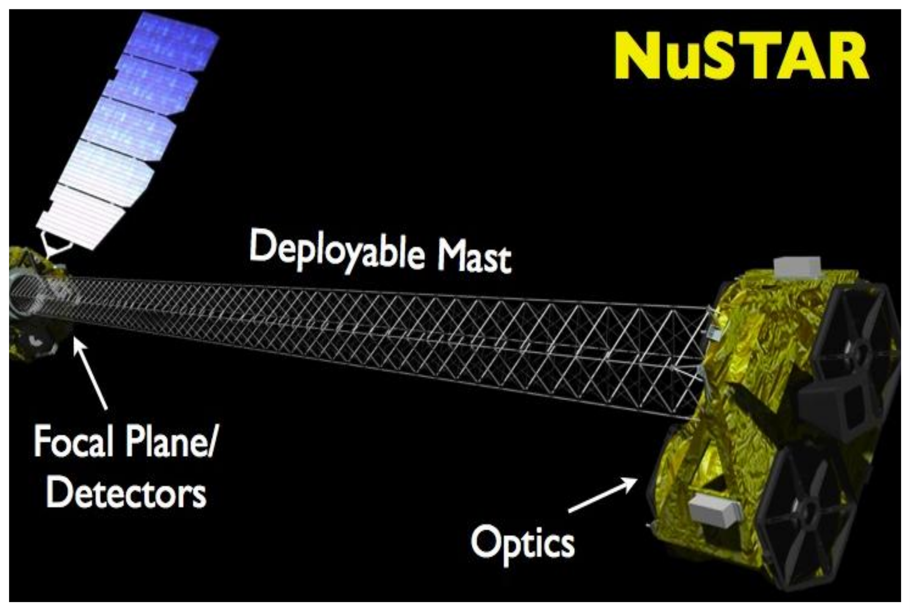
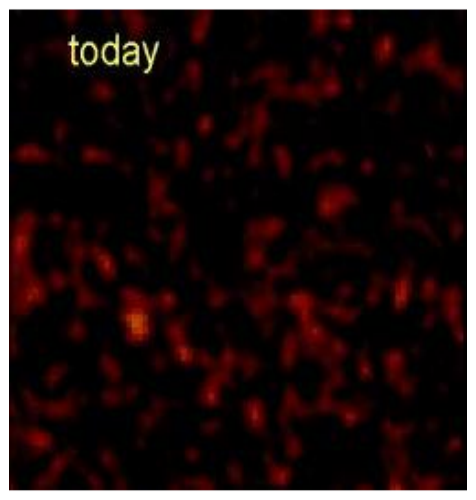
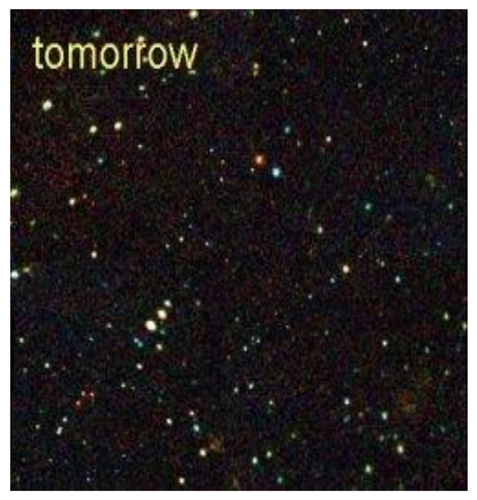


