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^{o} 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,*
  - *Aeff(NuSTAR) > Aeff(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 over100 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 above100 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

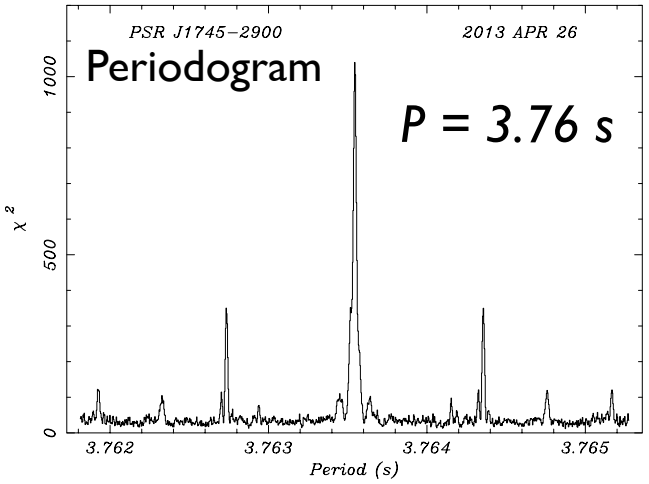
Daily Swift monitoring program of Sgr A (Degenaar 2013)*

Many Sgr A flares and (re-occuring) 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)



