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Searching for X-ray Pulsations from Neutron Stars Using NICER

Paul S. Ray[1] Zaven Arzoumanian[2] and Keith C. Gendreau[2], for the NICER Working Group on Pulsation Searches and Multiwavelength Coordination

[1]U.S. Naval Research Laboratory,
Washington, DC 20375-5352
email: paul.ray@nrl.navy.mil

[2]NASA/GSFC
Greenbelt, MD 20771

Abstract. The Neutron Star Interior Composition Explorer (NICER) presents an exciting new capability for exploring the modulation properties of X-ray emitting neutron stars, including large area, low background, extremely precise absolute event time stamps, superb low-energy response and flexible scheduling. The Pulsation Searches and Multiwavelength Coordination working group has designed a 2.5 Ms observing program to search for emission and characterize the modulation properties of about 30 known or suspected neutron star sources across a number of source categories. A key early goal will be to search for pulsations from millisecond pulsars that might exhibit thermal pulsations from the surface suitable for pulse profile modeling to constrain the neutron star equation of state. In addition, we will search for pulsations from transitional millisecond pulsars, isolated neutron stars, low-mass X-ray binaries (LMXBs), accretion-powered millisecond pulsars, central compact objects and other sources. We present our science plan and initial results from the first months of the NICER mission, including the discovery of pulsations from the millisecond pulsar J1231−1411.

Keywords. space vehicles: instruments, pulsars: general, (stars:) pulsars: individual (PSR J1231−1411), stars: neutron, X-rays: binaries

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1. Introduction

While the majority of pulsar studies are done in the radio band, multiwavelength information is critical to gaining a fuller understanding of these objects. Over the past decade this has been borne out by the spectacular success of the *Fermi* mission and now about 10% of the pulsar population is detected in gamma-rays, with a few dozen of those detections being radio-quiet systems. The Neutron Star Interior Composition Explorer (NICER) is poised to make similar advances in studies of the X-ray emission from pulsars.

X-rays can provide a direct view of the surface of the star, giving information about the cooling processes in young (or accretion-heated) neutron stars and the polar caps heated by magnetospheric return currents in older pulsars. Pulse profiles from these sources encode information about the mass and radius of the neutron star from special and general relativistic effects on the emitted radiation (see Bogdanov *et al.*, this volume). X-rays also probe non-thermal emission from the magnetosphere, providing another handle on the system geometry and can reveal shock emission from interaction of the pulsar wind with a companion star (see Roberts, this volume). Pulse timing studies in the X-ray band are free from the propagation effects, such as time-variable interstellar dispersion and scattering, that plague radio timing measurements.

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In addition, some neutron stars are far more prolific X-ray emitters than radio. The largest classes are the accreting systems like LMXBs and accreting pulsars, but this also includes most magnetars, isolated neutron stars and some radio quiet pulsars.

2. NICER

NICER is an X-ray telescope mounted on the International Space Station (ISS) that is highly optimized for pulsar studies (Gendreau *et al.* 2016). NICER covers the 0.2 to 12 keV band with large collecting area (> 1900 cm^2 at 1.5 keV). This is twice the area of the XMM-Newton EPIC-pn camera that has been used for many pulsar studies. It detects and telemeters every event, with time stamps referenced to GPS to an accuracy of better than 100 ns. The modular design with 56 co-aligned X-ray telescopes (52 currently functional on orbit) results in very high count rate capability with low dead time. The inexpensive single-reflection X-ray concentrator optics enable the use of small silicon drift detectors (SDDs), resulting in low radiation-induced background count rates. The SDDs also provide very good energy resolution of between 85 and 160 eV. This combination of capabilities will be transformational for pulsar and neutron star studies including pulsation searches, timing, spectral line studies, burst investigations and much more.

NICER was launched on 2017 June 3 and was robotically installed on the ISS ExPRESS Logistics Carrier (ELC) 2 on 2017 June 14. The first month was spent commissioning and calibrating the payload. NICER's 2-axis pointing system slews at 1° per second and achieves an accuracy of 66 arcsec by means of a star camera co-aligned with the X-ray telescope boresight. The individual telescopes are aligned to the overall boresight to an RMS of 28 arcsec. On 2017 July 17, NICER entered its science operations phase, which is scheduled to last 18 months.

