutron star distance from the observer. Timing thus can be applied to determine precise orbital parameters for X-ray binaries. With additional information one can obtain many more binary properties, e.g. eclipses give stellar radii and individual masses. Long-term timing studies can give orbital period changes which are related to tidal torques and dissipation within the stellar companion of the compact object (Wolff et al. 2008). Long-term timing also yields the pulse period history of the neutron star which is related to the accretion torques and the internal structure of the neutron star (Hartman et al. 2008). Long-term timing is thus often indispensable to detailed study of XRBs in general. The upcoming *Astrosat* mission will be useful in this regard. *Modest sensitivity all-sky monitoring with excellent timing resolution to detect bright outbursts and monitor the pulsations through outbursts is needed for a wide variety of applications.*

### 3.5 Relativistic Iron Lines

Observations of black holes (in both AGN (see §2.2) and X-ray binaries) have revealed some iron emission lines to be highly asymmetric (e.g. Miller et al. 2004). The iron line is caused by fluorescence from irradiated iron atoms in the accretion disc, and the shape of the line is caused by Doppler effects of the extreme motions of gas in the inner disc around black holes. Distorted, asymmetric emission lines indicate that some black holes are rotating at speeds near maximum, indicating efficient spin-up or, for stellar-mass black holes, birth with high angular momentum.

- **What is the spin distribution of black holes?** Measuring the iron lines in large numbers of black holes will constrain the spin distribution of stellar black holes (and thus the supernova process), while measuring iron lines in AGN will constrain the merger history of galaxies and their central black holes. *Studying iron lines requires a combination of excellent sensitivity, excellent spectral resolution, and good angular resolution. Excellent time resolution might furthermore allow one to follow the trajectories of individual clumps of matter as they accrete.*
- **Can Fe lines in neutron stars constrain mass and radius?** Iron lines in neutron star LMXBs have not been studied in the same detail. Only with recent high-sensitivity *XMM-Newton* and *Suzaku* observations have broad, asymmetric iron lines been observed in neutron stars (e.g. Cackett et al. 2008a, Papitto et al., 2009, see Fig. 6, Right). These observations highlight the potential to use iron lines in neutron stars as a probe of the inner disc radius; the inner disc radius is an upper limit on the neutron star radius (Bhattacharyya & Strohmayer 2007; Cackett et al. 2008a). It also may signify the innermost stable circular orbit predicted by General Relativity, allowing measurement of the mass of these neutron stars. *Excellent sensitivity, time and spectral resolution with good angular resolution will be critical for this work.*
- **What is the geometry of accretion discs?** X-ray polarimetry will explore the geometrical structure of X-ray-emitting regions, as any asymmetric structure involving scattering will produce polarized emission. Accretion discs will provide well understood polarization in the soft X-ray thermal disc emission, which can be used to measure the inclination of the accretion disc—the largest uncertainty in measurements of black hole spin (Li et al. 2009). Combining polarimetry with spectral information, we can explore the geometry of the hard X-ray component thought to be due to a corona or jet, and changes in this geometry at spectral state transitions. Combined with timing information, we can study the origin of QPO oscillations and broad iron lines, as the GR bending of spacetime induces polarimetric signatures (Fabian 2007). Finally, X-ray polarimetry promises to reveal the structure of accretion flows onto accreting neutron stars, determining whether there is a fundamental geometrical difference between accreting millisecond X-ray pulsars and non-pulsating LMXBs. *A broad-band X-ray polarimeter with even modest spectral, angular and timing resolution, and modest sensitivity, could yield important information.*

### 3.6 Low-Accretion Rate Black Holes: Is there Feedback in “Quiescence”?

The fate of matter falling onto black holes at low accretion rates is not well understood (see also §2.3). Current theory predicts that most of the energy of the infalling material is brought across the event horizon before it can radiate away (e.g. Narayan & Yi 1994). An alternative model suggests that most of the material is blown away in outflows (Blandford & Begelman 1999). Recent work suggests that low-accretion rate black holes put a large fraction of their luminosity budget into powerful jets (Gallo et al. 2005); this implies that supermassive black holes continue to shape their host galaxies’ evolution through jet power even when not “active” (Croton et al. 2006). Tests of these hypotheses will require deep observations of black holes at low accretion rates, with sufficient spectral resolution to determine the velocities and ionisation states of the gas. Observations of both stellar-mass and supermassive black holes will be extremely useful, and similar observations of low-accretion rate neutron stars will allow discrimination of the effects of a surface to the compact object from effects common to accretion flows. *These observations require excellent spectral resolution and sensitivity in soft X-rays.*



Figure 7: (Left) Artist's concept of a rotation-powered pulsar. (NASA) (Right) Schematic diagram of a cross-section of a neutron star (Brews Ohare/Wikipedia Commons).

### 3.7 Summary and Recommendations

The study of accretion-powered compact objects can constrain basic physics and astrophysics, through the observation and modelling of the usually dramatic behaviour of the various types of XRBs known. Given the science priorities we have described above, we recommend involvement in the following HEA missions:

- a soft (0.5-10 keV) X-ray mission with excellent sensitivity, spectral resolution, and good timing resolution and angular resolution, such as *IXO*
- a focussing hard X-ray mission (> 10 keV) with modest sensitivity and excellent spectral resolution, such as *Astro-H* or *Simbol-X*
- a soft-to-hard (2–60 keV) mission with excellent sensitivity and timing precision, modest angular resolution and spectral resolution, such as *AXTAR* or *EXIST*
- an X-ray polarimeter with modest broad-band sensitivity anywhere in 0.5-100 keV
- a sensitive all-sky X-ray monitor (such *EXIST* or the sky monitor proposed for *AXTAR*)

## 4 Magnetars, Rotation-Powered Pulsars, and Isolated Neutron Stars

### 4.1 Introduction

In contrast to accretion-powered neutron stars (§3), it is believed that the vast majority of neutron stars in the Galaxy are powered by an internal energy source. The objects discussed next are powered by one or more of the following internal sources: their loss of rotational kinetic energy (Fig. 7, Left), the decay of ultra-high magnetic fields, and residual cooling following formation. The science addressed by the existence and sometimes dramatic behaviour of these objects ranges from basic physics issues like the equation-of-state of ultradense matter and the behaviour of matter in quantum-critical magnetic fields, to fundamental astrophysical problems such as “How do jets form?” and “What is the fate of massive stars?”

### 4.2 Rotation-Powered Pulsars

These objects are rapidly rotating neutron stars (periods currently ranging from 1.4 ms to 8 s) having magnetic fields in the range  $\sim 10^9$  to  $\sim 10^{14}$  G. They produce radiation across the EM spectrum, however the bulk of their radiative energy comes out in the high-energy bands, namely in X-rays and  $\gamma$ -rays. Although they are traditionally easiest to observe at radio wavelengths, work over the past two decades has detected several dozen in the X-ray band, and the *Fermi* mission is currently greatly increasing the number of  $\gamma$ -ray identifications. Here we identify some of the major unanswered questions regarding these sources, in particular issues that are best addressed via HEA observations:

- **What is the Equation-of-State (EOS) of Ultradense Matter?** The nature of matter at supra-nuclear densities, as is commonly believed to exist in the cores of neutron stars, is currently unknown (see Fig. 7, Right, and §3.2). The possibilities range from kaon condensate to free quarks (Lattimer & Prakash, 2001). X-ray observations of isolated neutron stars can constrain EOS models in the following ways:

- Studying the cooling of neutron stars by measuring temperatures and ages of individual objects producing observable thermal emission. Although both such measurements can suffer from large systematic uncertainties (e.g. measured temperatures are, among other things, atmosphere-model dependent), strong upper limits like that obtained for the young rotation-powered pulsar PSR J0205+6449 (Slane et al., 2002) can be highly constraining. *Such work requires an excellent sensitivity soft X-ray mission, with good spectral and timing resolution.*
  - Measuring mass-to-radius ratios for thermally emitting neutron stars, particularly millisecond pulsars (Fig. 8, Left), via detailed modelling, including full relativistic and atmospheric effects (e.g. Cadeau et al., 2007; Leahy et al., 2008b; Bogdanov et al., 2008). See also §3.3. *Such work also requires an excellent sensitivity soft X-ray mission with good spectral resolution, and good timing resolution.*
  - Measuring the spin rates of fast-spinning neutron stars. X-ray observations do not suffer from pulse-broadening interstellar medium effects (as in the radio), and so can measure the spins of young or recycled neutron stars without bias. Finding neutron stars with periods faster than the fastest currently known ( $< 1.4$  ms; Hessels et al., 2006) would constrain their equation-of-state; demonstrating a sharp cutoff in the period distribution indicates a limit to rotational speed, possibly induced by gravitational radiation losses (Chakrabarty et al. 2003) or particularly large neutron star radii. *Such work requires excellent sensitivity and time resolution, but modest spectral and angular resolution.*
- **How do Pulsars Shine?** The brightest radiation from rotation-powered pulsars by far is from non-thermal, magnetospheric emission processes. However the nature of the pulsar emission mechanism has been a major puzzle in astrophysics. The question is simple: how does a rotating magnet manage to convert its energy into powerful EM radiation extending as high as GeV  $\gamma$ -rays, as well as into a relativistic particle wind that forms jets and torus structures? The answers to these questions are likely to have broad applications elsewhere in HEA, such as for understanding jets from XRBs and AGN. Specifically, open issues are:
    - **How are non-thermal pulsations produced?** *Fermi* is likely to provide important information, as it is expected to detect dozens of  $\gamma$ -ray pulsars, and it is in this regime that the bulk of the energy is emitted. Emission in the X-rays,  $\gamma$ -rays, and radio regimes is thought to come from different parts of the pulsar magnetosphere. Radio polarization studies have given us insight into the geometry and structure of the radio emission, but the X-ray radiation has not yet been similarly constrained. *X-ray polarimetry in the soft or hard X-ray band, even with modest sensitivity, has the potential to greatly elucidate emission mechanisms.*
    - **How is the pulsar wind produced?** How the rotating magnet manages to produce a relativistic electron/positron wind having, in many cases, a well defined torus/jets morphology, is not understood (see also §5). While modelling (e.g. Bucciantini, 2008) is important, the current observational state of affairs shows a myriad of morphologies, with most images currently Poisson-limited, owing to low detector sensitivity. *For such work, excellent angular resolution is required in the soft band, in addition to excellent sensitivity.*
  - **What is the Connection Between Rotation-Powered Pulsars and X-ray Binaries (XRBs)?** Millisecond radio pulsars (MSPs) have long been thought to be the descendants of low-mass X-ray binaries (LMXBs; see §3; Bhattacharya & van den Heuvel, 1991), with MSPs obtaining their very rapid rotation rates from the accretion of matter and angular momentum during a lengthy (billions of years) XRB phase. Although there is strong indirect evidence for this standard binary evolution picture, transition objects are expected. Quiescent LMXBs (qLMXBs) have been argued to harbour rotation-powered pulsars, which abruptly shut off when accretion turns on, owing to matter in the magnetosphere. However the evidence for this thus far is indirect (e.g. Burderi et al., 2003; Hartman et al., 2008). X-ray monitoring of qLMXBs and certain MSPs that harbour non-degenerate companions (e.g. Archibald et al., 2009) may identify transition behaviour, with either magnetospheric pulsations produced from a qLMXB, or sudden accretion onto an otherwise conventional MSP. *Astrosat* will contribute to these efforts. *Major progress requires a sensitive X-ray all sky monitor, as well as an X-ray mission with excellent sensitivity and timing resolution, and modest angular resolution.*
  - **Detecting Gravitational Waves with Millisecond Pulsars:** Long-term, high-precision phase-coherent timing of MSPs distributed roughly isotropically on the sky can be used to detect or set upper limits on gravitational waves either from a stochastic background or from individual sources (e.g. Kaspi et al., 1994; Jenet et al., 2006). Although the bulk of such timing will be done at radio wavelengths where most MSPs are most easily observable, some MSPs may be more amenable to timing at X-ray energies, where ISM effects matter less. *For such work, excellent sensitivity and timing resolution are necessary, but only modest angular and spectral resolution are required.*