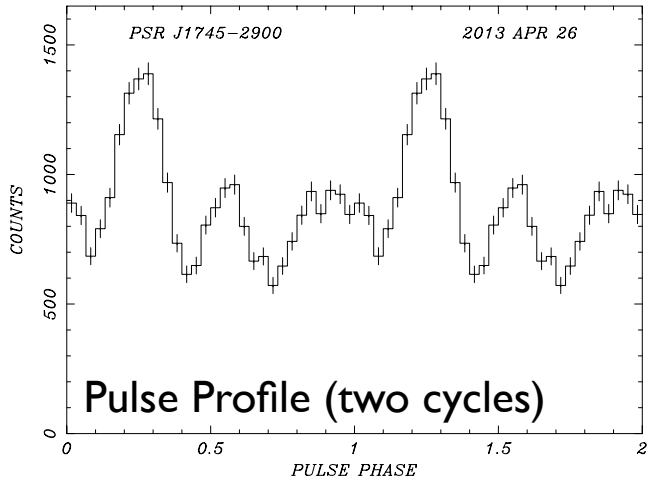
$\dot{P} = 6.5 \times 10^{-12}$

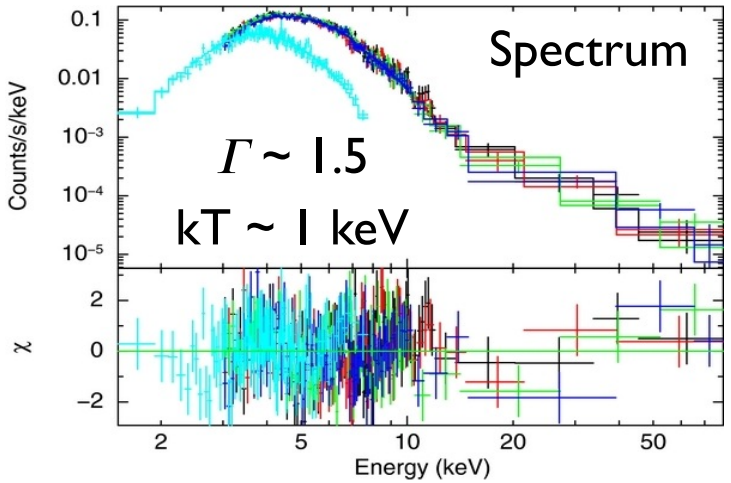
$\tau = P/2\dot{P} = 8800$ yr

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

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

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

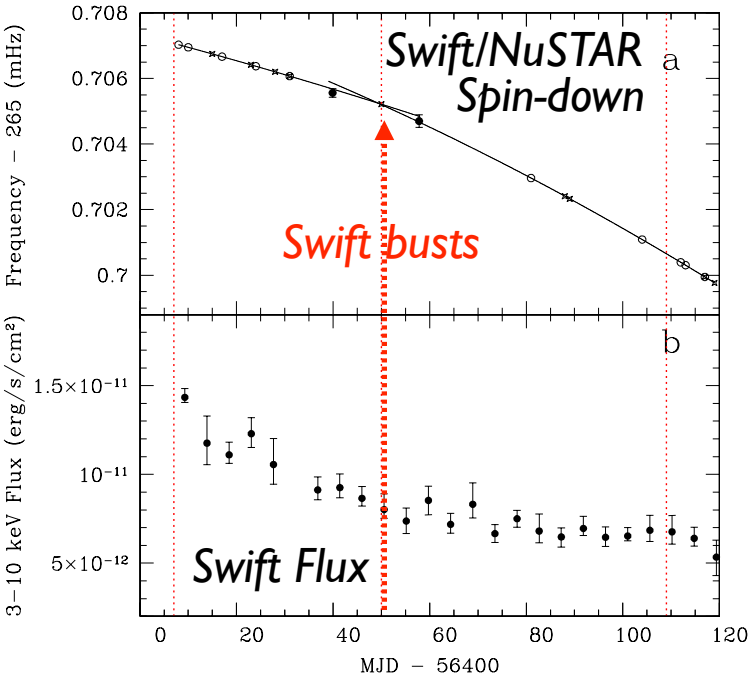




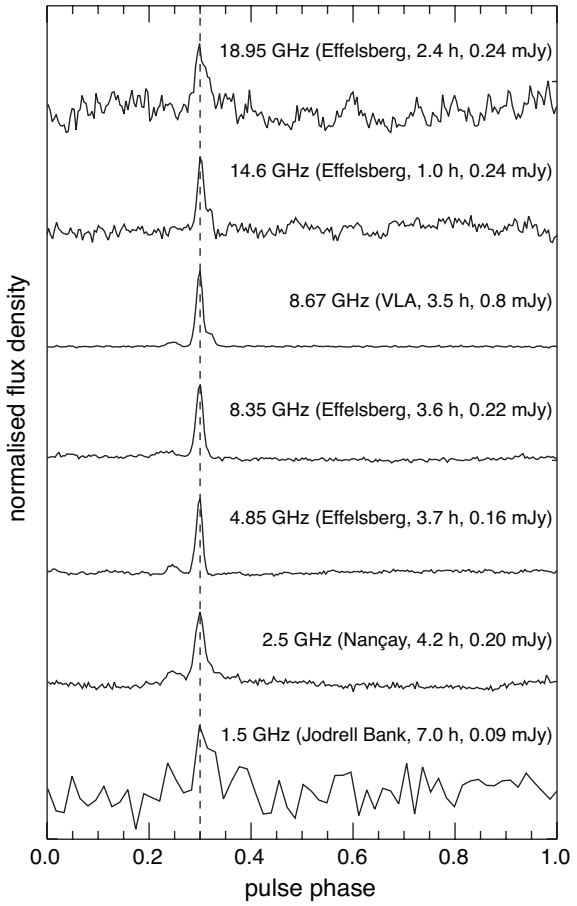
Close to BH, dynamical spin-down effects?

SGR J1745-2900: Temporal Evolution

(Kaspi et al. 2014)



Radio: Eatough 2013



- 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)*

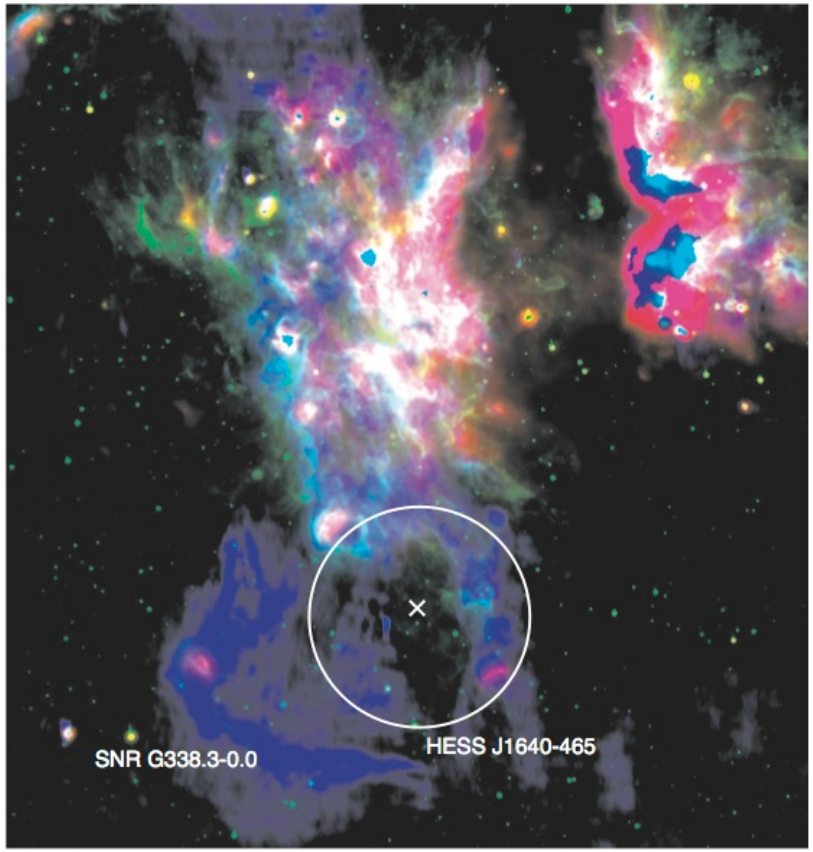
Now, Second NuSTAR pulsar discovery…

HESS J1640-465: The Most Luminous Galactic TeV Source

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

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

- *HESS Galactic Plane Survey Object,*
- *Slightly extended HESS TeV sources,*
- *Most luminous Galactic TeV source,*
- *L(0.2-10 TeV) = 2.8x10^{35} 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)*



From Castelletti et al. (2011)

"HESS Source of the Month" twice - different interpretations!

