The Neutron star Interior Composition ExploreR (NICER): an Explorer mission of opportunity for soft x-ray timing spectroscopy

Keith C. Gendreau*[a], Zaven Arzoumanian[a,b], Takashi Okajima[a], on behalf of the NICER team
[a]NASA GSFC, Greenbelt, MD, USA 20770; [b]CRESST-USRA, Columbia, MD, USA 21044

ABSTRACT

The Neutron star Interior Composition ExploreR (NICER) is a proposed NASA Explorer Mission of Opportunity dedicated to the study of the extraordinary gravitational, electromagnetic, and nuclear-physics environments embodied by neutron stars. NICER will explore the exotic states of matter within neutron stars, where density and pressure are higher than in atomic nuclei, confronting theory with unique observational constraints. NICER will enable rotation-resolved spectroscopy of the thermal and non-thermal emissions of neutron stars in the soft (0.2–12 keV) X-ray band with unprecedented sensitivity, probing interior structure, the origins of dynamic phenomena, and the mechanisms that underlie the most powerful cosmic particle accelerators known. NICER will achieve these goals by deploying, following launch in December 2016, an X-ray timing and spectroscopy instrument as an attached payload aboard the International Space Station (ISS). A robust design compatible with the ISS visibility, vibration, and contamination environments allows NICER to exploit established infrastructure with low risk. Grazing-incidence optics coupled with silicon drift detectors, actively pointed for a full hemisphere of sky coverage, will provide photon-counting spectroscopy and timing registered to GPS time and position, with high throughput and relatively low background. In addition to advancing a vital multi-wavelength approach to neutron star studies through coordination with radio and γ-ray observations, NICER will provide a rapid-response capability for targeting of transients, continuity in X-ray timing astrophysics investigations post-RXTE through a proposed Guest Observer program, and new discovery space in soft X-ray timing science.

Keywords: astrophysics, International Space Station (ISS), neutron stars, timing, X-ray

1. INTRODUCTION

Neutron stars squeeze more than 1.4 Solar masses into a city-size volume, giving rise to the highest stable densities and pressures known anywhere (Figure 1). The nature of matter under these conditions, in which all four fundamental forces of Nature are simultaneously important, is a decades-old unsolved problem, one most directly addressed with measurements of the masses and, especially, radii of neutron stars to high precision (i.e., to better than 10% uncertainty). Existing instrumentation does not provide the critical measurement capability — combined time and spectral resolutions in X-rays — needed to probe the physics of neutron star interiors. With order-of-magnitude advances in time-coherent

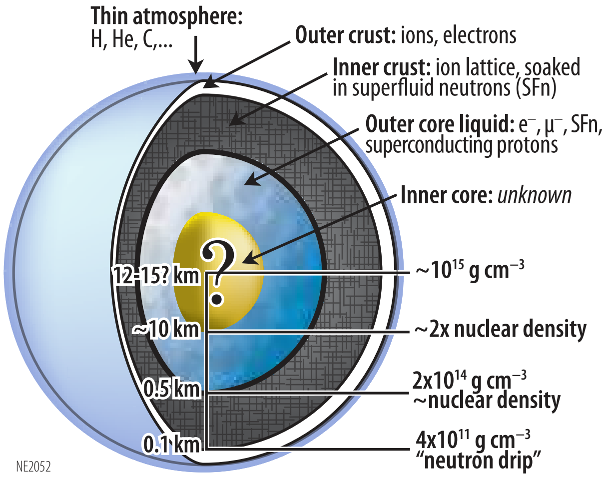

Figure 1. NICER will infer the masses and radii of neutron stars to reveal the composition of matter in their interiors, at the highest stable densities allowed in nature.

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sensitivity and timing resolution, the proposed Neutron star Interior Composition ExploreR (NICER) — led by NASA's Goddard Space Flight Center in collaboration with the Massachusetts Institute of Technology (MIT), commercial partners, and a science team affiliated with a variety of universities — will carry out rotation-resolved spectroscopy of rapidly rotating neutron stars, enabling lightcurve analyses with unique power to constrain models of neutron star structure, dynamics, and energetics.