### 4.3 Magnetars

Magnetars are ultrahighly magnetized ( $B \simeq 10^{14}$ – $10^{15}$  G) young, isolated neutron stars (Thompson & Duncan, 1996). This rare class (only 15 are known so far) are observed to have relatively long spin periods (2–12 s) and to

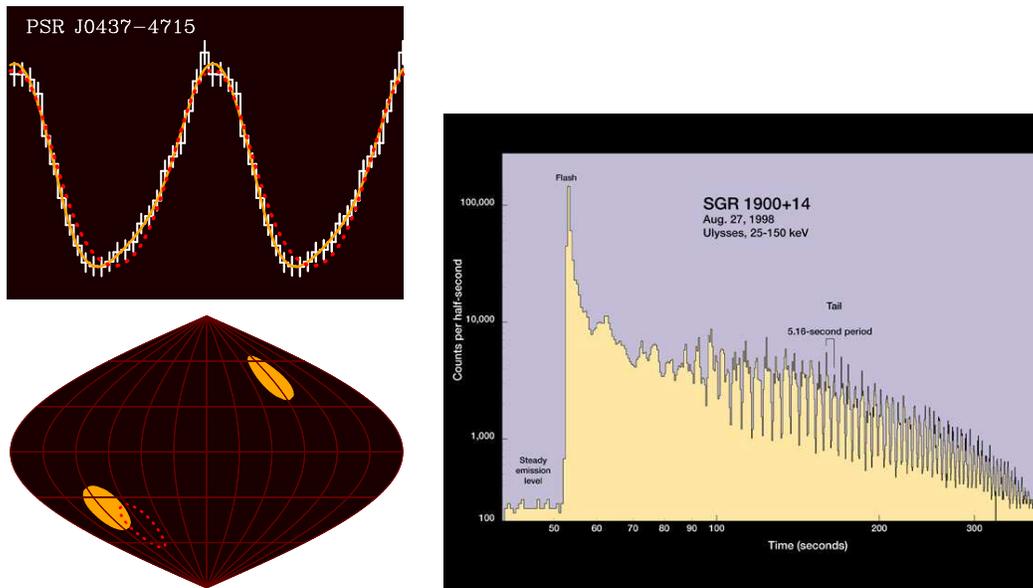


Figure 8: (Left) Top: Pulsed thermal X-ray emission from the nearest millisecond pulsar PSR J0437–4715. The dotted red curve shows a theoretical model of a rapidly rotating neutron star with two antipodal X-ray–emitting polar caps. A model with polar caps that are not antipodal (orange curve) provides a much better description of the X-ray data. Bottom: Equal-area map projection of the entire neutron star surface showing the positions and sizes of the two X-ray emitting polar caps (orange) of PSR J0437–4715. The expected position of the bottom polar cap if it were diametrically opposite to the top one is shown by the dotted red line. (Courtesy S. Bogdanov). (Right) Giant flare from SGR 1900+14 that occurred August 27, 1998. (NASA).

exhibit often extremely dramatic radiative behaviour, including large X-ray and  $\gamma$ -ray bursts, flares, and so-called “giant flares,” (Fig. 8, right) which can greatly outshine, for one brief moment, the entire cosmic  $\gamma$ -ray sky (e.g. Hurley et al., 2005), even sometimes noticeably affecting the Earth’s ionosphere. Two “flavours” of magnetars are known: Soft Gamma Repeaters (SGRs) which show giant flares and are generally very active, and Anomalous X-ray Pulsars (AXPs) which are generally less active but can be brighter when not in outburst. Magnetar emission is far too luminous to be rotation-powered; rather their emission is thought to be powered by the decay of the ultrahigh magnetic field. The major open questions regarding these exotic objects are:

- **What is the Connection Between Magnetars and High- $B$  Rotation-Powered Pulsars?** Although there is clear overlap in  $B$  space (as inferred from the pulsars’s periods and rates of spin-down, assuming magnetic dipole radiation in both classes), magnetar and conventional pulsar radiative behaviours are strikingly different. Two magnetars have presently been detected at radio wavelengths (e.g. Camilo et al., 2006). Recently clear transition behaviour was seen when a high- $B$  rotation-powered pulsar metamorphosized temporarily into a magnetar (see Fig. 9, Left; Gavriil et al., 2008; Kumar & Safi-Harb, 2008). Do all high- $B$  rotation-powered pulsars do this, with frequency correlated with inferred  $B$ ? And when do *bona fide* magnetars show radio emission? *These questions can be answered with a sensitive all-sky X-ray monitor, via detection of outbursts from high- $B$  rotation-powered pulsars. Monitoring with good sensitivity and timing resolution, but modest angular and spectral resolution, is also important here.*
- **Can we Constrain the Physics of Matter in QED-Strength  $B$  Fields?** Magnetar radiative behaviour is dramatic and extreme and closely tied with rotational evolution, with most, if not all, major radiative events seen in AXPs (and possibly SGRs, though this is not yet established) accompanied by rotational anomalies, usually spin-up “glitches.” This is as observed via *RXTE* monitoring programs (e.g. Kaspi et al., 2003; Dib et al., 2008). This observably ties the physics in the stellar interior, where glitches are thought to arise, with the exterior of the star. The often dramatic glitches and subsequent radiative afterglows are not well modelled but likely hold crucial information regarding the geometry and evolution of the  $B$  field. Similarly, putative features seen in some magnetar burst spectra (e.g. Gavriil et al., 2002; Ibrahim et al., 2002) may hold interesting clues to the emission mechanism and/or provide a direct measure of the  $B$  field strength. Finally, AXPs have only recently been recognized as being among the hardest X-ray sources in the sky. Their surprising spectral turnover above  $\sim 15$  keV (Kuiper et al., 2004) is not well understood but could be explained by a stellar “corona” (Beloborodov & Thompson, 2007). The pathfinder focussing hard-X-ray mission *NuSTAR* will make progress on this. *Studying overall magnetar behaviour is best done with a sensitive all-sky X-ray monitor, and/or by target-of-opportunity monitoring with a good sensitivity, good spectral resolution X-ray telescope. X-ray polarimetry also holds tremendous promise for understanding the emission geometry. Observations of magnetars with a focussing hard X-ray telescope of even modest sensitivity would also be valuable.*

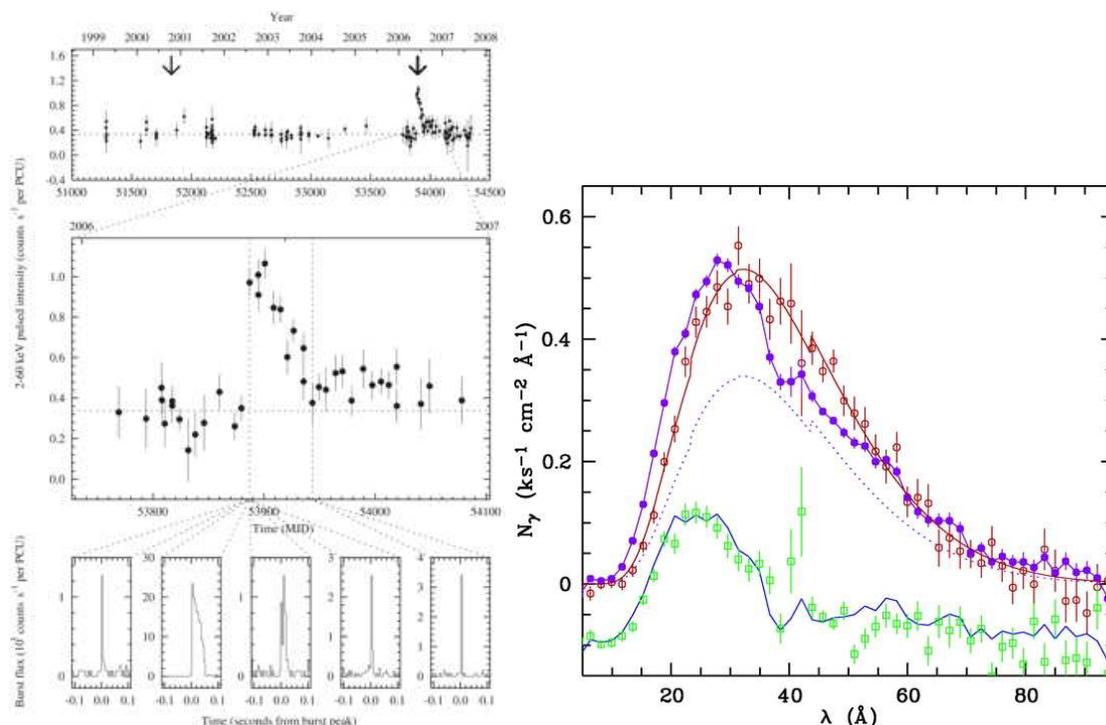


Figure 9: (Left) Top: Pulsed flux history of PSR J1846–0258 showing the prominent outburst of June 2006 as recorded in the 2–60 keV band by *RXTE*. The horizontal dotted line represents the persistent flux level. Middle: The light curve around the outburst. The vertical dashed lines indicate the epochs of the observations containing the bursts. Bottom: The 2–60 keV *RXTE* X-ray light curves corresponding to five bursts detected from PSR J1846–0258. After Gavriil et al. (2008). Right: *Chandra* grating spectra of two isolated neutron stars. The spectrum of RX J0720.4–3125 from 2000 (red open circles) is well described by an absorbed blackbody – the red solid curve passing through red open circles). The average post-2003 spectrum (magenta filled circles) could be a superposition of spectra from unchanged and changed parts of the surface. As an indication, a close to maximum contribution by the unchanged spectrum is indicated (magenta dotted curve). The residual (blue wiggly curve, offset down by 0.1 units for clarity) is remarkably similar to the spectrum of RX J1308.6+2127 (green open squares, scaled by a factor 1.2). After van Kerkwijk et al. (2007).