The NICER Science Team is divided into several topical working groups whose purpose is to design a program of observations that accomplishes a portion of the mission's overall science objectives (Arzoumanian *et al.* 2014). The working groups, with their chairpersons and time allocations are:

- Lightcurve Modeling — Slavko Bogdanov (Columbia), 5.0 Ms
- Bursts & Accretion Phenomena — Feryal Ozel (U. Arizona), 2.0 Ms
- Searches & Multiwavelength Coord. — Paul Ray (NRL), 2.5 Ms
- High-Precision Timing — Andrea Lommen (Haverford), 4.0 Ms
- Magnetars & Magnetospheres — Teru Enoto (Kyoto U.), 1.5 Ms
- Observatory Science — Ron Remillard (MIT), 2.5 Ms
- Calibration — Craig Markwardt (GSFC), 1.0 Ms

Coauthor KCG is NICER's Principal Investigator; ZA is Deputy PI and Science Lead. In this paper, we will describe the work of the Searches & Multiwavelength Coordination working group.

3. Searches & Multiwavelength Coordination

The primary goal of this group is to achieve one of NICER's baseline science requirements, which is to deeply search for pulsations from at least 20 pulsar candidates. We will achieve this using coherent pulsation searches spanning all periods but targeting candidate MSPs especially. The top priority for these searches is to discover X-ray pulsations from MSPs suitable for the light curve modeling work to constrain the radius of a neutron star, but we have developed a ranked list of sources that span over a dozen categories of candidate source classes. Our final list includes 32 specific sources and reserves some time as well for transients and other sources that may be identified during the mission.

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Search Target Categories

Expand set of sources useful for equation of state studies
Search for fastest-spinning and non-thermal emitting MSPs
Pulsation periods in persistent LMXBs
Pulse periods and timing in AMXP transients
Flux modulation properties in transitional MSPs in both states
Searches for pulsations in candidate Fermi LAT MSPs
Pulsation searches in gamma-ray binaries
Pulsation searches in SNRs/CCOs
Survey dense stellar regions for X-ray pulsations
X-ray pulsations in the Small and Large Magellanic Clouds
X-ray pulsations near the Galactic Center
X-ray pulsations from neutron stars in globular clusters
X-ray Isolated Neutron Stars
X-ray emission from nearby rotation-powered pulsars
Searches for ULX pulsations
Asteroseismology with NICER
Transients and TOOs

Search Targets

Source	POC	Category	Exposure (ks)
IGR J17062–6143	Mahmoodifar	AMXP	10
SAX J1808.4-3658	Chakrabarty	AMXPs	50
HESS J1731_offset	Guillot	CCO	200
qLMXB in Omega Cen	Guillot	Dense Regions	250
PSR J1231-1411	Ray	EOS Candidates	80
PSR J1614-2230	Wolff	EOS Candidates	100
PSR J0751+1807	Ray	EOS Candidates	100
PSR J1012+5307	Deneva	EOS Candidates	80
PSR J0636+5129	Ray	EOS Candidates	100
PSR J2241-5236	Kerr	EOS Candidates	100
PSR J1744-1134	Kerr	EOS Candidates	
3FGL J0212.1+5320	Bogdanov	Fermi Candidates	50
LSI +61 303	Kerr	Gamma-ray binaries	50
LS 5039	Enoto	Gamma-ray binaries	90
PSR B1259-63	Wood	Gamma-ray binaries	30
4U 1820-30	Keek	LMXB pulsations+	100
Sco X-1	Bult	LMXB pulsations+	20
Cyg X-2	Mahmoodifar	LMXB pulsations+	40
M15 (GC, 2 LMXB)	Strohmayer	LMXB pulsations+	60
GX 349+2	Chakrabarty	LMXB pulsations+	20
4U 1636-536	Strohmayer	LMXB QPOs	0
PSR J0614-3329	Ransom	RPP	100
PSR J1833-1034	Wolff	RPP	100
PSR B1957+20	Arzoumanian	RPP (BW)	50
1RXS J154439.4–112820	Bogdanov	Transitional MSPs	60
Cen X-4	Chakrabarty	Transitional MSPs	50
PSR J1723-2837	Bogdanov	Transitional MSPs	50
RX J1605.3+3249	Bogdanov	XINS	50
2XMM J104608.7-594306	Bogdanov	XINS	100
1RXS J213944.3+595016	Bogdanov	XINS	50
1RXS J044048.0+292440	Bogdanov	XINS	50
1RXS J171502.4-333344	Bogdanov	XINS	50
Planned TOOs			
SMC Transient #1	Wilson-Hodge	Dense Regions	20
GalCen Transient #1	Wilson-Hodge	Dense Regions	50
Transient ULX #1	Strohmayer	ULX	50
Transient AMXP #1	Chakrabarty	AMXPs	30
Candidate AMXPs	Chakrabarty	AMXPs	20
TOTAL			**2410**