Galactic Science with *NuSTAR*

V. M. Kaspi (McGill U.) for the NuSTAR Team

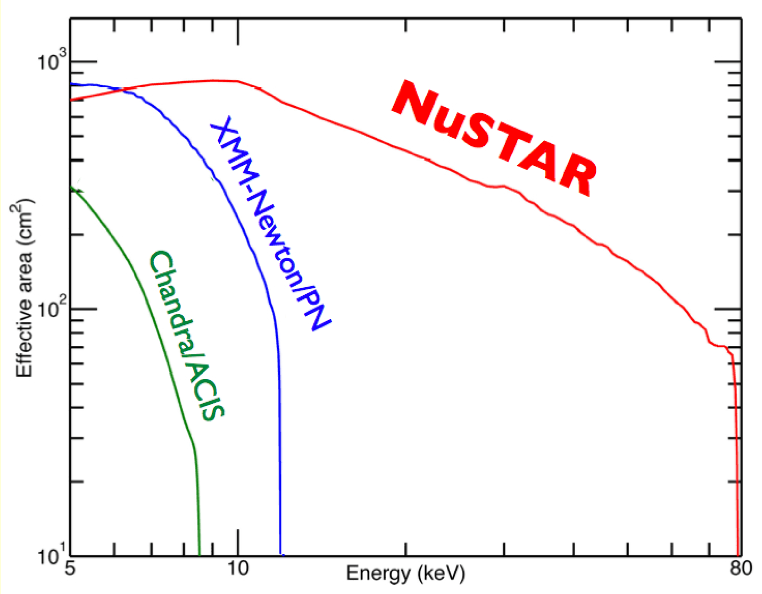




ABSTRACT: The Nuclear Spectroscopic Telescope Array (*NuSTAR*), scheduled for launch in Spring 2012, will allow for sensitive studies of high energy sources in the Milky Way Galaxy at an unprecedented depth in the 5-80 keV range. The baseline 2-year mission includes a mixture of field surveys and targeted observations of known sources. Several months will be spent mapping Galactic fields, both near the Galactic center and towards the Norma arm. These surveys should identify large numbers of X-ray binaries, compact stellar remnants, as well as observe diffuse high energy emission. Targeted observations include studies of high energy emission from magnetars, local supernovae and supernova remnants, pulsars, pulsar wind nebulae, X-ray bursters, and ultraluminous X-ray sources.

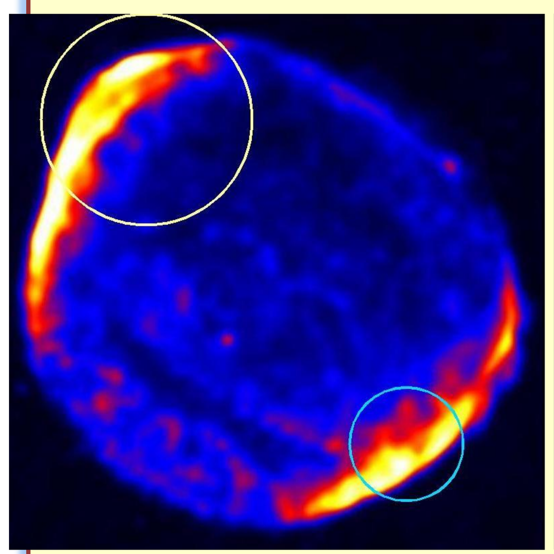
Overview

- *NuSTAR* will deploy the first focusing telescopes to image the sky in the high energy X-ray (5 - 80 keV) band. Our view of the Universe in this window has been limited because previous orbiting hard X-ray telescopes have not employed true focusing optics, while focusing X-ray telescopes have had little sensitivity above 10 keV (see effective area curve below and poster 254.25 by Harrison et al.).
- A NASA Small Explorer (SMEX) mission, *NuSTAR* is currently in Phase C/D and is scheduled to launch into low-Earth orbit in Spring 2012.
- In addition to its core science program , *NuSTAR* will offer opportunities for a broad range of science investigations, ranging from probing cosmic ray origins to studying the extreme physics around collapsed stars to mapping microflares on the surface of the Sun.
- Here we survey planned Galactic science targets and programs to be done with *NuSTAR*. See poster 254.13 by Madsen et al. for extragalactic science to be done with *NuSTAR*, and poster 142.42 by Elvis et al. for *NuSTAR* AGN science.