HESS J1640-465: The Most Luminous Galactic TeV Source

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

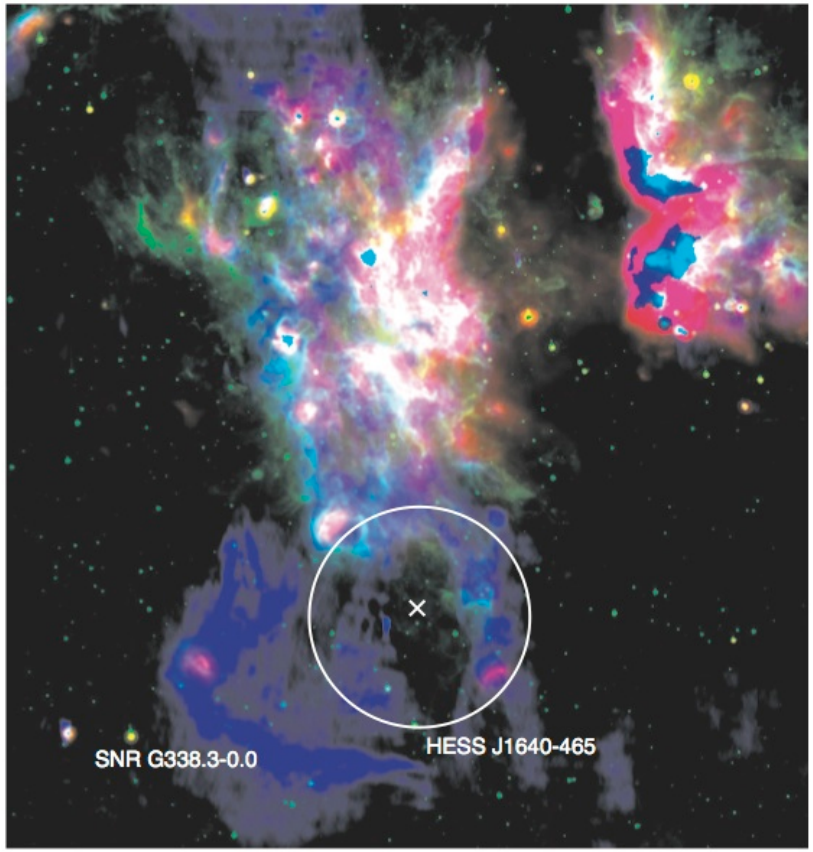
Key Science:

What is powering the TeV source and how?

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

Key Challenge:

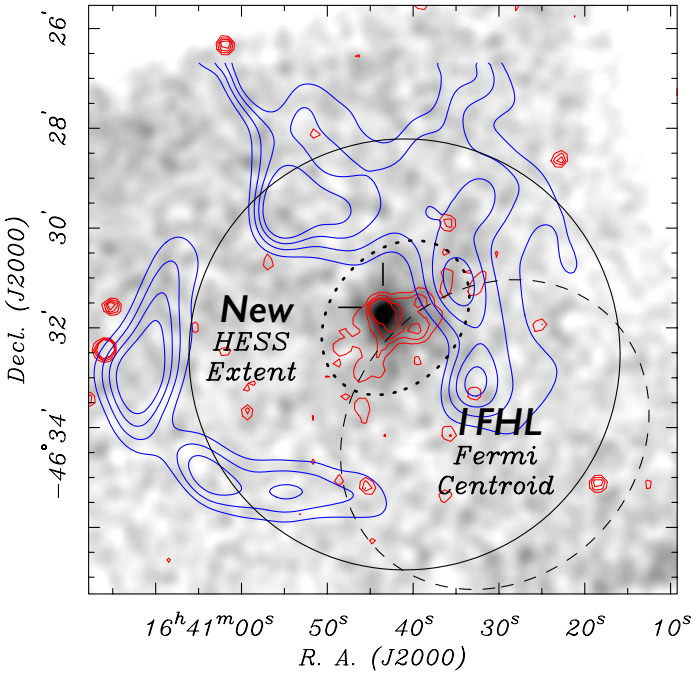
Pinpointing counterparts in a complex local Galactic environment