Figure 1. *Left:* Source categories identified for the NICER Searching WG science program. *Right:* Recommended target list for Searching WG time allocation.

4. Discovery of Pulsations from PSR J1231−1411

The top priority source for this group is PSR J1231−1411. This 3.68 millisecond pulsar is one of the many radio MSPs discovered in searches of Fermi LAT unassociated sources. X-ray imaging observations with XMM-Newton revealed a moderately bright point source with a spectrum consistent with thermal emission from a neutron star surface (Ransom *et al.* 2011). Prior to NICER all X-ray observations of J1231−1411 were done with instruments/modes that did not have the timing resolution to determine if the emission was pulsed. A detection of pulsed emission from this source would make it a potentially important target for neutron star equation of state studies using pulse profile modeling.

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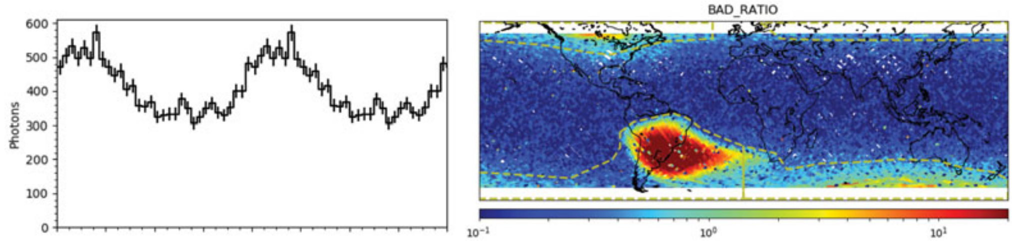

Figure 2. *Left:* Preliminary NICER 0.4–1.5 keV pulse profile (2 periods shown) of PSR J1231−1411. *Right:* Map of a particle background proxy observed through the NICER orbit. The regions of the orbit inside the dashed polygons are excluded from the analysis to provide the lowest background rates.

We analyzed data from 12 days of NICER observations of this source totaling a raw time of 127 ks. From that total exposure, we selected times where NICER was pointed at the target, which was at an elevation of > 30 deg, and outside of the enhanced-background portions of the orbit (see Figure 2), resulting in 61.7 ks of exposure. We selected only photon events with energies > 0.4 keV and rejected likely particle energy-deposition events.

Pulse phases were computed using the `photonphase` code in PINT (Jing *et al.* 2017) and a radio timing ephemeris from Abdo *et al.* (2013). We then found the energy cuts that optimized the H-test detection statistic (de Jager *et al.* 1989). For an energy cut of 0.4–1.5 keV, we get an H-test value of 405, corresponding to an 18.6 σ detection (not accounting for a small number of trials to optimize the energy cuts). Note that this is work in progress and will be revised as calibration and event filtering procedures are improved.

The pulsations are soft and highly sinusoidal, as expected from thermal emission from the surface, making PSR J1231−1411 a good addition to the targets for the NICER light curve working group.

5. Summary

As the early discovery of PSR J1231−1411 demonstrates, NICER is now a powerful instrument for X-ray studies of pulsars and other neutron star systems, and will be equally exciting for non-neutron star science such as AGN, black hole binaries, cluster spectroscopy, stellar coronae, CVs and more. The community will have access to NICER through the Guest Observer program, which will issue its first call for proposals in early 2018. All NICER data will become public, with releases beginning in early 2018. Finally, the PI has significant discretionary time, so we invite collaborations and requests for observations from the community.

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Ransom *et al.* 2011, *ApJ* 727, L16

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