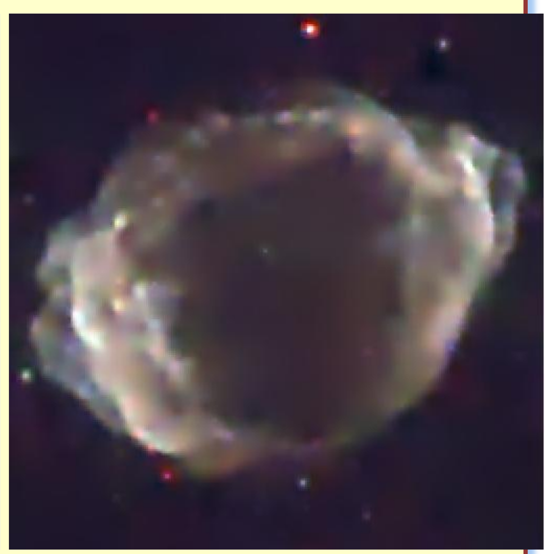


Supernova Remnants (SNRs)

- ~10 Galactic SNRs have shock speeds >1,000 km/s and show synchrotron X-ray emission from electrons with energies >10 TeV (see Reynolds 2008, ARAA, 46,89).
- Shape of X-ray spectrum contains information on magnetic fields, electron diffusion, and shock physics.
- *NuSTAR* can find and study regions where the highest-energy electrons are produced (see SN 1006 below).
- Hadronic and leptonic models for TeV emission make different spectral predictions in *NuSTAR* band (e.g., Ksenofontov et al. 2010, ApJ, 714, 1187).
- The two youngest Galactic remnants, Cas A and G1.9+0.3 (see below) & SN 1987A should show detectable line emission at 68 keV from nuclear de-excitations in 44Sc, produced by the radioactive decay of 44Ti synthesized in the supernova (Vink et al. 2001, ApJ, 560, L79; Borkowski et al. 2010, ApJ, 724, L161).
- 44Ti production is a sensitive indicator of explosion conditions. *NuSTAR* should detect resulting 44Sc emission and may localize it in Cas A and G1.9+0.3.



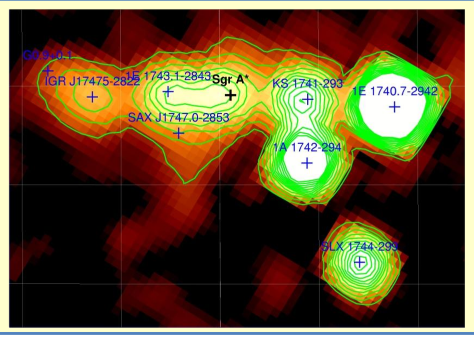
Chandra image of SN 1006, convolved to 45", with *NuSTAR* FOV at 10 keV (6' radius) and at 78 keV (3' radius) shown (NASA/CXC).



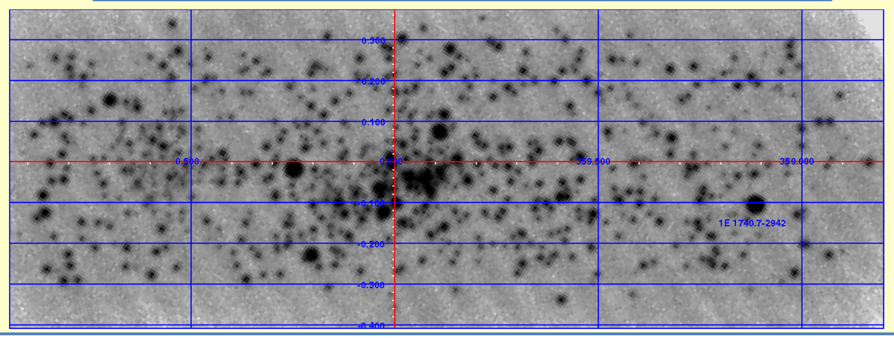
G1.9+0.3 (3-color image from *Chandra* 250 ks observation; Borkowski, et al. 2010, ApJ, 724, L161).