- What Fraction of Neutron Stars Become Magnetars?** One interesting question is what produces a magnetar versus a conventional rotation-powered pulsar. The discovery of an AXP in a massive star cluster (Muno et al., 2006) as well as some SGRs being in massive star clusters (e.g. Eikenberry et al., 2004) suggest that massive stars preferentially produce magnetars, although this does not preclude low-mass progenitors. A closely related question is how many magnetars exist in the Galaxy, and how that number compares to the number of rotation-powered pulsars. This is particularly pressing given the discovery of transient magnetars (Ibrahim et al., 2004). This can be addressed via population synthesis studies (e.g. Faucher-Giguère & Kaspi, 2006; Keane & Kramer, 2008). This may also be relevant for gamma-ray bursts (e.g. Bucciantini et al., 2008, see §2.6). *One way to identify magnetars is via their hard X-ray emission; a wide survey with a wide-field hard X-ray telescope of good sensitivity could in principle detect every active Galactic magnetar. A sensitive all-sky X-ray monitor would also be useful.*

#### 4.4 “Isolated Neutron Stars” (INs)

The *ROSAT* All-Sky survey was very sensitive to nearby, cooling neutron stars. It found a surprise: not just the known middle-aged radio pulsars (including the radio-quiet Geminga pulsar), but also seven cooling neutron stars that had much longer periods, from 3 to 11 s (van Kerkwijk & Kaplan, 2007), that showed thermal X-ray emission only, with no sign of non-thermal, magnetospheric emission from radio to  $\gamma$ -ray energies. These have come to be known as “isolated neutron stars<sup>1</sup>”. It is not yet clear what these sources are, though some evidence points towards rotation-powered pulsars with beams that miss the Earth. Other evidence suggests they are quiescent descendants of magnetars.

The thermal emission almost certainly arises from the surface, and the spectra show broad and in one case variable absorption features (see Fig. 9, Right). This offers the prospect of studying neutron star atmospheres in detail, and using them to determine the composition and state of the neutron-star surfaces. Do neutron stars, like white dwarfs,

<sup>1</sup>Alternatively, they are sometimes referred to as “X-ray Dim Neutron-Stars” (XDINS). Note neither name is truly appropriate as many rotation-powered pulsars, and all magnetars, are isolated as well.

have outer layers composed of pure hydrogen or helium (gravitationally separated)? Or heavy elements, reflecting the composition of the progenitor’s core? As yet, we do not understand what the absorption features are due to, the main complicating factor being that the sources have strong magnetic fields, of a few  $10^{13}$  G (as inferred from X-ray timing; e.g. Kaplan & van Kerkwijk, 2005). This strongly influences atomic features, making it difficult to model the atmospheric emission (with most work so far done for hydrogen (e.g. Ho & Lai, 2004). Indeed, for heavy elements, it is not clear if the state of the surface would be gaseous or condensed. (For a sufficiently strong magnetic field, heavy elements can condense even at  $10^6$  K (e.g. Medin & Lai, 2007). But if we can understand the emission, we will be able to use it to measure radii, gravitational redshifts, and perhaps even surface gravity. Major open questions are:

- **What is the Composition and Physical State of Neutron Star Surfaces?** The different compositions and states lead to different predictions not only for the energies and widths of the various features, but also how they vary with magnetic field strength and temperature. These can be tested by detailed spectroscopy of different sources, of a given source at different rotational phases, and of any sources that vary (of which one is known so far). *This requires excellent sensitivity, good spectral resolution, and good timing resolution in the soft X-ray band, as well as soft X-ray monitoring capabilities. Modest sensitivity in the soft band and excellent spectral resolution may be useful too.*
- **What are the Interior Properties of Neutron Stars?** With the surface emission understood, modelling it will yield temperatures, gravitational redshifts, and possibly surface gravity. Combined with parallaxes and proper motions determined from astrometry, one finds radiation radii and ages. With these, one can constrain the interior equation-of-state and cooling processes by comparing the observations with predicted masses, radii, and luminosities. *This requires the same X-ray observations as the previous item, supplemented with optical astrometry.*
- **With What Properties are Neutron Stars Born?** The proximity of the INs as well as their relatively low luminosities argues for the known sources being the tip-of-the-iceberg. However prior to the identification of this class, conventional rotation-powered pulsars were thought, thanks to population synthesis models, to have birthrates consistent with the expected neutron-star-producing core collapse supernova rate for the Milky Way. Along with magnetars, which, though generally bright, are also thought to be short-lived, the INs may imply a sizable increase in the calculated birthrate of Galactic neutron stars, as may the enigmatic “Rotating Radio Transients” (RRATs) (McLaughlin et al., 2006). Just how large this actually is, and whether the neutron-star birthrate agrees with the core-collapse supernova rate, is still unclear (Keane & Kramer, 2008, see also §4.3). *This question is best addressed by a wide-field survey modestly sensitive particularly to very soft X-ray emission.*

#### 4.5 “Central Compact Objects”

There exists a small class of objects that are difficult to classify, all found near the centres of supernova remnants (SNRs), hence their informal designation as “central compact objects” (CCOs). Examples are the central source in the SNRs Cas A (Fig. 12, Left) and RCW 103. The nature of these objects is not well understood. After much study, some appear to be very unenergetic, relatively slowly spinning neutron stars (e.g. Gotthelf & Halpern, 2007), but for others their nature remains elusive. For instance, the source in Cas A shows no evidence for any pulsar activity, neither pulsations nor any wind. As another extreme, the source in RCW 103 shows a 6.7-hr period and is highly variable (De Luca et al., 2006). All these suggest neutron stars have even more varied manifestations. Indeed, also puzzling is that many SNRs appear to be empty. In a detailed study of ten nearby supernova remnants, Kaplan et al. (2004, 2006) find no compact objects in any of them, in many cases setting limits fainter than the central source in Cas A. The supernova remnants were selected to be those of core-collapse supernovae, so this again suggests unexpected variety in the types of compact objects produced. Perhaps some neutron stars cool much faster (because they are more massive?) and are much less energetic (because they are born spinning relatively slowly?), or perhaps supernovae lead more often than thought to (low-mass?) black holes. *The most promising avenues for progress on these puzzling objects are excellent sensitivity and time resolution observations, with monitoring and good spectroscopy, and good angular resolution.*

#### 4.6 Summary and Recommendations

Neutron stars offer unique windows into extreme physics. From basic physics questions including the nature of matter at supra-nuclear density to the behaviour of matter in ultra-strong magnetic and gravitational fields, the science questions addressed by neutron stars impact on many different areas of HEA and astrophysics in general. Recommendations for future mission priorities are:

- excellent sensitivity with good spectral resolution and timing resolution, as in *IXO*
- a modest sensitivity focussing hard X-ray telescope such as *Astro-H* or *Simbol-X*
- an excellent sensitivity and time resolution mission with modest angular and spectral resolution, like *EXIST* or *AXTAR*

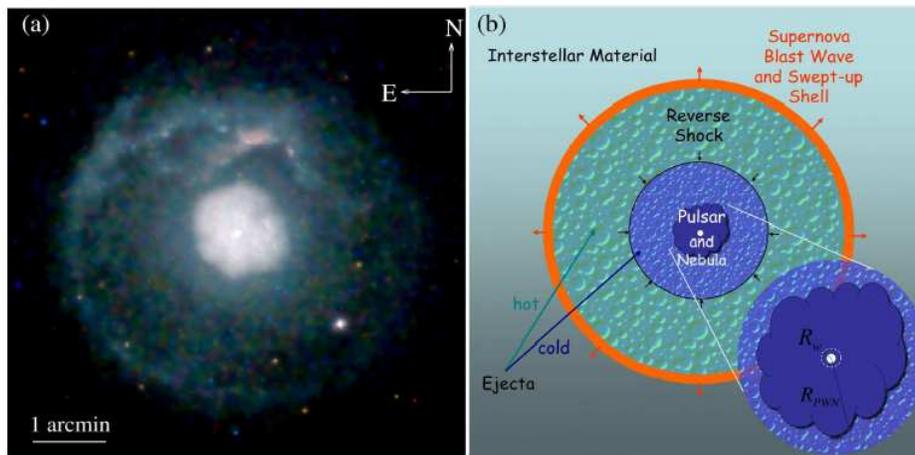


Figure 10: (Left) *Chandra* image of Pulsar Wind Nebula (PWN) G21.5–0.9 showing the different components of an SNR: a central pulsar powering a PWN (bright core near the centre) and a faint SNR shell discovered after accumulating over  $\sim 0.5$  Msec of observations with *Chandra* (Matheson & Safi-Harb, 2005). (Right) A schematic diagram showing a composite-type SNR: a forward shock, a reverse shock, a PWN, and a pulsar. After Gaensler & Slane (2006).

- modest sensitivity, angular and spectral resolution broad-band X-ray polarimetry with good timing resolution
- sensitive all sky monitoring as in *EXIST* or the sky monitor on *AXTAR*
- modest sensitivity and excellent spectral resolution as for the microcalorimeter on *Astro-H*

## 5 Supernova Remnants and Pulsar Wind Nebulae

### 5.1 Introduction

Supernova (SN) explosions are among the most energetic such events in the Universe, releasing about  $10^{51}$  ergs of kinetic energy. The SN blast wave initially travels in the interstellar medium with velocities of  $10,000$ – $20,000$   $\text{km s}^{-1}$ , thus shocking it to X-ray emitting temperatures, compressing the ambient magnetic field, and accelerating particles at the forward shock. As the blast wave sweeps the ambient medium, a reverse shock forms, heating the ejecta to X-ray emitting temperatures (see Fig. 10).

The line emission from young SNRs is important as it reveals information about the nucleosynthesis yields of the explosion, which can then be compared to theoretical SN models. In particular, in the  $0.5$ – $10$  keV energy range (the energy to which current focussing X-ray missions are sensitive), alpha elements (synthesized by alpha-capture in type II SNe) from O to Ni are detected in the X-ray spectra of young (up to  $\sim 10^4$  yr-old) SNRs; with type II explosions being O-rich, while type Ia explosions are Fe-rich. Note that type Ia SNe are believed to originate from white dwarfs in binary systems. These white dwarfs are thought to explode by deflagration and are not expected to leave behind a compact remnant.

The X-ray emission from the forward and reverse shocks is generally thermal and dominated by line emission. Some SNR shells however have a featureless, non-thermal spectrum, showing evidence for cosmic ray acceleration to TeV energies (e.g. SN 1006, Koyama, 1995). As such, X-ray studies of supernova remnants (SNRs) offer nearby laboratories for tracking the heavy elements created in the Universe, determining the type and physical parameters of the SN explosion, as well as studying shock acceleration and the origin of high-energy cosmic rays.