NICER will fly on the International Space Station (ISS; Figure 2). NICER's design conforms with all human-spaceflight safety requirements, while the generous mass, power, and telemetry resources provided by the Station's ExPRESS Logistics Carriers (ELCs) simplify the payload design, significantly reducing mission cost and risk. NICER thus provides science return comparable to a free-flyer mission at a fraction of the cost.

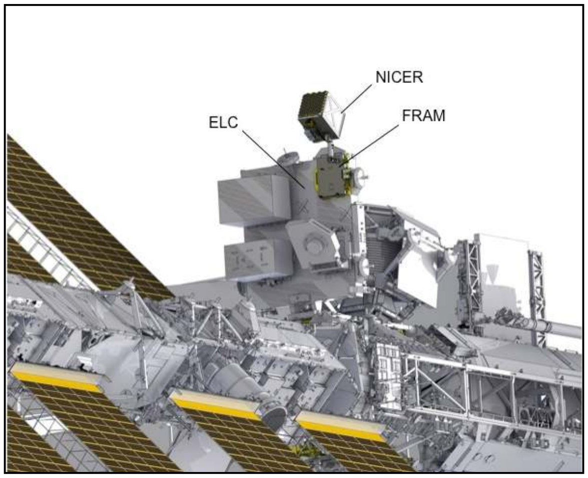

Figure 2. The NICER payload, integrated with a standard Flight Releasable Attachment Mechanism (FRAM), is attached to one of the International Space Station's zenith-side ExPRESS Logistics Carriers (ELC). The ELC provides power and a telemetry interface; installation is accomplished robotically. Shown in its deployed state, NICER offers a full hemisphere of sky coverage with high viewing efficiency even when obscurations by ISS components (such as the solar arrays) and interruptions due to ISS operations (such as spacecraft docking) are taken into account.

2. SCIENCE

2.1 Neutron star investigations

Constraining the presence or absence of exotic phases within neutron star cores (the question mark in Figure 1) is key to understanding the basic physics of dense matter as well as the astrophysics of late stellar and binary evolution, which govern the relative abundances of neutron stars and black holes. Whatever the nature of matter beyond nuclear density, it exists in abundance: millions of neutron stars inhabit the Galaxy. Usually observed as pulsars, the number of known neutron stars has expanded dramatically in recent years, especially as the *Fermi* γ-ray space telescope has proven to be a remarkable engine of pulsar discovery.[1,2]

A compact star's interior structure is captured, in a global sense, by the equation of state (EOS), a distinct hypothesis of the nature of dense matter. The EOS relates density to pressure within a star; equivalently, for a given theory of gravity, it relates the star's mass M to its radius R. Most EOSs predict that R will shrink as M grows and the self-gravitational force increases, but different assumptions about interior composition produce differences in the detailed mass-radius relation. Thus, measurements of M and R probe dense matter.

Nuclear theory predicts distinct mass-radius relationships — the S-shaped curves in Figure 3 — for many proposed models of particle composition and interaction in cold, dense matter.[3] NICER will confront these predictions with measurements, isolating those models that are consistent with observed neutron stars and ruling out large numbers of alternatives. Graphically, NICER's mass and radius measurements will define "allowed" regions in the M-R plane, as shown for PSR J0437–4715 in Figure 3. EOS curves that do not pass through every allowed region must be ruled out, while the remaining models are viable.[4]

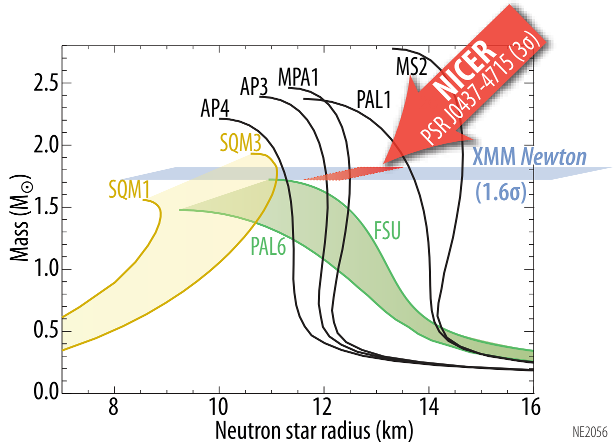

Figure 3. Mass and radius measurements probe the nature of dense matter by testing proposed equations of state (EOSs; representative labeled curves). Current weak radius bounds allow virtually all EOSs. NICER will improve radius measurements by an order of magnitude, isolating viable models of dense matter.