Galactic Surveys

- *NuSTAR's* excellent spatial resolution will allow surveys of unprecedented sensitivity in the Galactic Center (see below; poster 254.25 by Harrison et al.), Bulge and Norma arm.
- Surveys will characterize populations of black holes, neutron stars, white dwarfs, including accreting compact objects, magnetars, pulsars, and perhaps new kinds of objects.
- *NuSTAR* will provide spectral and timing data, with the source nature to be determined by same observations.



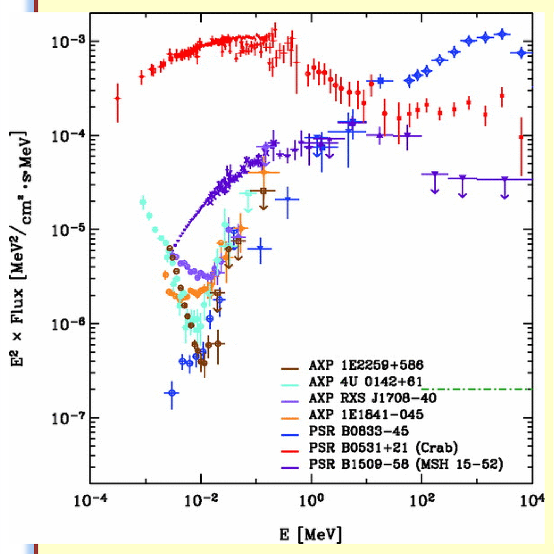
INTEGRAL 20-60 keV image of the Galactic center and inner Galactic bulge. The size of the image is 2.5-by-1.5 degrees. The angular resolution of INTEGRAL/IBIS is about 10'.



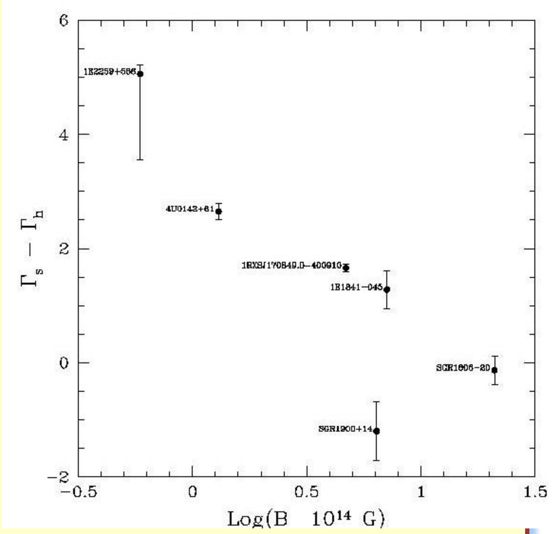
NuSTAR **simulations of the 2-by-0.8 degree region at the Galactic center (5-80 keV) with exposure time is 1 Ms, corresponding to ~12 ks per pixel. The brightest source in the field is 1E 1740.7-2942, with flux 10 mcrab (0.01875 ph/cm2/s or 4.4x10^{-10} ergs/cm^2/s in the 5-80 keV band), or count rate of 12 c/s. The limiting (5-σ) count rate is 0.0076 c/s (6 μcrab). Instrumental and diffuse cosmic X-ray backgrounds, but not ghost-rays, are included. Individual sources are extrapolated as a power-law from *Chandra* measurements. Many sources may have a cutoff somewhere in the *NuSTAR* bandpass,so the region is likely to be less crowded than is shown.**

Magnetars

- Magnetars (both Anomalous X-ray Pulsars and Soft Gamma Repeaters) are surprisingly hard X-ray sources; some are the hardest X-ray sources in the sky in spite of being very soft below 10 keV.
- Some have very strong spectral turnovers (see below) around 15 keV.
- Origin of the hard X-ray emission and the spectral turnover unknown; both were unpredicted.
- Also interesting spectral features seen in some magnetar bursts near ~13 keV (e.g. Gavriil et al. 2002, Nature, 419, 142; Gavriil et al. 2011, ApJ, submitted).
- NuSTAR will make progress on magnetars by:
  - * obtaining high quality spectra on many magnetars, allowing a check of a possible correlation of spectral turnover with magnetic field (see below)
  - * looking for correlated soft and hard X-ray variability
  - * measuring high quality spectra of X-ray bursts from magnetars in outburst