Furthermore, those SNRs that result from core-collapse explosions of massive ( $M \geq 8M_{\odot}$ ) stars host some of the most extreme forms of matter as they are expected to harbor neutron stars (or black holes for the most massive progenitor stars). An active rotation-powered pulsar emits a relativistic wind of electrons and positrons. As the wind gets confined by its surrounding medium (supernova ejecta or the ambient matter), it gets shocked and emits synchrotron radiation, thus forming a pulsar wind nebula (PWN) which can be visible from radio energies to the highest energy  $\gamma$ -rays, and which gives the SNR a centrally filled morphology (see Fig. 10). PWNe have a non-thermal spectrum from radio to high-energy  $\gamma$ -rays and are polarized. X-ray studies of PWNe, combined with multi-wavelength observations, have allowed the determination of the physical parameters of pulsar winds, and even in the absence of a pulsar detection, the energetics and geometry of the powering engine (see Gaensler & Slane, 2006, for a review).

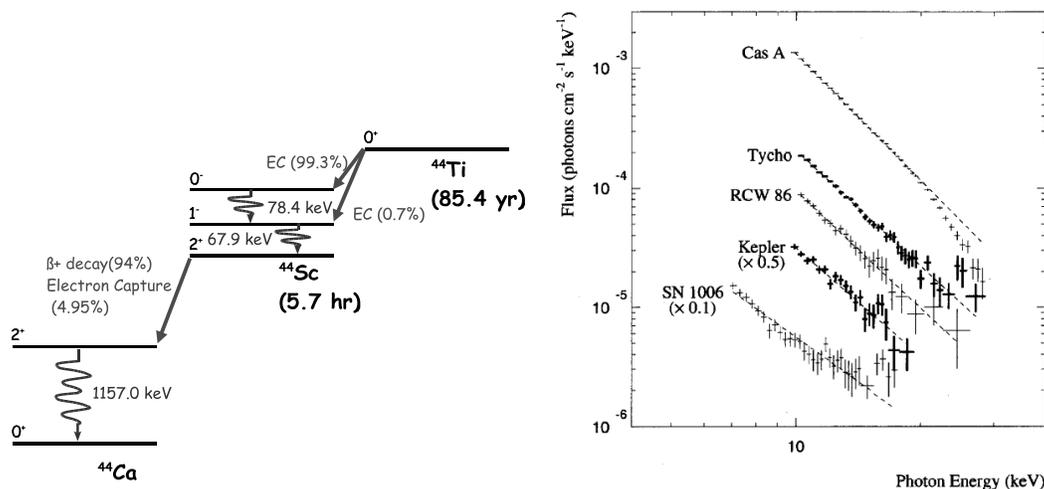


Figure 11: (Left) The decay scheme of  $^{44}\text{Ti}$  showing the hard X-ray lines expected. After (Vink, 2004). (Right) Hard spectra from SNRs using *RXTE*. The non-thermal emission is believed to be produced by synchrotron radiation from electrons accelerated to TeV energies. Image credit: Petre et al. (2001).

## 5.2 Where are the Missing SNRs?

With a SN rate of 1–2 per century and with Cas A (see Fig. 12, Left) being the youngest ( $\sim 330$  year-old) SNR in our Galaxy associated with a historical event<sup>2</sup>, a SN is long overdue. It is likely that we are missing SN explosions in our Galaxy due to extinction and their exploding in complex regions of the Galactic plane, especially near the Galactic centre. One way to search for obscured and young SNRs is through  $^{44}\text{Ti}$  decay lines (see Fig. 11, Left) since the decay time of  $^{44}\text{Ti}$  into  $^{44}\text{Sc}$  is  $\sim 86$  years. Furthermore,  $^{44}\text{Ti}$  is an excellent explosion diagnostic since its yield is very sensitive to the mass cut (the mass above which matter is ejected), the explosion energy and asymmetries; see Vink (2004) for a review and for an interpretation of the detection of the  $^{44}\text{Ti}$   $\gamma$ -ray lines in Cas A. Sensitivity to the 68 keV and 78 keV lines is thus of great interest. This can be addressed with the planned *NuSTAR* and *Astrosat* missions. *Future hard X-ray missions with good spectral resolution, either focussing telescopes or sensitive all-sky scanners, will be very useful for this work. Also a Compton telescope (sensitive in the MeV range) can search for obscured/missing SNRs through the detection of the 1.157 MeV  $\gamma$ -ray line resulting from the decay of  $^{44}\text{Ti}$  into  $^{44}\text{Ca}$  (Fig. 11, Left).*

## 5.3 What is the Origin of Cosmic Rays?

SNRs have long been thought to be the primary source of cosmic ray (CR) acceleration up to the ‘knee’ of the CR spectrum ( $\sim 3 \times 10^{15}$  eV). While the non-thermal radio emission from SNR shells indicates the presence of GeV electrons, the presence of TeV electrons was first demonstrated with X-ray/*ASCA* observations of SN 1006 (Koyama, 1995), and later with hard X-ray imaging and spectroscopy of young historical SNRs using e.g. *Chandra* (see Fig. 12) and *RXTE* (Fig. 11, Right; Petre et al., 2001). However, the maximum energy of electrons has been estimated to be a few hundred TeV, still much below the ‘knee’. More importantly, so far there is no convincing evidence that ions, which constitute the bulk of the cosmic rays observed on Earth, are accelerated up to or beyond the ‘knee’ of the CR spectrum.

Recent HESS TeV observations of SNRs (e.g. Aharonian, 2004, see Fig. 12, Right), have opened a new window to address cosmic ray acceleration in SNRs. The observed  $\gamma$ -ray emission has been generally interpreted as due to either inverse Compton scattering (ICS) of  $\geq 10$  TeV electrons (leptonic), or the decay of neutral pions created by energetic ion collisions (hadronic). As a result, the energies to which protons or ions are accelerated remains an open question. This can be addressed spectroscopically with modeling the broadband spectral energy distribution (SED) – see Fig. 13 illustrating the relative contribution of the different components to the hard X-ray spectrum in the leptonic and hadronic models. *Constraining the models can be achieved by studying the unexplored hard X-ray/soft  $\gamma$ -ray regime with good sensitivity and good angular resolution hard X-ray telescopes. When the SNR shell is not resolved, simultaneous coverage in the soft band is needed to disentangle the soft (thermal) and hard (non-thermal) emission.*

## 5.4 What is the Relation of keV and TeV Emission in SNRs?

As for SNRs, HESS has revealed extended TeV emission from a number of PWNe (see e.g. Horns et al., 2006). These findings are shedding light on the acceleration mechanism in ultra-relativistic shocks. By measuring the broad-band

<sup>2</sup>Note however that Reynolds et al. (2008) have recently claimed that G1.9+0.3 is the youngest ( $\sim 100$  year-old) SNR in our Galaxy based on the expansion of the SNR as measured from radio and *Chandra* observations.

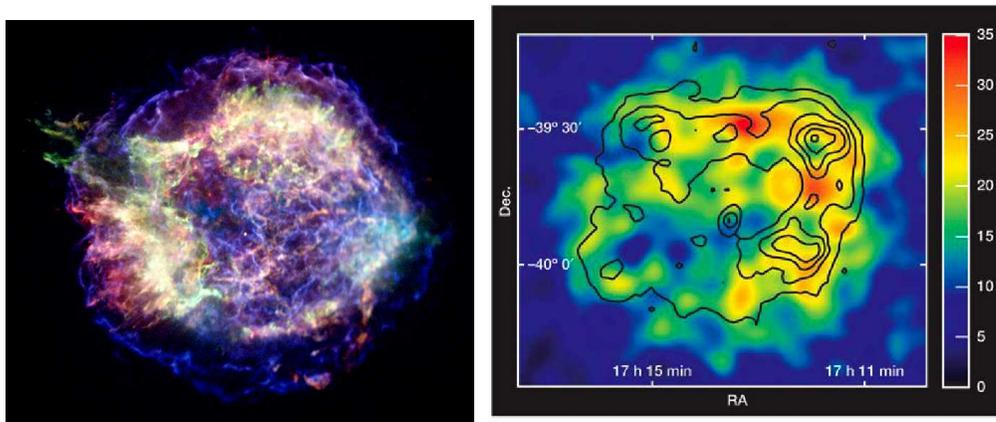


Figure 12: (Left) Energy-colour image of Cas A displaying non-thermal emission from accelerated particles to TeV energies (in blue) mixed with thermal emission from millions K hot gas (in red and green). The point source near the SNR centre is the Central Compact Object (CCO) whose nature remains unknown. Credit: NASA/CXC/MIT/UMass Amherst/M. Stage et al. (Right) HESS image of SNR G347.3–0.5 with *ASCA* X-ray contours superimposed. After Aharonian (2004).

SED from the TeV emitting PWNe, we are gaining insights on the composition of pulsar winds and on the mechanism for accelerating ions to TeV energies.

The presence of ions has been indirectly inferred in pulsar winds from imaging observations of wispy-like structures in the Crab and Vela PWNe. Spectroscopic studies of the SED of Vela-X led to the interpretation of its  $\gamma$ -ray emission as a nucleonic component, suggesting acceleration of protons in pulsar winds to TeV energies (Horns et al., 2006). The origin of TeV emission from most PWNe remains, however, an open issue: it is not yet clear whether the emission is leptonic or hadronic in origin. *To answer this question, as with SNRs, multi-wavelength modeling of the SED is needed (see e.g. Fig. 13), which requires coverage in the hard X-ray/soft  $\gamma$ -ray band in order to constrain the models.*

## 5.5 What is the Nature of SN Progenitors?

To date, the nature of many SN explosions (i.e. whether type I or II), the mass of their progenitors, and the nature of their central ‘hot X-ray spots’ (see §4.5) remain unknown. High-resolution X-ray studies in the 0.5–10 keV band have been particularly useful in addressing these questions as they allow us to search for any compact stellar remnant and map the SN ejecta, in particular the oxygen-rich and iron-rich ejecta which shed light on the SN type (see e.g. Safi-Harb et al., 2005). However in most cases uncertainties arise due to (a) the lack of spectral resolution or sensitivity needed to study in detail the nucleosynthesis yields across the SNR, (b) the mixing of thermal and non-thermal emission in many SNRs, and/or (c) the lack of hard X-ray coverage (above 10 keV). *Combined good angular resolution and excellent sensitivity and spectral resolution in the soft X-ray band would be of significant utility for disentangling thermal and non-thermal emission. Furthermore excellent-resolution non-dispersive soft-X-ray spectroscopy with a focussing telescope would provide a powerful diagnostic for constraining the plasma conditions in SNRs.*

## 5.6 Magnetic Field Structures of SNRs and PWNe: X-Ray Polarization

Synchrotron emission is expected to be polarized from the radio regime to the high-energy X-rays. Radio polarization studies of PWNe and SNRs reveal that these sources are polarized with a polarization fraction less than the maximum expected from synchrotron radiation. Radio polarization studies are however often hampered by Faraday rotation and depolarization effects. At optical wavelengths, most SNRs in the Galactic plane are heavily absorbed.