In pursuit of its key science objective, NICER exploits a well-founded and accessible approach to mass and radius constraints: analysis of X-ray flux modulations due to rotating hot spots on the surface of a neutron star (Figure 4). NICER enables such lightcurve analysis at a level that achieves the standard set by nuclear theory for distinguishing between proposed EOS models: ±5% uncertainty on radius measurements.[3,5] To realize such precision, large numbers of photons, typically $10^{5–6}$, must be collected.

Rotating hot spots are seen from both rotation- and accretion-powered pulsars. Lightcurve analysis to constrain neutron star properties has been demonstrated in both cases — for steady thermal X-ray pulsations from nearby *millisecond pulsars*[6] (MSPs), and for transient accretion-powered pulsations and burst oscillations from low-mass X-ray binaries[7] — but with broad statistical and, in the case of the accreting systems, systematic uncertainties. NICER delivers data suited to both investigations; its prime focus, however, is on the non-accreting MSPs, which are unaffected by the complexities of accretion flows. Rotation-powered MSPs are ideal for this approach: they appear frequently in binary systems, offering independent mass measurements, their radiative properties are well described by hydrogen atmosphere models, and they are always "on" with lightcurves stable in time, producing steady and predictable gains in signal-to-noise ratio with increasing exposure.

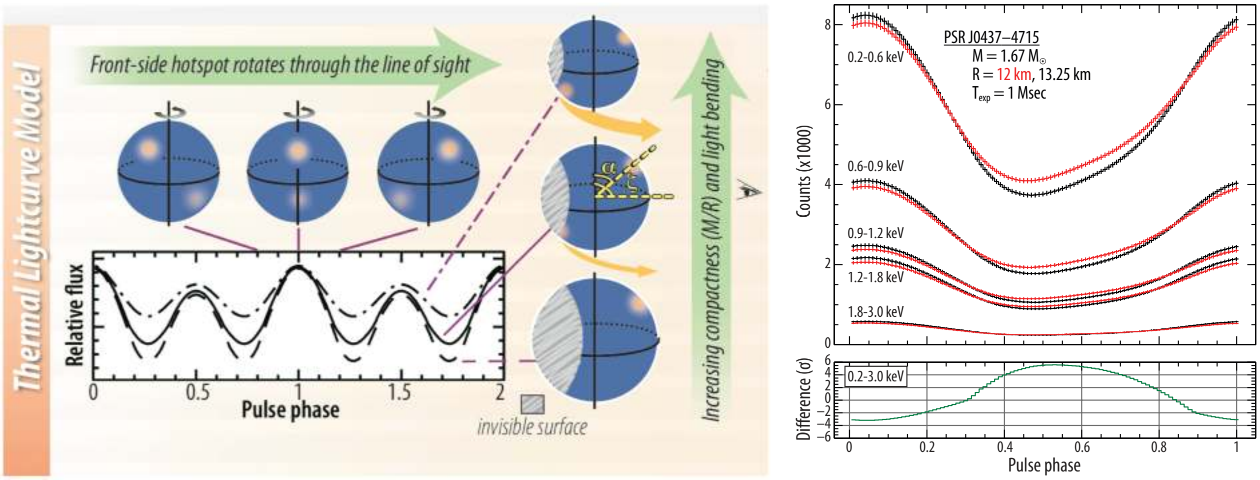

Figure 4. (*Left*) A distant observer sees X-ray intensity grow and fall as hot-spots on a neutron star surface spin through the line of sight. The far-side spot becomes more visible for smaller stars through gravitational light-bending, which depends on M/R; thus, depth of modulation constrains compactness. (*Right*) Two sets of simulated NICER lightcurves, for stellar radii differing by ±5%, show measurable differences in several energy bands for a 1 Msec exposure: 4–6σ differences per phase bin pinpoint the star's radius.