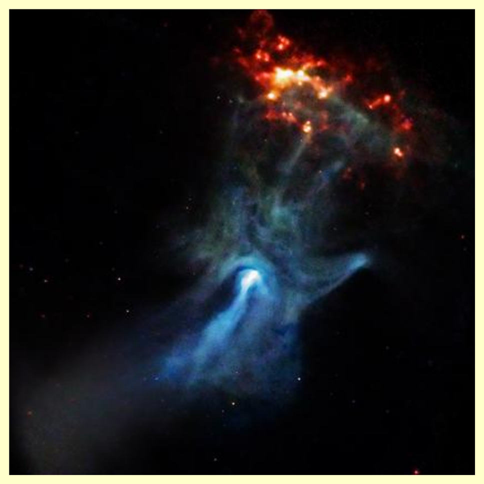
Spectra of 4 AXPs and several rotation-powered pulsars (Kuiper et al. 2006, ApJ, 645, 556). Note strong spectral turnover in AXPs , of unknown origin.



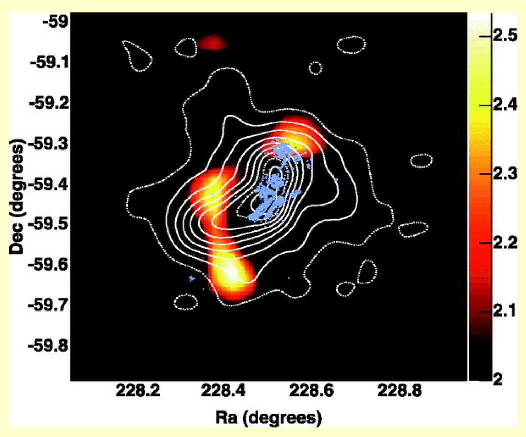
Possible correlation between degree of spectral turnover and magnetic field strength in magnetars (Kaspi & Boydstun 2010, ApJ, 710 L115).

Pulsar Wind Nebulae (PWNe)

- Pulsar-wind nebulae (PWNe) act as calorimeters for pulsar energy loss, and also show the effects of electrons accelerated in the relativistic pulsar-wind termination shocks (for a review see Gaensler & Slane 2006, ARAA, 44, 17).
- Is the steeper X-ray spectrum than in the radio band due to intrinsic structure, or energy losses? Models make different predictions for the effects of energy loss on post-shock flow, and are testable with *NuSTAR* (e.g., Reynolds 2009, ApJ, 703, 662).
- *NuSTAR* will spatially resolve some PWNe for the first time in this energy band (e.g. PWN surrounding pulsar B1509-58; see below, possibly resolved by *INTEGRAL*).
- For all observations of young pulsars with PWNe, *NuSTAR* will obtain collateral science of imaging extended synchrotron emission.



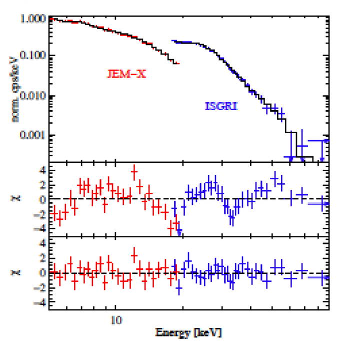
Chandra image of dramatic pulsar wind nebula surrounding pulsar B1509-58 (Red (0.5-1.7 keV); Green (1.7-3.0 keV) ; Blue (3.0-8.0 keV); NASA/CXC/SAO/P.Slane, et al.).