X-ray polarization was first detected from the Crab Nebula back in 1976 using a graphite crystal X-ray polarimeter aboard the OSO-8 satellite (Weisskopf et al., 1976). Since then no other X-ray polarization measurements have been made. X-ray polarimetry offers a new window to address the magnetic field structure in PWNe and SNRs. For example, for SNRs, radio polarization studies indicate that the magnetic field is measured to be radial in the young SNRs (with low polarization fractions) and tangential or confused in the older ones, with the polarization structure becoming more complex with increasing resolution (Milne et al., 1989). *A modest sensitivity focussing X-ray polarimeter would be useful in this regard.*

## 5.7 Summary and Recommendations

Supernova remnants require broad-band observations to answer many questions related to stellar evolution, behavior of shocks, the interstellar medium, and the origin of cosmic rays. Recommendations for future mission priorities are:

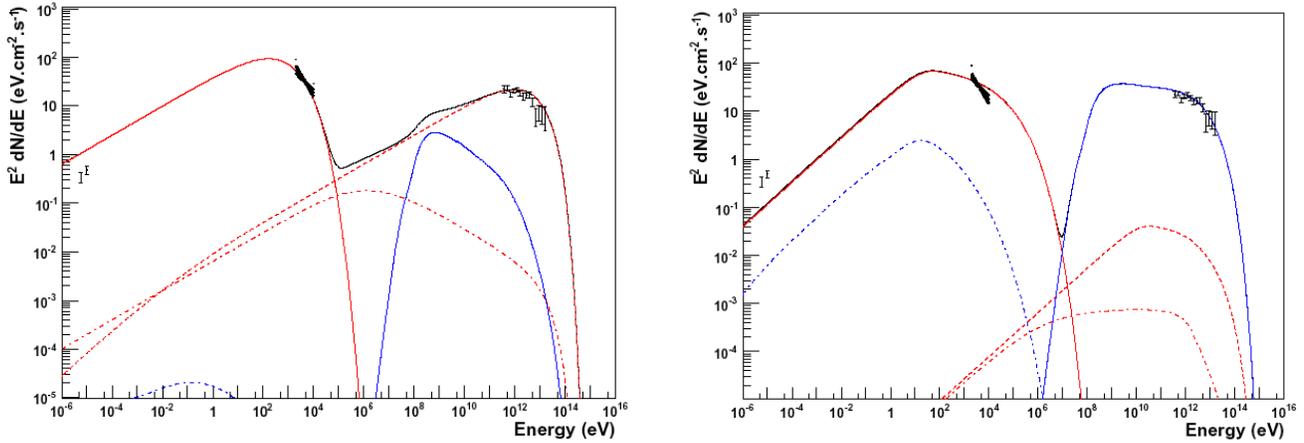


Figure 13: The broadband SED of SNR RXJ0852–4622 for an electronic/hadronic (left/right) scenario. Red/blue lines correspond to electrons/protons. The different components arise from synchrotron radiation from primary (solid red line) and secondary (dotted blue line) electrons, ICS (dotted red line), bremsstrahlung (dotted-dashed red line), and proton-proton interaction (solid blue line). Image credit: Aharonian (2007).

- modest sensitivity in the hard X-ray regime with good spectral resolution, with focussing, as in *Astro-H* or *Simbol-X*
- excellent sensitivity with good spectral and angular resolution, as in *IXO*
- modest sensitivity, focussing broad-band X-ray polarimetry
- excellent sensitivity with good angular resolution and spectral resolution in the hard X-ray band (as in *EXIST*)
- excellent spectral resolution with modest sensitivity and angular resolution in the soft X-ray band, as in the micro-calorimeter on *Astro-H*

## 6 Massive Stars

### 6.1 Introduction

Massive stars are usually taken to be those (single) stars that started with masses above  $\sim 8 M_{\odot}$  on the Main Sequence (MS) at solar metallicity (e.g. Conti, Crowther & Leitherer 2008). In contrast to their medium-mass cousins, which end their lives without completing all phases of nuclear burning as white-dwarf (WD) degenerates, massive stars generally only reach a degenerate state in their iron-rich cores after all possible nuclear burning has taken place. Those with initial masses up to  $\sim 25 M_{\odot}$  will first evolve to become red supergiants (RSGs), whose iron cores will then implode, producing H-rich type II supernovae (SN) and leaving a neutron star (NS) remnant. Those with initial masses between  $\sim 25$  and  $\sim 60 M_{\odot}$  will become unstable luminous blue variables (LBVs) near their Eddington limit, losing large quantities of H-rich surface matter and becoming classical He-burning Wolf-Rayet (WR) stars. These WR stars are then expected to core-implode and produce type Ib or Ic SN, leaving behind a black hole (BH) in most cases, with the event accompanied by a gamma-ray burst in  $\sim 0.1\%$  of cases, of which  $\sim 1\%$  are observable from Earth (see §2.6). Those MS stars with original mass between  $\sim 60$  and  $\sim 120 M_{\odot}$  already have an exotic MS phase, with WR-like emission lines, yet normal H abundance. After becoming very luminous LBVs (as in the famous  $\eta$  Carina), they may explode as pair-instability SN, leading to complete disruption. Many of the above details depend on the initial metallicity.

Despite their relatively small numbers, massive stars dominate the ecology of the Universe. This was especially true during the first generation of star-formation in the Universe, when the so-called “population III” stars were born, having masses mostly in the range  $\sim 100$ – $1000 M_{\odot}$ .

Massive stars were not believed to have convective envelopes (but see Cantiello et al., 2009), so they were not expected to show X-rays from release of energy via acoustic waves at their surfaces, as in low-mass stars. However, MS massive stars having initial masses  $\gtrsim 15 M_{\odot}$  have increasing luminosities which blow progressively stronger, faster winds. Because of these winds, massive stars do in fact manifest themselves as significant high-energy sources, in several ways. Internal wind-shocks, in the form of stochastic clumps, reveal soft X-ray spectra for most massive stars. Another form of wind shocks are the co-rotating interactive regions, due to rotating large-scale wind perturbations. These may produce similar properties as the stochastic clumps. Also, wind collisions yield high-energy emission. These can occur in several forms: one star’s wind colliding with the interstellar or circumstellar medium (ISM/CSM),

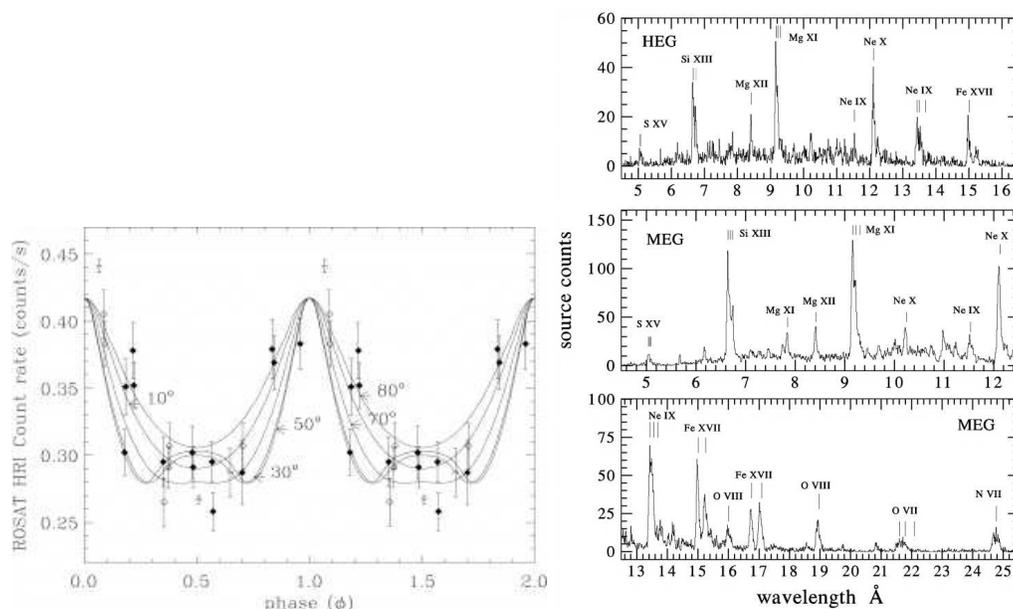


Figure 14: (Left) Magnetically confined wind shock model applied to  $\theta^1$  Ori C (O7V) (Babel & Montmerle, 1997). Plot shows X-ray flux as a function of rotational phase for different axis inclination angles. (Right) Probing hot plasmas using high-resolution X-ray spectroscopy on the O4Ifn supergiant  $\zeta$  Pup (Cassinelli et al., 2001). Note the asymmetric profiles, implying X-ray sources embedded in the strong, hot wind.

wind-wind collisions in binary systems, or mutual wind collisions in young, massive star clusters. Finally, accretion via wind or Roche-lobe overflow onto a normal, medium-low mass companion, or a compact WD, NS or BH companion yields high-energy emission (see §3).

