NuSTAR Pulsar Discoveries

SGR J1745-2900 near the Galactic Center and
PSR J1640-4631 associated with HESS J1640-465

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for

The NuSTAR Science Working Groups

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Talk Outline

- The NuSTAR Observatory Brief Overview
- Pulsar Timing with NuSTAR
- A Magnetar Close to the Galactic Center
- A Pulsar Associated with the Most Luminous HESS Source
- Summary
Nuclear Spectroscopic Telescope Array (NuSTAR)

• Launched 2013 June 13; Low Earth Orbit, 6° inclination, 10 yr orbit lifetime.
• Two co-aligned hard X-ray imaging-spectrometer telescopes
  – XMM-type mirror coupled with CdZnTe detector array (64 x 64 pixels),
  – energy bandwidth 3 - 79 keV,
  – spectral resolution ~ 4% @ 10 keV and ~ 1% @ 68 keV,
  – $\text{A}_{\text{eff}}(\text{NuSTAR}) > \text{A}_{\text{eff}}(\text{XMM})$ above 6 keV (for two telescopes),
  – field-of-view ~10’x10’ (max, fov is energy dependent),
  – mirror spatial resolution FWHM ~ 18” and HPD ~58”,
  – temporal resolution ~2 ms
• Science working groups provided over 100 initial target list plus survey fields
• Guest Observer program approved (~March 2015)
Pulsar Timing With NuSTAR

• All photons time-tagged to 2 microsecond precision
  – full timing resolution for all imaging-spectroscopic data

• Deadtime, 2.5 ms to process a single event
  – significant for detector rates above 100 cps
  – livetime calculated to 1% accuracy even for highest event rates

• Relative time resolution, 2 ms after applying clock drift correction
  – limited by clock drift correction, 2 ms rms residuals to a spline fit.

• Absolute time resolution, 2 ± 2 ms, limited by calibration quality
  – Swift-NuSTAR calibration using PSR B1509-58 (Mori et al 2014)

• Currently NuSTAR not suitable for ms pulsar timing
  – orbital dependent temperature variation on click rate
  – however, sub-millisecond calibration underway to account for above
OK, let’s see what NuSTAR can do…
First NuSTAR Pulsar Discovery…
The First Detected Galactic Center Pulsar

Daily Swift monitoring program of Sgr A* (Degenaar 2013)
Many Sgr A* flares and (re-occurring) transients detected in the GC region.

- Apr 24 2013 - unusual X-ray flare from Sgr A* detected by Swift (Degenaar 2013)
- Apr 25 - bright, hard 32 ms X-ray burst triggered Swift BAT (Barthelmy 2013)
- Swift temporal/spectral results consistent a magnetar (Kennea 2013)
- Apr 27 - NuSTAR ToO reveals 3.76 s pulsations from the new source (Mori 2013)
- Apr 28 - Transient radio pulsar counterpart detected (Burgay 2013; Buttu 2013; Eatough 2013; Shannon & Johnston 2013)
- Apr 29 - Chandra HRC confirm pulsations, localization 2.4” of Sgr A* (Rea 2013)
- May 3 - Swift timing ToO rapid spin-down implies magnetar B-field (Gotthelf 2013)
- Swift/NuSTAR timing results consistent with a magnetar (Kennea 2013, Mori 2013)
SGR J1745-2900: a Young Magnetar in Outburst
(Mori et al. 2014)

\[ P = 3.76 \text{ s} \]

\[ \dot{P} = 6.5 \times 10^{-12} \]

\[ \tau = P/2\dot{P} = 8800 \text{ yr} \]

\[ B_s = 3.2 \times 10^{19} \sqrt{P\dot{P}} = 1.6 \times 10^{14} \text{ G} \]

\[ \dot{E} = 4\pi\dot{P}/P^3 = 5.0 \times 10^{33} \text{ erg/s} \]

(cf. \( L_x = 3.5 \times 10^{35} \text{ erg/s} \))

Pulse Profile (two cycles)

Spectrum

\( \Gamma \sim 1.5 \)

\( kT \sim 1 \text{ keV} \)

Close to BH, dynamical spin-down effects?
SGR J1745-2900: Temporal Evolution  
(Kaspi et al. 2014)

- Spin-down rate increased by factor of 2.6,
- With no apparent frequency shift,
- Spin-down break coincident with a Swift bust,
- Precludes measurement of dynamical effects due to SMBH.
SGR J1745-2900: Conclusions and Implications

- First detected Galactic center pulsar (2.4" from Sgr A*, next ~10’)
  - thousands expected to populate the dense Sgr A* nuclear region,
  - radio pulsar searches suffer from extremely large DM,
  - X-rays highly absorbed by extremely large $N_H$
- Fourth example of outburst of a magnetar with radio emission,
- Radio RM/DM value constrains GC B-field near Sgr A* (Eathough 2013),
  - probe of local magnetization near SMBH
  - provides a unique test of radiative accretion theory for SMBH
- SMBH Dynamical effects on spin-down (Mori 2013, Rea 2013),
  - long term monitoring would require highly stable spin-down (Rea 2013)
  - precluded by abrupt change in spin-down rate (Kaspi 2014)
Now, Second NuSTAR pulsar discovery...
HESS J1640-465: The Most Luminous Galactic TeV Source

Most Galactic TeV emission associated with supernova products, PWNe, SNRs, SFRs, HMXBs

- HESS Galactic Plane Survey Object,
- Slightly extended HESS TeV sources,
- Most luminous Galactic TeV source,
- $L_{(0.2-10 \text{ TeV})} = 2.8 \times 10^{35} \text{ erg/s @12 kpc}$,
- Coincident with radio SNR G338.3-0.0,
- Unresolved ASCA X-ray source,
- Diffuse XMM source (Funk 2007),
- Chandra point + nebula (Lemiere 2009),
- Overlapping Fermi GeV source (Slane 2010)

“HESS Source of the Month” twice - different interpretations!
HESS J1640-465: The Most Luminous Galactic TeV Source

Key Science:

What is powering the TeV source and how?