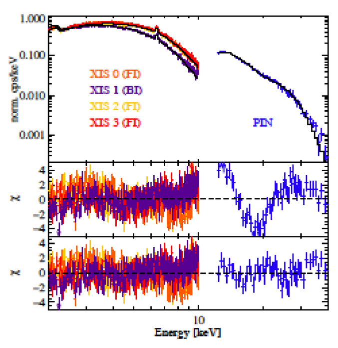
INTEGRAL smoothed significance map excess after point-source contribution removal between 17 and 40 keV. White contours outline TeV emission as seen by HESS; blue ones correspond to *Chandra* observations. Two excesses visible in the jet direction (northwest-southeast) are in global agreement with the HESS contours, bearing in mind the smearing due to the PSF (Forot et al. 2006, ApJ, 651, L45).

X-Ray Binaries (XRBs)

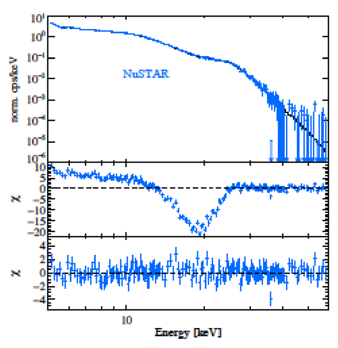
- Advances in hard X-ray sensitivity and energy resolution will allow for pulse phase-resolved cyclotron line measurements with unprecedented detail (see simulation below), allowing improved understanding of accretion onto magnetized neutron stars.
- Detections of photoionization edges of Fe, Co, Zn, and Ni at 9-13 keV during type I X-ray bursts could provide a robust measurement of the gravitational redshift (in 't Zand & Weinberg 2010).
- *NuSTAR* will provide high-quality measurements of the spectral and timing properties of the numerous faint hard X-ray sources discovered by *INTEGRAL*. Many of these are High-Mass X-ray Binaries; the improvement in hard X-ray measurements will allow searches for neutron star or black hole signatures.
- *NuSTAR* will provide the first hard X-ray measurements of neutron star and black hole Low-Mass X-ray Binaries in quiescence. Such measurements can be used to test models for X-ray production, potentially allowing us to determine if some component of the X-ray emission is magnetically-powered (for neutron stars) or jet powered.



INTEGRAL observation of XRB 4U 1907+09 with 1.2 Ms exposure.



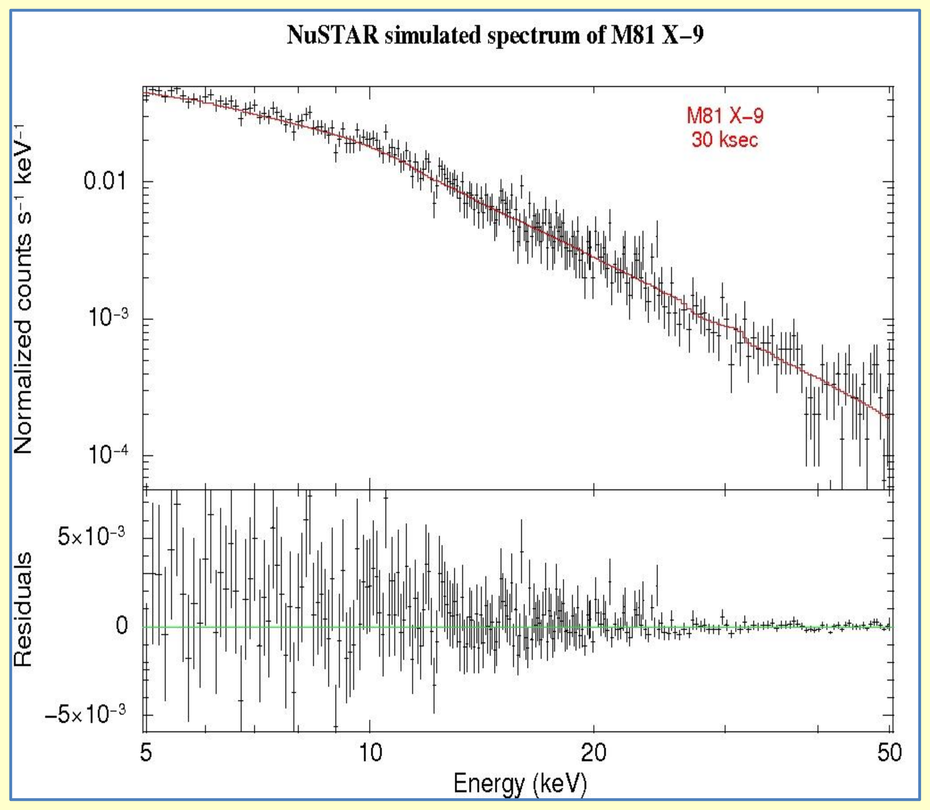
Suzaku observation of XRB 4U 1907+09 with 60 ks exposure.