## 6.2 What is the Nature of Shocks in Hot-Star Winds?

Understanding the strengths, structure and clumping of massive-stellar winds is crucial for understanding massive-star evolution, their contribution to the ISM, and the progenitors of SN (Moffat, 2008). X-rays are believed to be caused by shocks/clumps in the winds, and X-ray variability is a potentially powerful probe of the phenomenon. Of particular importance are reliable estimates of mass-loss rates, which depend sensitively on the degree of clumping. No previous attempts have succeeded here, although not for lack of trying (e.g. Berghoefter et al., 1997), because of the modest flux levels even for the X-ray brightest massive hot stars in the sky, and because of the expected low level of variability (up to a few percent). *Probing X-ray variability at the  $\sim 1\%$  level on timescales of minutes to hours will require excellent sensitivity and good angular resolution in the soft X-ray band.*

## 6.3 Is There a Magnetism/X-ray Connection?

We are only beginning to detect magnetic fields in massive hot stars, an area that is expanding with improving technology. Magnetic fields are likely to have an important impact on stellar evolution of massive stars both on the MS and beyond, including during the final collapse as a long-duration gamma-ray burst. The stellar magnetic field may also play a role in the formation of magnetar-strength fields in neutron stars. The best method of detection is probably via rotation-driven variability as high-energy wind particles are accelerated in the process. Expected variability levels are a few percent in several hours. Of particular note here is the magnetically-confined wind-shock model applied to the rotating young O7V star  $\theta^1$  Ori C, the brightest star in the central Orion trapezium (Babel & Montmerle, 1997, see Fig. 14, Left). This led to the discovery of a longitudinal magnetic field of  $B \sim 300$  G in this object (Wade et al., 2006). So far, only 3 O stars have detected magnetic fields, although intense searches for more are underway currently. The important point is the possibility of a magnetic-field/X-ray connection that requires quantification in a viable sample of targets. In addition, there is always the possibility of detecting polarization in the X-rays, produced here by acceleration of charged particles in a magnetic field. *Good sensitivity and angular resolution in the soft and hard bands would be useful for measuring the expected variability, in a monitoring campaign with a wide-field or all-sky hard X-ray survey. An X-ray polarimeter may also provide important advances.*

## 6.4 What is the Composition of Hot-Star Winds?

The composition of massive-stellar winds and its relation to the stellar surface composition is an important open issue. Are the wind abundances the same as the surface abundances? Do we see any evidence of a forbidden, intercombination, resonance) effect in hot star X-ray line emission? Hot-star winds provide ideal laboratories to

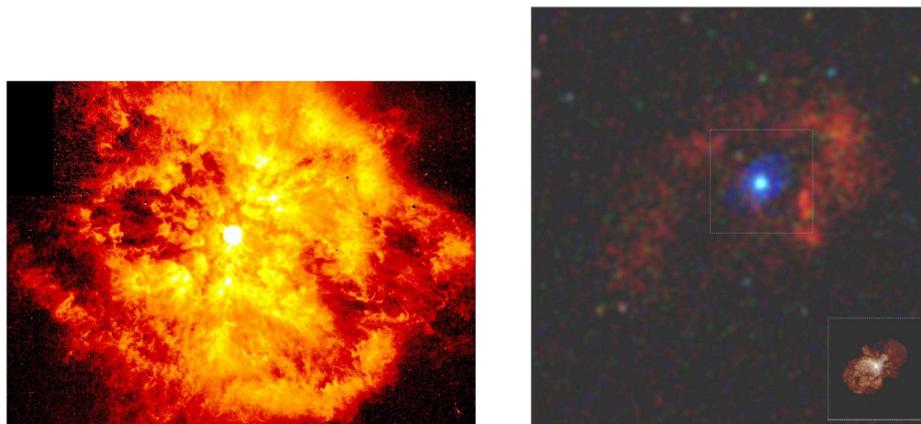


Figure 15: (Left) Example of a hot WR wind catching up and colliding with a previous, slow (LBV/RSG) wind: the relatively young nebula M1-67 around the population I runaway WN8 star WR124, here seen in a net  $H\alpha$  *HST* image (Grosdidier et al., 1998). (Right) *Chandra* image of  $\eta$  Carina showing an extended source of soft X-rays around a compact source of hard X-rays that are modulated by the highly elliptical binary motion. An optical *HST* image insert is shown at the same scale, with centre coinciding with the hard X-ray source (Corcoran et al., 2004).

probe such plasmas. High-resolution X-ray spectroscopy can now be used to constrain abundances and physical conditions in hot-star winds as a function of distance from the central star (e.g. Cassinelli et al., 2001, see Fig. 14, Right). *A modest sensitivity soft X-ray telescope is required, with excellent spectral resolution.*

## 6.5 What is the Physics of Colliding Winds (CWs)?

Three classes of CWs arise among massive stars. The first class occurs during the evolution of a massive star, when the first wind produced by the MS O star collides with and pushes back the surrounding ISM. This produces a hot cavity and shock interface zone that can be observed in soft X-rays. Later, when a slower-wind phase ensues as an LBV (or RSG), a denser nebula is formed well inside the first bubble, which is then swept up into the form of a ring-like nebula, once the fast-wind WR phase kicks in, again creating a zone of hot plasma and shock front (see Fig. 15, Left). All of these phases are seen, but require high spatial resolution to probe in X-rays. This has not been done adequately thus far.

The second class of CWs occurs in binaries with periods of up to hundreds of years. Here, colliding hot-star winds (or one wind crashing onto the surface of the companion star) can lead to spectacular high-energy effects, such as seen by *Chandra* in  $\eta$  Carina (see Fig. 15, Right). We are just beginning to use these shock-produced X-ray fluxes in CW binaries to constrain the clumping-independent mass-loss rates, although there are precious few data so far. Such regions can be used to probe chemical mixing in the CW shock in chemically inhomogeneous binary stars. CW binaries such as WR140 may also be observable in  $\gamma$ -rays (e.g. Reimer & Reimer, 2007).

The third class of CWs involves massive stars, most of which tend to occur in clusters, where their mutual winds collide. This creates hot expanding plasma from the cluster as a whole. Resolved X-ray imaging of local clusters as a function of age and density can then serve as templates for galactic-size blow-outs. *CW studies of the first and third classes require X-ray telescopes with excellent angular resolution in the soft X-ray band, while studies of the second class require sensitive monitoring in the soft X-ray band..*

## 6.6 Summary and Recommendations

Understanding massive stars and their key role in the global ecology of the Universe requires high-energy observations of individual sources ultimately to constrain their properties as a population. Recommended future missions are:

- excellent sensitivity in the soft X-ray band with good angular resolution and modest time resolution, as in *IXO*
- modest sensitivity but excellent spectral resolution in the soft band, as in the microcalorimeter on *Astro-H*
- a broad-band good sensitivity X-ray polarimeter

# 7 Fundamental Physics via High-Energy Astrophysics

## 7.1 Introduction

The general domain of observational high-energy astrophysics, which we take to include observations of cosmic rays, neutrinos or photons at keV energies or higher, is a rich source of tests of fundamental physics. Experiments in this

field can test many established branches of physics including General and Special Relativity, the Standard Model of particle physics, nucleosynthesis, and neutrino physics, and they can also probe beyond known physics, seeking answers to the mysteries of dark matter and dark energy.

The topics outlined below could contribute substantial added value to HEA missions proposed in other areas, and might even inspire new ideas for projects with multiple goals. A successful space mission dealing with fundamental physics tests would receive support from the very strong theoretical community in Canada, and would also draw experimentalists and instrument designers from other branches of physics into this field.

**Studies of the Strong Gravity Regime around Black Holes:** Einstein’s General Relativity (GR) is our current best theory of gravity. It is experimentally confirmed over a range of scales in the weak-field limit (Williams et al., 2004; Bertotti et al., 2003). In the strong-field limit, binary radio pulsar systems, most recently the double pulsar, have permitted very sensitive tests of GR as well (e.g. Kramer et al., 2006; Breton et al., 2008; Kramer & Stairs, 2008).

To truly test the theory, however, we need to study gravity in the very strong-field limit. Only astrophysical systems such as black holes or neutron stars provide the necessary environment to perform these tests. As discussed elsewhere in this report (§2.2), observations of high-energy emission from regions close to the event horizon of black holes can in principle test models for the local metric and relativistic effects such as frame-dragging (Fabian et al. 1989; see Reynolds and Fabian 2007 for a recent summary). The specific observations required for this science include detailed spectroscopy of iron emission lines around 6.4 keV produced by the highly redshifted material close to the event horizon, and X-ray timing observations at similar energies to study quasi-periodic oscillations and other variations related to the accretion geometry. Broader high-energy spectral energy distributions (SEDs) around this wavelength are also required to model the line shapes and understand the properties of the accreting material. *Required instrumental capabilities for this task are excellent sensitivity in the soft and hard X-ray bands, with excellent spectral resolution for Fe line studies and excellent timing resolution for QPO studies. X-ray polarimetry may also provide new insights.*

**Gamma-Ray Burst Time Delay Experiments:** On small scales, the relativistic theory of gravity must eventually break down as it becomes quantized. Quantum gravity is currently an important field of theoretical research (with a strong Canadian presence), but has few experimental or observational tests. One of the only realistic tests proposed involves searching for dispersion (i.e. energy-dependent propagation times) in sharp pulses of  $\gamma$ -rays from a large sample of distant  $\gamma$ -ray bursts with known redshifts. This dispersion would indicate a non-trivial refractive index for free space at large photon energies, due to its quantum nature on microscopic scales (Ellis et al. 2008).

This test was first performed with the AGN flare observed by Biller et al. (1999), using the Whipple 10-m air Cerenkov telescope, the forerunner of present-day arrays such as VERITAS, MAGIC and HESS. There have been more recent attempts to detect dispersion using these instruments as well as the *Fermi* telescope (see e.g. Ellis et al. 2009 for a summary of the results, and Greiner et al. 2009 for the most recent test case). The two types of facilities have complementary advantages: ground-based detectors have a huge lever arm in energy (50 GeV to tens of TeV), although they are limited in source distance at high energy by pair-production off the extragalactic background light (EBL). Their narrow fields-of-view limit the number of flares they expect to detect, however. *Fermi* has a wider field of view and can see sources at greater distances over its energy range, but has a small collection area and limited energy range (up to 10 GeV or so). *An ideal next-generation facility would allow sensitive gamma-ray burst or blazar monitoring over a very wide energy range, e.g. from hundreds of keV up to hundreds of GeV or higher, with < 50 ms time resolution, and a wider field of view, if ground-based, or larger collecting area, if space-based.*

**Exotic MeV-scale Decays or Emission:** Currently, a substantial flux of 511 keV electron-positron annihilation emission is detected coming from the region around the Galactic Centre (e.g. Knodlseder et al. 2005; Weidenspointner et al. 2008). From spectroscopy of the line there are constraints on the environment in which the positrons are produced (e.g. Sizun, Casse, & Schanne 2006), but their ultimate source is still unknown, and exotic particles such as light dark matter have been proposed to explain the emission (Boehm et al. 2004). There are also several other nuclear lines around this energy which trace various phases of nucleosynthesis and the evolution of stellar remnants, and possibly also hypernovae and gamma-ray bursts. Thus sensitive all-sky surveys at these energies have great discovery potential in many fields of high-energy astrophysics. *The ideal facility for this task would be a sensitive, wide field, spatially and spectrally resolved hard X-ray/ $\gamma$ -ray telescope operating in the 50 keV–10 MeV range, with particular sensitivity around 511 keV.*

**High Magnetic Field Physics:** The importance of neutron stars as sources of extremely high magnetic fields has been discussed elsewhere in this report (§4.3). The magnetic fields associated with these objects, or with Active Galactic Nuclei (AGN), can be used to search for conversions between photons and axions (e.g. Chelouche et al., 2009). The axion is a hypothetical particle invoked to explain some of the symmetries of the Standard Model, which remains as yet undetected. Photon-to-axion conversion might appear as a deficit in emission over a wide range of X-ray and  $\gamma$ -ray energies, e.g. 10 keV–10 TeV, in pulsars or AGN (e.g. Serpico 2009). *The ideal facility to search for axionic signatures would have good spectral and/or polarization sensitivity, and excellent calibration & stability, over the widest possible spectral range.*

**“Indirect” Detection of Dark Matter:** Despite its dominant role in structure formation, particle dark matter remains undetected due to its lack of electromagnetic interactions. “Indirect” detection methods attempt to detect dark matter through its annihilation to  $\gamma$ -rays in regions of high density. In particular, the supersymmetric dark matter candidates favoured by current theory should decay producing pions in the GeV–TeV energy range (as should

several other classes of candidate). Spectroscopy of emission from the Galactic Centre, from nearby dwarf galaxies or even of the extragalactic background might provide a smoking gun for the existence of electroweak-scale particle dark matter, a discovery of fundamental importance to astrophysics and high-energy physics (comparable in scientific significance, for instance, to the past 10 years of CMB observations).