Using XMM-*Newton* data for PSR J0437–4715, Bogdanov et al. (2007) establish the viability of constraining the neutron star EOS through lightcurve analysis. Their model successfully reproduces both the pulsar's lightcurve and its phase-averaged spectrum. Their result (Figure 3), however, encompasses virtually all EOS families, including strange quark matter (SQM), condensate (the region between the PAL6 and FSU curves), and soft and stiff nucleonic models (black curves). Because of limitations in XMM's onboard timekeeping, these radius constraints cannot be improved upon with additional XMM observations by more than a factor of two, and there is no possibility of attaining ±5% (3σ) uncertainty in *R*, which is NICER's goal and an improvement by a factor of more than 12. Simulations show that NICER achieves this goal for PSR J0437–4715 with an accumulated 1 Msec exposure.

To infer neutron star masses, NICER offers collecting area and photon time-tagging precision sufficient for measurement in X-rays (for the first time) of the general-relativistic Shapiro delay in binary systems. For orbits viewed edge-on, this retardation of a pulsar signal traversing the gravitational well of its companion is the most accessible of the well-known "post-Keplerian" timing effects traditionally accessible only to radio observations. Delays of tens of μs are measurable whenever timing precisions of a few μs are achieved on timescales small compared to the orbital period. For orbital periods longer than a few days, in systems containing either rotation- or accretion-powered MSPs, NICER's pulse time-of-arrival (TOA) measurements will yield masses through the Shapiro delay.

Additional core NICER science investigations will include:

- Searches for coherent pulsations and quasi-periodic oscillations (QPOs) in steady and transient systems. Discovery of a neutron star's rotation rate, its most consequential observable property, is important for eventual lightcurve analysis, characterization of orbits and component masses in binaries, and for understanding the origins of kHz QPOs, which probe the extreme neutron star environment[8]. NICER also offers the prospect of a new capability to perform asteroseismology measurements of neutron stars.
- Definitive determination of the intrinsic clock stabilities of MSPs, free of the interstellar propagation effects that plague radio timing observations.
- Cooling histories of young neutron stars. Existing temperature measurements suffer from poor statistics, blending together cooling-surface emission, heated polar caps, and nonthermal magnetospheric emission. NICER will disentangle the various components through phase-resolved spectroscopy, including constraining the origins of absorption features near 1 keV seen in some objects.
- Characterization of spin variations and outbursts associated with "glitches" in normal pulsars and magnetars.
- Determining radiation patterns, spectra, and relative phases of nonthermal emissions across wavelength bands.

2.2 The NICER Guest Investigator/Observer program

The NICER mission includes a proposed Guest Investigator/Observer (GI/O) program. Modeled after the *Swift* mission's GO program, the first NICER Announcement of Opportunity (AO) will solicit GI proposals for concurrent observations of NICER's neutron star targets in the radio, optical, and γ-ray bands (Figure 5), and also to support theoretical work relevant to NICER investigations. The first GI period will overlap with the first year of the mission, during which the NICER observing program will be dedicated to fulfilling its core neutron-star science investigation. To facilitate planning and coordination of complementary observing efforts, NICER target schedules will be published well in advance. GI/O proposals received within this and subsequent AOs will be selected via a peer-review process.

The second AO will solicit GO proposals, for observing time using NICER to target objects not part of the core NICER science agenda, concurrently with baseline science observations during a 12-month period. The Rossi X-ray Timing Explorer (RXTE), recently decommissioned after 16 years of service, revolutionized X-ray timing astrophysics, discovering many new phenomena and resulting in more than 2,500 publications; NICER will provide a natural extension of much RXTE science, while similarly opening a new discovery window in soft X-rays. With the highest time resolution of any astronomy instrument flown, 30 times the sensitivity of RXTE to background-dominated sources, and a factor of 8 improvement in energy resolution, NICER will enable new observing strategies and science for a wide variety of sources, from active stars to clusters of galaxies. Unique science outcomes could include establishing the existence of intermediate mass black holes through characterization of QPOs in ultraluminous X-ray sources (ULXs); unification of stellar-mass and supermassive black holes via measurement of break timescales in AGN power-spectra; testing models of polar accretion onto magnetic white dwarfs in binary systems; detecting photon bubble oscillations