- Neighboring HII region - hadronic?
- Pulsar Wind Nebula - leptonic?
- Bit of both, other?

Key Challenge:

Pinpointing counterparts in a complex local Galactic environment

Radio (blue), IR (8 μm green; 24 μm red), X-ray source (cross)

From Castelletti et al. (2011)
**NuSTAR observations of HESS J1640-465**

**HESS J1640-465 observed as part of NuSTAR Norma Survey**

Sep 29 2013: 3x50 ks exposures

FFT of light curve yields a significant signal (~7 sigma), but not conclusive because not evident in all pointings/telescopes - large variance or spurious? New mission caution…
Discovery of a Young Pulsar Powering HESS J1640-465
(Gotthelf et al. 2014)

Re-observation:
significant frequency shift due to rapid spin-down of the pulsar

Overlaid Periodograms

PSR J1640-4631

\[ P = 206 \text{ ms}, \]
\[ P_{\text{dot}} = 9.7 \times 10^{-13} \]

Two cycles show for clarity

\[ \tau = 3350 \text{ yr} \]
\[ \dot{E} = 4.4 \times 10^{36} \]
\[ B_s = 1.4 \times 10^{13} \text{ G} \]
\[ L_{\gamma}(0.2-10 \text{ TeV}) / \dot{E} = 6\% \]

PSR J1640-4631: young, energetic pulsar sufficient to power HESS J1640-465

No gamma-ray pulsation in a search using 5 years of Fermi data

\( \dot{E} \) is same as assumed for lepton models, characteristic age is much less
Broad-band Pulsar and Nebula X-ray Spectrum

Use Chandra Spectrum of pulsar to isolate PWN in NuSTAR spectrum

X-ray Spectrum of PSR J1640–4631 and its Wind Nebula.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chandra only</th>
<th>Chandra + NuSTAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H$ (cm$^{-2}$)</td>
<td>$(1.2 \pm 0.6) \times 10^{23}$</td>
<td>$(1.8 \pm 0.6) \times 10^{23}$</td>
</tr>
<tr>
<td>$\Gamma_{PSR}$</td>
<td>$1.2^{+0.9}_{-0.8}$</td>
<td>$1.3^{+0.9}_{-0.5}$</td>
</tr>
<tr>
<td>$F_{PSR}$ (2–10 keV)</td>
<td>$1.9^{+0.2}_{-1.4} \times 10^{-13}$</td>
<td>$(1.8 \pm 0.4) \times 10^{-13}$</td>
</tr>
<tr>
<td>$\Gamma_{PWN}$</td>
<td>$2.3^{+1.2}_{-1.0}$</td>
<td>$2.2^{+0.7}_{-0.4}$</td>
</tr>
<tr>
<td>$F_{PWN}$ (2–10 keV)</td>
<td>$5.4^{+0.6}_{-2.3} \times 10^{-13}$</td>
<td>$(5.5 \pm 0.8) \times 10^{-13}$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>1.0 (56)</td>
<td>0.82 (79)</td>
</tr>
</tbody>
</table>

$F(0.2-10\text{TeV}) / F(2-10\text{keV}) = 13$

IC losses now dominate over synchrotron emission (for leptonic model)
**Latest SED Modeling of HESS J1640-465**
*(Gotthelf et al. 2014)*

Gelfand one zone PWN/SNR evolution model using timing results

- Latest HESS TeV data,
- Fermi >10 GeV spectrum, *
- NuSTAR X-ray results
- $d = 12$ kpc

![Graph showing SED modeling results](image)

**Model inputs:**
- $T$ (age) = 3.5 kyr;
- $\dot{E} = 4 \times 10^{36}$ erg/s
- $d = 12$ kpc

**Fit results:**
- $E_{\text{min}} = \text{TeV}$
- $E_{\text{max}} = 1.3$ PeV
- $\alpha = 0.017$

**Initial values:**
- $P_0 = 15$ ms
- $\dot{E}_0 = 10^{40}$
- $E_0 = 10^{49}$

* 2FGL flux and 1FHL flux < Slane flux; no evidence for source < 10 GeV; cf. hadronic model
**HESS J1640-465: Conclusions and Future Work**

The X-ray PWN in SNR G338.3-0.0 is powered by a young, energetic pulsar

PSR J1640-4631 is sufficiently energetic to power HESS J1640-465

No gamma-ray pulsation in a search using 5 years of Fermi data

1FHL J1640.5-4634 is marginally coincident with PSR J1640-4632

The Fermi <10 GeV excess is not likely to be real / knowable

A leptonic interpretation can explain the spectral energy distribution

Gelfand PWN/SNR evolutionary model predicts $n \sim 2$ and initial $P_0 \sim 15$ ms

A hadronic component is not excluded and is consistent with SNR/H II interaction

**Deep radio search underway using Parks (preliminary non-detection)**

Braking index campaign underway using NuSTAR to better estimate the true age of the pulsar.
Summary

NuSTAR is an excellent observatory for pulsar timing studies

Allows simultaneous timing / imaging / spectroscopy in the 3-79 keV band

Current calibration allows 2 ms relative and absolute timing

New calibration underway to allow millisecond pulsar studies

Detected first GC pulsar - important for probing SMBH accretion

Detected pulsar engine for the most luminous HESS Galactic Plane source

The project looks forward to more discoveries in GO phase next year