The classic signature of weakly-interacting massive particle (WIMP) dark matter would be a faint but distinct spectral feature (an edge, and possibly a faint line) at the mass of the WIMP,  $M_{WIMP} \sim 30 \text{ GeV} - 3 \text{ TeV}$ , from WIMP-WIMP annihilation into  $\gamma$ -rays, and a ‘bump’ at lower energies from annihilation via other particles into pions. Neutral pions (mass 135 MeV) are responsible for most of the  $\gamma$ -rays in the final spectrum. The resulting pion bump is a broad feature at  $M_{WIMP}/25 \sim 1-100 \text{ GeV}$ . (WIMP annihilation should also produce charged pions, which in turn decay into leptons such as electrons and positrons; these may have been detected in cosmic rays, as discussed below.) Currently *Fermi* is searching for  $\gamma$ -ray signals from dark matter annihilation (Ylinen et al. 2008). *An ideal follow-up experiment would be capable of high-energy  $\gamma$ -ray spectroscopy in the 30 GeV–3 TeV range, with some spatial resolution and a reasonable combination of (sensitivity  $\times$  field of view).*

**Space Anti-matter Experiments:** This is a category of experiments that deals with fundamental physics but targets cosmic rays, and thus involves quite different technology or observations. These experiments are essentially flying magnetic spectrometers. They detect cosmic rays in general and anti-matter specifically, testing cosmic-ray physics and the matter-antimatter asymmetry, and searching for exotic phenomena such as dark matter decay. Examples include PAMELA and the upcoming AMS experiment (soon to be installed on the ISS), as well as related balloon-borne experiments such as ATIC. PAMELA and ATIC have both been in the news recently, detecting possible signatures of new phenomena in the 100 GeV energy range characteristic of electroweak-scale particles (Adriani, 2008; Chang, 2008). The AMS experiment, when installed on the ISS, will constitute a more sensitive near-term follow-up to PAMELA and ATIC. Depending on results from AMS, development of an even more capable detector may become attractive.

## 7.2 Summary and Recommendations

The tests of fundamental physics presented in this section cover a very wide range in wavelength, spectral, spatial and temporal resolution, such that a single facility would not be able to address them all. Most are probably best considered as additional science goals for large, multi-purpose facilities. Indirect detection of dark matter is probably the most important science goal in HEA astrophysics, but plans for new facilities in this area will depend strongly on the results forthcoming from *Fermi* over the next 2–3 years. Black hole monitoring is an important science goal that should be considered in any future instruments or facilities targeting compact objects or AGN. Tests of dispersion, photon-to-axion conversion and MeV-scale physics all require a broad energy range and good sensitivity in facilities operating in the hard X-ray to  $\gamma$ -ray regime. All of these capabilities should be considered as additional requirements for the facilities proposed elsewhere in this report.

## 8 Overall Recommendations and Opportunities

### 8.1 Recommendations

The following set of recommendations represents the outcome of consideration of the above-described science interests of the Canadian HEA community. The recommendations were agreed upon unanimously by the DWG as being primarily enabling of excellent science, but simultaneously well matched to Canadian scientific expertise, with topics well aligned with those of the international HEA community. See Appendix A for more mission information.

- **Short-term (present–2014) Ordered Priorities:**

- Involvement in a focussing hard X-ray ( $E > 10$  keV) mission with excellent angular resolution ( $< 1'$ ) and spectral resolution, and ideally good ( $\sim 100 \mu\text{s}$ ) timing resolution. One particularly attractive opportunity is the upcoming JAXA/NASA *Astro-H* (formerly *NEXT*; PI T. Takahashi, JAXA) mission, with planned launch 2013. This has the advantage of also carrying a soft X-ray microcalorimeter, having modest sensitivity and excellent spatial resolution. An alternative for a focussing hard X-ray instrument is the ESA *Symbol-X* mission, with planned launch 2014.
- Involvement in a broad-band, modest sensitivity X-ray polarimeter operating anywhere in the 0.1–100 keV band. Focussing ability is a plus that would allow extragalactic work. Good ( $100 \mu\text{s} - 1$  ms) time resolution is also important. We note the Phase A development of the *GEMS* X-ray polarimetric mission as part of the 2008 NASA Small Explorer competition (PI J. Swank, NASA/GSFC).

- **Long-term (2014–2020) Ordered Priorities:**

- Involvement in a soft-band (0.1–10 keV) mission having excellent sensitivity (effective area  $> 10 \times$  *XMM-Newton*) and excellent ( $R > 1000$ ) spectral resolution with good ( $< 5''$ ) angular resolution and good ( $100 \mu\text{s} - 1$  ms) time resolution, such as *IXO*, a joint ESA/NASA/JAXA mission (formerly ESA's *XEUS* and NASA's *Constellation-X*). Project scientists on this mission are A. Parmar (ESA), N. White (NASA), and H. Kunieda (JAXA).
- Involvement in a mission with excellent sensitivity (effective area  $> 10 \times$  *XMM*) and excellent timing resolution ( $< 10 \mu\text{s}$ ), with modest angular resolution and spectral resolution, in the soft/hard (2–100 keV) band. Possible implementations are the envisioned wide field-of-view all-sky survey *EXIST* mission (PI J. Grindlay, Harvard), or the proposed *AXTAR* mission (PI D. Chakrabarty, MIT).

Note that all of our recommendations are for involvement in international missions led by foreign countries. This in itself demonstrates the alignment of Canadian HEA science aspirations with those of international HEA communities. For example, regarding alignment for our top short-term priority, the JAXA-led mission *Astro-H* is already in Phase B, and NASA has already agreed to participate in *Astro-H* via its Missions of Opportunity program. Also, *Constellation-X* (now part of *IXO*), is widely accepted by US HEA astronomers as their top priority, having been ranked just third (after JWST and a ground-based initiative) in the last U.S. Decadal Survey of Astronomy and Astrophysics. Indeed *IXO* also has considerable steam in Europe.

We do not currently recommend any Canadian-led HEA mission. This is primarily because currently HEA research in Canada is practically exclusively scientific in nature, with little or no active research in any area of HEA technology development. Although there are pockets of related expertise (DWG member J. Hutchings' UV detector development; DWG members D. Hanna's and K. Ragan's ground-based  $\gamma$ -ray telescope design and construction; various research groups involved in particle detection for particle physics experiments), there is no instrumentation development program in Canada that has as its ultimate goal doing HEA research (but see §8.2.1 below). This may be because, during the last decade's hiring activities, HEA instrumentalists did not see Canada as an attractive place to work and so did not apply; additionally, Canadian institutions doing the hiring may not have seen a roadmap for supporting such a hire. A future CSA commitment in this direction could have a major impact on future Canadian faculty hires, it would clearly demonstrate that a solid HEA foundation exists in Canada, and enable the attraction of talented young HEA instrumentalists.

### 8.2 Opportunities

#### 8.2.1 Technology Opportunities

Although, as discussed above, there is not currently HEA technology R&D per se in Canada, there are in fact industrial R&D programs in Canada that potentially have great relevance for possible international HEA mission involvement. These include:

- *Metrology*: Multiple Canadian companies (e.g. NEPTEC in Ottawa, ON) have significant metrology capabilities that can be very useful for HEA missions, particularly those in which very long focal lengths require extendable masts (as in *NuSTAR*, *Astro-H*, and possibly *IXO*) or detector/mirror formation flying (as in *Symbol-X*). For example, extendable masts are subject to motions including torsions and vibrations that require an independent measure of relative detector/mirror locations. This happens to be a Canadian strength; for example NEPTEC has provided laser metrology systems to NASA for the Space Shuttle as well as for docking with the ISS.

- *Formation Flying*: Some incarnations of *IXO* have enabled the very large desired collecting area by using formation flying of multiple individual mirror/detector combinations. This is seen as one viable way to allow great sensitivity while keeping spacecraft weight, hence launch cost, low. There is formation flying expertise in Canada, notably in the Engineering faculty of York University as well as at UTIAS at the University of Toronto, as well as in Canadian industry, for example ComDev in Ottawa, ON. We note that formation flying is planned for other (some non-HEA) missions like NASA's *LISA* and possibly for NASA/JPL's *TPF*.

### 8.2.2 Overall Opportunities

Our top recommendations are made particularly attractive, above and beyond their scientific relevance, by the current existence of opportunities for involvement. Our top short-term recommendation, involvement with the JAXA-led *Astro-H* mission (launch expected 2013), is extremely timely, as they require a metrology system for determining relative positioning for their extendable mast, and have expressed great interest in Canadian technological capabilities. Thus we have a rare opportunity to provide an important component of a forefront HEA mission, possibly establishing a "niche" capability in a field in which focal lengths are only likely to increase.

Our top recommendation for long-term mission involvement, the planned NASA/ESA/JAXA mission *IXO*, is also scientifically very attractive, particularly because of the strengths of the Canadian HEA community. Moreover, current plans are for it to also have a long focal length; success with *Astro-H* in the near term could be a stepping stone toward providing *IXO* with a similar Canadian-built metrology system. With *IXO* currently in a pre-Phase-A state, Canada has the option of getting in "on the ground floor."

Finally, we comment on what we see is a crucial need for the ability to respond rapidly to opportunities, when necessary, particularly in HEA. As a community of scientists without a focussed HEA technology development program, we do not currently have the expertise to design, build and lead a forefront HEA mission. We must hope for involvement in external initiatives both to further our science goals, as well as to begin to develop our own HEA technological foundations. We thus absolutely require the ability to react quickly to international opportunities (like that offered by *Astro-H*), which will almost always have timelines and scheduling that are beyond our control. Such involvement, once established, has the potential to pave the way toward future projects with more and more Canadian involvement.

That said, we also recognize that rapid response to external opportunities should ultimately not be the primary way of accomplishing scientific goals. It is a way to get started, but ultimately, as put forward in the Introduction, a mature scientific community has the ability to control its future and the future of its science, rather than merely react to the visions and accomplishments of colleagues in other countries. In this, the first HEA science document in Canada, our recommendations reflect the youth of our community; their acceptance by the CSA will be a signal that a foundation is being laid for the development of a world-class HEA program, one with a balanced portfolio of science and technology expertise, and hence the ability to shape our own destiny with a unique Canadian HEA vision.