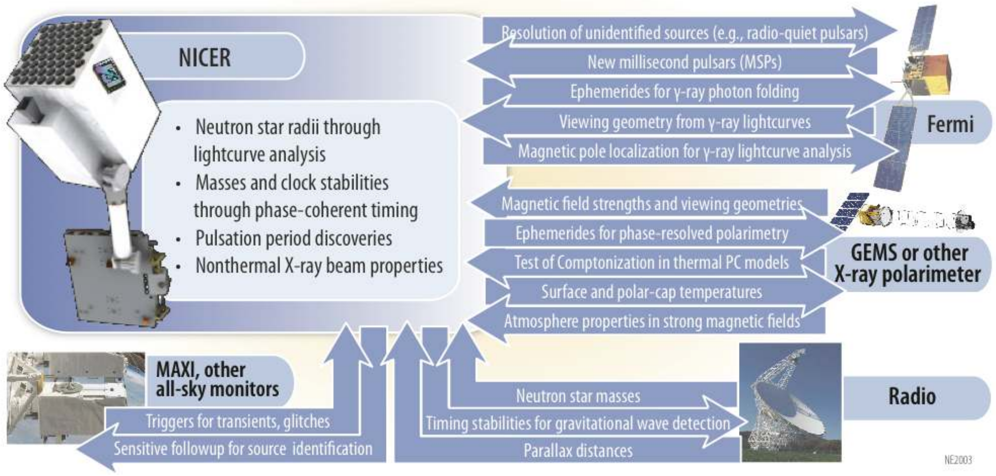

Figure 3. NICER capabilities and measurement products are highly complementary to those of other X-ray, radio, and γ-ray facilities for neutron star studies. Interplay between them amplifies the scientific returns from all.

driven by high-rate accretion; probing galaxy evolution in clusters with Fe line measurements in the intracluster medium out to redshifts z ~ 1 or more; and others.

3. THE NICER X-RAY TIMING INSTRUMENT

At the heart of NICER is the X-ray Timing Instrument (XTI), a co-aligned collection of 56 X-ray concentrator (XRC) optics and associated silicon drift detectors (SDD). Each XRC collects photons over a large (~50 cm^2) geometric area from a 15 arcmin^2 patch of sky, and focuses them onto a small SDD. The SDDs detect individual X-ray photons, recording their energies and times of arrival to high precision. Together, this assemblage provides a photon counting capability with large effective area (Figure 6), high time resolution, moderate energy resolution, and low background in 0.2–12 keV X-rays. Figure 7 depicts the XTI functional components:

- The XRCs “concentrate” X-rays using grazing-incidence reflections. Individual optical elements are truncated conical shells, approximations of ideal mirror figures that are inexpensive to make and provide large throughput. Each XRC consists of 24 nested conical foils, together with a lightweight support structure. Unlike past metal-foil optics flown on ASCA, *Suzaku*, and other missions, NICER’s XRCs are not imaging optics — X-rays undergo a single reflection. The absence of secondary mirrors increases efficiency and decreases mass and complexity, resulting in an optical system that is optimized for observations of point sources. NICER’s optical system, including the optical bench, is provided by NASA GSFC.

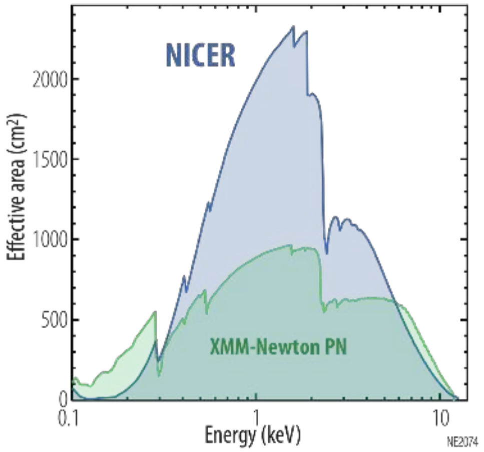

Figure 4. NICER’s peak effective X-ray collecting area exceeds that of XMM-*Newton’*s timing camera by more than a factor of two.