NuSTAR simulated observation of XRB 4U 1907+09 with 10ks exposure.

Ultraluminous X-ray Sources

- *NuSTAR* will yield the first detailed hard X-ray ULX study and infer any general X-ray spectral properties for the distinctive subclass of bright and hard ULXs.
- *NuSTAR* will observe any energy cut off in the 20-50 keV energy band.
- Reflection component at high energy can establish whether it is beaming due to a funnel-like accretion disk structure or disk corona, or presence of a jet in the system.
- *NuSTAR* will observe QPOs present in these systems and breaks in power density spectra, providing clues to the mass of the BH.



NuSTAR simulated spectrum of a bright ULX M81 X-9 for a 30 ksec exposure time. A simple absorbed power law model, with Γ=1.75 and N_H=2.1 x 10^{21} cm^{-2}, has been used for the simulation.

Other Galactic Science

- **Millisecond Gamma-Ray Pulsars:** Recent *Fermi* discoveries of many millisecond pulsars (Abdo et al. 2010, ApJS, 187, 460) having soft X-ray spectra below 10 keV are potentially interesting *NuSTAR* targets as the origin of the spectral upturn is poorly understood.
- **Sgr A* Flares:** Hard X-ray flare detection from the Galactic Center (Sgr A*) could constrain accretion models and the origin of the X-ray emission (disk or jet).
- **Unusual Binaries:** Several notable gamma-ray binaries, including LSI 61+303, LS 5039, and PSR B1259-63 are interesting *NuSTAR* targets, as they are have unusual spectra and behaviors, producing gamma rays up to TeV energies, and strong variability at lower energies, of unknown origin. Also of interest is the millisecond radio pulsar/XRB transition object PSR J1023+0023, with its surprisingly hard X-ray spectrum (Archibald et al. 2009, Science, 324, 1411; Archibald et al. 2010, ApJ, 722, 88)..
- **HMXB Evolution and Gravity Waves:** *NuSTAR* will uncover low-luminosity HMXBs, constraining the ages of the populations in different parts of the Galaxy and provide a better understanding of HMXB evolution. Winds from high-mass stars are of interest for predicting yields of different types of compact objects from supernovae, hence for determining the likelihood of detecting gravity waves from NS/NS, NS/BH, and BH/BH binaries (Voss & Tauris 2003, MNRAS, 342, 1169).
- **Reflection Nebulae:** Detecting the Compton reflection component of Galactic Center reflection nebulae and comparing the emission to that from Fe fluorescence can test whether the emission is really X-ray reflection; could also detect motion of the reflection emission due to light echoes (e.g. Revnivtsev et al. 2004, A&A, 425, L49) .
- **Young Massive Clusters:** *NuSTAR* will find compact objects in young, massive clusters. E.g. Westerlund 1 has had ~100 SNe in recent history. *NuSTAR* can constrain how many are HMXBs vs isolated neutron stars (see e.g. Clark et al. 2008, A&A, 477 147).
- **Small Magellanic Cloud:** There are many HMXBs in the Small Magellanic Cloud (e.g. Coe et al. 2010, MNRAS, 406, 2533). A *NuSTAR* population study will provide an interesting comparison with the Galactic populations.