### 8.3 Final Remarks

The DWG opportunity provided by CSA has been extremely valuable for the HEA community. Hired independently and at different times in the past decade, the community was brought together for the first time in support of the DWG mandate. For this we are grateful to the CSA.

For the future, the HEA community (as likely to other DWGs supported by CSA) look forward to the serious consideration and ultimate implementation of DWG recommendations. While the next Long-Range Plan for Canadian astronomy will play a major role in prioritizing initiatives for the next decade, the CSA, with DWG program now complete, is in an excellent position to consider the possibilities in depth and act on any important time-critical opportunities that arise. The HEA DWG stands ready to assist the CSA in anyway possible in clarifying any aspect of this document, or related topics, in support of such an endeavor.

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## Appendix A

### Recommended Short-Term (present–2014) Mission Information

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#### Astro-H (formerly *NEXT*)

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Lead Agency/Country:	JAXA/Japan
Principle Investigator:	T. Takahashi
Level of Approval:	Phase B
Timeline:	Launch expected 2013
Other Agency/Country Involvement:	NASA/USA (via MoO)
Reference:	Takahashi et al. 2008, Proc. SPIE, 7011, 70110O-1
URL:	<a href="http://astro-h.isas.jaxa.jp/index.html.en">astro-h.isas.jaxa.jp/index.html.en</a>
Configuration:	multiple instruments with
Instruments:	hard X-ray mirror at 12-m focal length on extendible mast wide-band focussing hard X-ray spectroscopy (3–80 keV) soft-X-ray micro-calorimeter (0.3–10 keV) soft X-ray CCD camera non-focussing soft $\gamma$ -ray detector
Comments:	JAXA interested in CDN metrology JAXA sent CSA letter of interest, January 22, 2009 HEA DWG sent JCSA letter of information, February 9, 2009

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#### GEMS

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Lead Agency/Country:	NASA/USA
Principal Investigator:	J. Swank (NASA/GSFC)
Level of Approval:	Phase A/SMEX
Timeline:	Launch 2012 or 2015
URL:	<a href="http://www.nasa.gov/centers/goddard/news/topstory/2008/gems.html">http://www.nasa.gov/centers/goddard/news/topstory/2008/gems.html</a>
Instruments:	focussing soft X-ray polarimeter

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## Recommended Long-Term (2014–2020) Mission Information

### IXO (formerly *XEUS* and *Constellation-X*)

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Lead Agency/Country:	ESA/Europe, NASA/USA, JAXA/Japan
Project Scientists:	A. Parmar (ESA), N. White (NASA/GSFC), H. Kunieda (JAXA)
Level of Approval:	pre-Phase A
Timeline:	Launch beyond 2020
Reference:	<a href="http://ixo.gsfc.nasa.gov/resources/presentations/0209_Decadal_WhitePapers.html">ixo.gsfc.nasa.gov/resources/presentations/0209_Decadal_WhitePapers.html</a>
URL:	<a href="http://ixo.gsfc.nasa.gov/">ixo.gsfc.nasa.gov/</a>
Configuration:	large single X-ray mirror and extendible optical bench with 20 m focal length
Instruments:	TBD

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### EXIST

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Lead Agency/Country:	NASA/USA
Principal Investigator:	J. Grindlay (Harvard/CfA)
Level of Approval:	proposed
Timeline:	Launch beyond 2020
Reference	Grindlay et al. 2005, <i>New Astronomy Reviews</i> , 49 436
URL:	<a href="http://exist.gsfc.nasa.gov/">http://exist.gsfc.nasa.gov/</a>
Instruments:	wide-field coded aperture telescope for 5–600 keV 1.1 m optical/IR telescope in 0.3–2.4 $\mu\text{m}$ range anti-coincidence system also measuring GRB spectra

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### AXTAR

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Lead Agency/Country:	NASA/USA
Principal Investigator:	D. Chakrabarty (MIT)
Level of Approval:	proposed
Timeline:	Launch beyond 2020
URL:	<a href="http://xte.mit.edu/AXTAR/Main.html">http://xte.mit.edu/AXTAR/Main.html</a>
Instruments:	large-area timing array for 2–50 keV with 4 m <sup>2</sup> area wide-field X-ray sky monitor

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## Appendix B

### 2007–9 Canadian Space Agency Discipline Working Group in High Energy Astrophysics Membership List

Arif Babul (University of Victoria)  
Andrew Cumming (McGill University)  
Sarah Gallagher (University of Western Ontario)  
Luigi Gallo (St. Mary's University)  
Patrick Hall (York University)  
David Hanna (McGill University)  
Craig Heinke (University of Alberta)  
Jeremy Heyl (University of British Columbia)  
Gil Holder (McGill University)  
John Hutchings (National Research Council/Herzberg Institute of Astrophysics)  
Victoria Kaspi (Chair, McGill University)  
Denis Leahy (University of Calgary)  
Brian McNamara (University of Waterloo)  
Tony Moffat (Université de Montréal)  
Dae-Sik Moon (University of Toronto)  
Sharon Morsink (University of Alberta)  
Lorne Nelson (Bishop's University)  
Ken Ragan (McGill University)  
Robert Rutledge (McGill University)  
Samar Safi-Harb (University of Manitoba)  
Ingrid Stairs (University of British Columbia)  
James Taylor (University of Waterloo)  
Chris Thompson (CITA)  
Marten van Kerkwijk (University of Toronto)

## Appendix C

### 2007–9 Canadian Space Agency Discipline Working Group in High Energy Astrophysics Meetings and Teleconference List

#### Face-to-Face Meetings:

June 7, 2007; Kingston, ON; CASCA Annual General Meeting

March 27-28, 2008; Montreal, QC; McGill University

May 21, 2008; Victoria, BC; CASCA Annual General Meeting

July 16-17, 2008; Montreal, QC; COSPAR Meeting

December 11, 2008; Vancouver, BC; Texas Symposium on Relativistic Astrophysics

#### Teleconferences:

January 24, 2008

March 13, 2008

## Appendix D

### Acronyms

AGN	Active Galactic Nucleus
AMS	Alpha Magnetic Spectrometer; <a href="http://ams.cern.ch/">http://ams.cern.ch/</a>
ATIC	Advanced Thin Ionization Calorimeter; <a href="http://atic.phys.lsu.edu/aticweb/">http://atic.phys.lsu.edu/aticweb/</a>
AXP	Anomalous X-ray Pulsar
AXTAR	<i>Advanced X-ray Timing Array</i> ; <a href="http://xte.mit.edu/AXTAR/Main.html">http://xte.mit.edu/AXTAR/Main.html</a>
BH	Black hole
CASCA	Canadian Astronomical Society/Société Canadienne D'Astronomie
CCO	Central Compact Object
CMB	Cosmic microwave background
CR	Cosmic ray
CSM	Circumstellar medium
CW	Colliding winds
CXO	<i>Chandra X-ray Observatory</i> ; <a href="http://asc.harvard.edu/">http://asc.harvard.edu/</a>
EBL	Extragalactic background light
EM	Electromagnetic
EOS	Equation-of-State
EXIST	Energetic X-ray Imaging Survey Telescope; <a href="http://exist.gsfc.nasa.gov/">http://exist.gsfc.nasa.gov/</a>
GEMS	Gravity and Extreme Magnetism; <a href="http://heasarc.gsfc.nasa.gov/docs/gems/">http://heasarc.gsfc.nasa.gov/docs/gems/</a>
GRB	$\gamma$ -ray Burst
HEA	High-Energy Astrophysics
HESS	High Energy Stereoscopic System; <a href="http://www.mpi-hd.mpg.de/hfm/HESS/">http://www.mpi-hd.mpg.de/hfm/HESS/</a>
HMXB	High-mass X-ray Binary
HXMT	Hard X-ray Modulation Telescope; <a href="http://www.hxmt.cn/english/">http://www.hxmt.cn/english/</a>
ICS	Inverse Compton scattering
INS	Isolated neutron star
ISM	Interstellar medium
ISS	International Space Station
IXO	<i>International X-ray Observatory</i> ; <a href="http://ixo.gsfc.nasa.gov/">http://ixo.gsfc.nasa.gov/</a>
LBV	Luminous blue variable
LISA	<i>Laser Interferometric Space Antenna</i> ; <a href="http://lisa.nasa.gov/">http://lisa.nasa.gov/</a>
LMXB	Low-mass X-ray Binary
MAGIC	Major Atmospheric Gamma Imaging Cherenkov telescope; <a href="http://wwwmagic.mppmu.mpg.de/">http://wwwmagic.mppmu.mpg.de/</a>
MS	Main sequence
MSP	Millisecond pulsar
NICE	<i>Neutron-Star ISS Composition Explorer</i> ; <a href="http://adsabs.harvard.edu/abs/2008cosp...37..134A">http://adsabs.harvard.edu/abs/2008cosp...37..134A</a>
NS	Neutron star
NuSTAR	<i>Nuclear Spectroscopic Telescope Array</i>
PAMELA	Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics; <a href="http://pamela.roma2.infn.it/index.php">http://pamela.roma2.infn.it/index.php</a>
PSR	Pulsar
PWN	Pulsar wind nebula
QED	Quantum Electrodynamics
qLMXB	Quiescent LMXB
QPO	Quasi-periodic oscillation
ROSAT	<i>Röntgen Satellite</i> ; <a href="http://heasarc.gsfc.nasa.gov/docs/rosat/roskof.html">http://heasarc.gsfc.nasa.gov/docs/rosat/roskof.html</a>
RSG	Red supergiant
RXTE	<i>Rossi X-ray Timing Explorer</i> ; <a href="http://heasarc.gsfc.nasa.gov/docs/xte/XTE.html">http://heasarc.gsfc.nasa.gov/docs/xte/XTE.html</a>
SED	Spectral energy distribution
SGR	Soft Gamma Repeater
Simbol-X	<a href="http://www.asdc.asi.it/simbol-x/">http://www.asdc.asi.it/simbol-x/</a>
SN	Supernova
SNR	Supernova remnant
TPF	<i>Terrestrial Planet Finder</i> ; <a href="http://tpf.jpl.nasa.gov">http://tpf.jpl.nasa.gov</a>
VERITAS	Very Energetic Radiation Imaging Telescope Array System; <a href="http://veritas.sao.arizona.edu/">http://veritas.sao.arizona.edu/</a>
WD	White dwarf
WIMP	Weakly interacting massive particle
WMAP	<i>Wilkinson Microwave Anisotropy Probe</i> ; <a href="http://map.gsfc.nasa.gov/">http://map.gsfc.nasa.gov/</a>
WR	Wolf-Rayet
XMM-Newton	<i>X-ray Multi-Mirror Newton</i> telescope; <a href="http://xmm.esac.esa.int/">http://xmm.esac.esa.int/</a>
XRB	X-ray Binary