- The NICER SDDs are commercial devices that include integrated thermoelectric coolers (TECs) and thermal/optical-blocking filters. The SDDs are housed in Focal Plane Modules (FPMs) that provide pre-amplification of the SSD signal. Groups of eight FPMs are connected to a Measurement/Power Unit (MPU) via analog connections; the MPUs provide bias voltages and TEC controls, while the FPMs return the output of the preamplifiers and SDD temperature data. Each of the seven MPUs has a fast channel in parallel with a slow channel for each FPM detector. The fast channel has a very fast shaping time (30 nsec) that enables precise individual X-ray photon timing. Absolute time-stamping to high precision is accomplished with the help of an oscillator on the MPU that is compared to a one-pulse-per-second (1 PPS) signal from an on-board GPS receiver. The slower channel, with a much longer shaping time (300 nsec), provides better energy resolution of the detected X-rays, which enables the NICER spectroscopic science objectives and a cleaner selection against background events. The NICER detector system is provided by MIT.
- The Instrument Optical Bench (IOB) holds the optical and detector systems in a compact, co-aligned assembly, providing mechanical rigidity, thermal stability, and ease of integration for the highly modular instrument.

SDDs offer energy resolutions typical of silicon-based detectors, approaching the Fano limit. NICER's anticipated performance is 3% energy resolution at 6 keV and 8% at 1 keV. The SDD's timing resolution is limited by the spread of electron drift times for photons interacting at various distances from the central sensing anode. The resulting timing jitter is less than 155 nsec. NICER's anticipated background level will be dominated below 2 keV by the diffuse cosmic X-ray background (0.05 cts/sec over the 15 arcmin^2 non-imaging field of view at high Galactic latitudes), and by unrejected particle background at higher energies (0.01 cts/sec/keV across the entire NICER band). Figure 8 shows the combined capabilities of NICER as an X-ray astrophysics tool. For countrate and spectral-fitting simulations, NICER is recognized by the online WebPIMMS and WebSpec tools at GSFC's High Energy Astrophysics Science Archive Research Center.

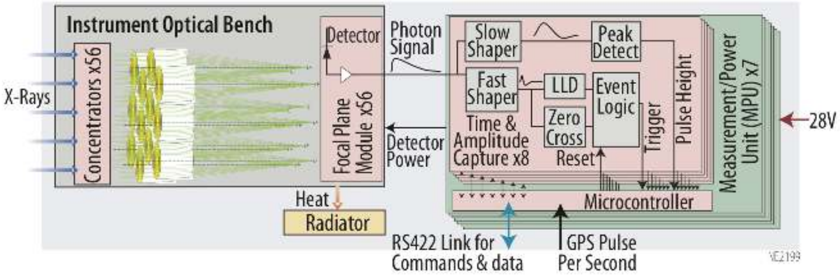

Figure 7. Functional block diagram of the NICER X-ray Timing Instrument's components: concentrator optics, Focal Plane Modules that house silicon drift detectors, and Measurement/Power Units.

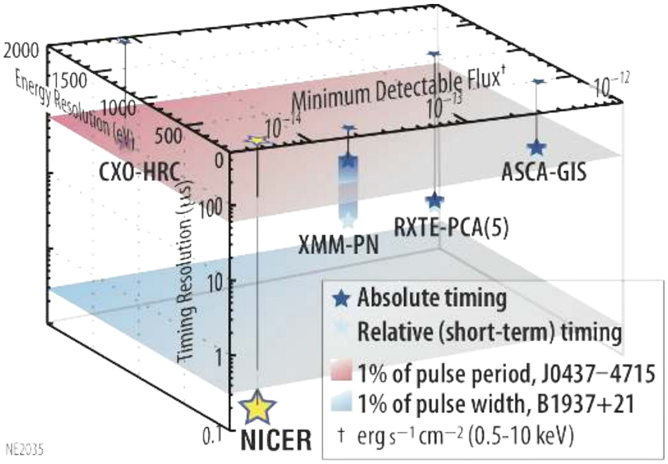

Figure 8. NICER plumbs unexplored depths in time resolution, spectral resolution, and sensitivity. The time-tagging resolution benchmarks represented by the upper and lower shaded planes enable, respectively, high precision timing for mass and clock-stability measurements, and lightcurve analysis for radius measurements.

4. MISSION DESIGN AND SCIENCE OPERATIONS

After instrument-level testing and verification, the NICER instrument is integrated onto a standard, government-furnished ISS/ELC interface, the Flight Releasable Attachment Mechanism (FRAM). The FRAM also serves as NICER's interface to the transport vehicle that will ferry the payload to the ISS. The transport vehicle berths with the ISS; NICER is then transferred robotically to its zenith-side ELC location. Upon deploying from its stowed state, NICER begins on-orbit checkout and calibration, and soon after, its science program. During observations, NICER points to and tracks targets while maintaining viewing constraints that preserve the instrument's health. The NICER mission life of 18 months enables baseline science, after which NICER can be re-stowed and de-orbited, or indefinitely turned off and left on the ELC.

NICER's subsystems are summarized below.

- A pointing and deployment system (Figure 9) extends the XTI above the ELC and points it toward inertial targets. The system uses high-heritage components including a star tracker, gimbals, and software that enables the XTI to track celestial objects as the ISS orbits the Earth. NICER's instrument boresight remains locked onto specified targets to better than 90 arcsec. The pointing system easily overcomes the expected jitter from ISS vibrations at the ELC platform, and allows NICER to stow to protect its optics during potential contamination events such as the arrival or departure of visiting spacecraft.
- A Main Electronics Box (MEB) hosts the instrument's command and data handling system (C&DH), power converter, power switching boards, and Global Positioning System (GPS) electronics. MEB interfaces to the ELC include uplink (via 1553), downlink (via Ethernet for science data and 1553 for housekeeping), and power. The MEB uses RS422 to communicate with the gimbal controllers, star trackers, and detectors within the instrument. The GPS system provides position and time, which are critical to interpreting the science data.
- A simple mechanical design takes advantage of the large mass allowance on the ELC. It provides a stiff IOB that accommodates the expected thermal-mechanical forces. It also includes launch locks, gimbals, and the pointing system deployment boom.
- A simple thermal system controls and maintains all components within temperature limits through a combination of cold biasing (via radiators), controlling (with thermostats and heaters), and phase-change materials; this is accomplished using the abundant power resources on the ISS. The SDDs have built-in thermoelectric coolers. NICER has two basic thermal configurations: one to maintain survival temperatures during the mission launch phase and installation onto the ELC, followed by a second operational configuration once installed and the instrument has uninterrupted power.
- High heritage software handles C&DH requirements and the instrument pointing system.

Normal NICER operations occur independently and on a non-interference basis with the ISS and its other payloads. Preplanned observation schedules will incorporate and account for radiation belt passages, contamination constraints (such as when re-supply vehicles are present), and the additional viewing constraints imposed by the Earth, Moon, Sun (a 45º exclusion zone from the instrument boresight), and ISS structures. Typically, NICER observes three or more

Figure 5. The NICER payload in its stowed, deploying, and fully deployed states.

targets during an ISS orbit: the first target is tracked until a viewing constraint (e.g., Earth or solar panel blockage) is encountered, then NICER slews to a second target fairly rapidly (0.6º per sec), acquires the second target and tracks it until a viewing constraint is encountered, slews to a third target, and so on. The number and distribution of NICER targets allows for a nearly continuous opportunity to do science throughout the year. Factoring in all restrictions, NICER will achieve and exceed its requirement of 15 Msecs of valid observing time over an 18-month span by nearly a factor of two, easily accommodating the baseline science and allowing for a robust GO program.

The NICER science team generates the observation list; operations personnel in a Science and Mission Operations Center (SMOC) convert the target lists to command loads. The uploads are delivered to the instrument via the ISS communication and command system well in advance of the currently executing command plan's expiration. NICER executes these chronological sequences, buffers the resulting science data, and then downlinks them through the established ISS communications infrastructure, which forwards the data to the NICER SMOC.

The complete science dataset for a given target will include many individual observations, potentially accumulated over hours, days, or years. NICER will carry a time and position standard based on GPS that enables multiple observations to be piece together into a coherent dataset spanning the entire mission lifetime (as *Fermi* has effectively demonstrated). Each photon detected by NICER is time-tagged with an absolute precision of much better than 300 nsec and with NICER position knowledge to better than ±5 m.

5. CONCLUSION

NICER is a pioneering Explorer that reaps the benefit of NASA's continued investments in the ISS. In 2017, the NICER payload will help fulfill the promise of ISS as an enabler of high-priority science, revealing the strange and mysterious physics of neutron stars while bringing novel capabilities — simultaneous fast timing and spectroscopy with low background and high throughput — to a broad set of X-ray astrophysics investigations.

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