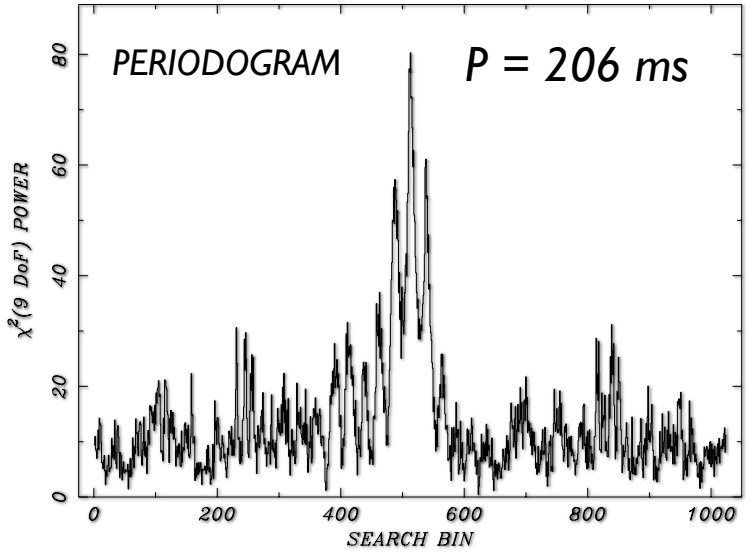
From Castelletti et al. (2011)

NuSTAR observations of HESS J1640-465

HESS J1640-465 observed as part of NuSTAR Norma Survey



Sep 29 2013: 3x50 ks exposures

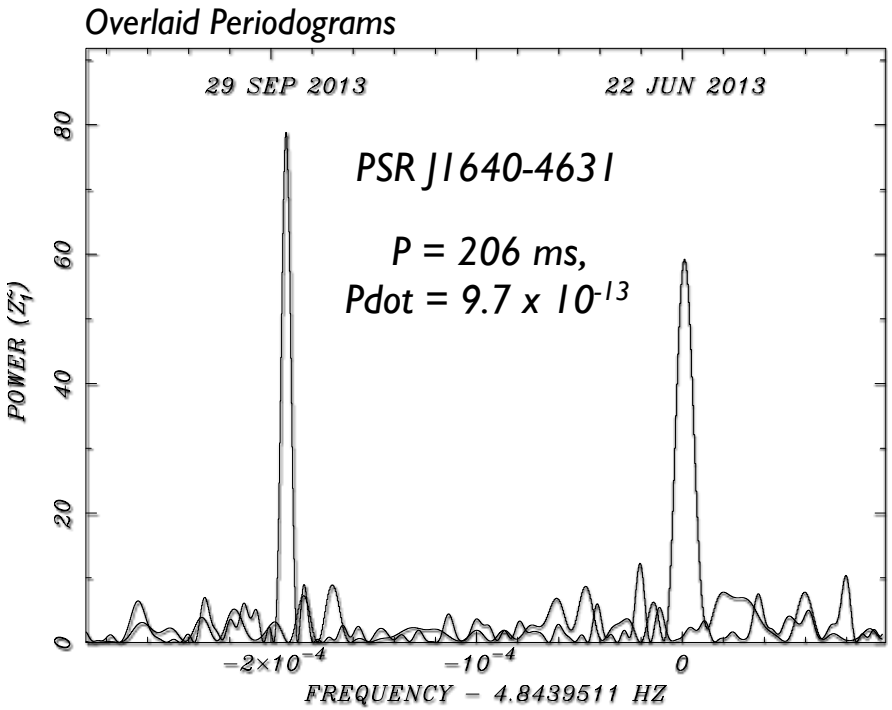


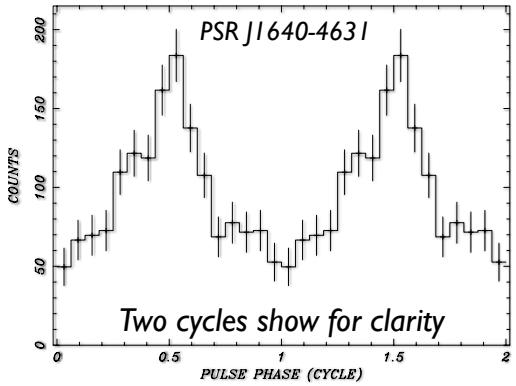
FFT of light curve yields a significant signal (~7 sigma), but not conclusive because not evident in all pointings/telescopes - large variance or spurious? New mission caution…

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





τ = 3350 yr

$\dot{E}$ = 4.4 x 10^{36} !!

B_s = 1.4 x 10^{13} G

$L\gamma$(0.2-10 TeV) / $\dot{E}$ = 6%

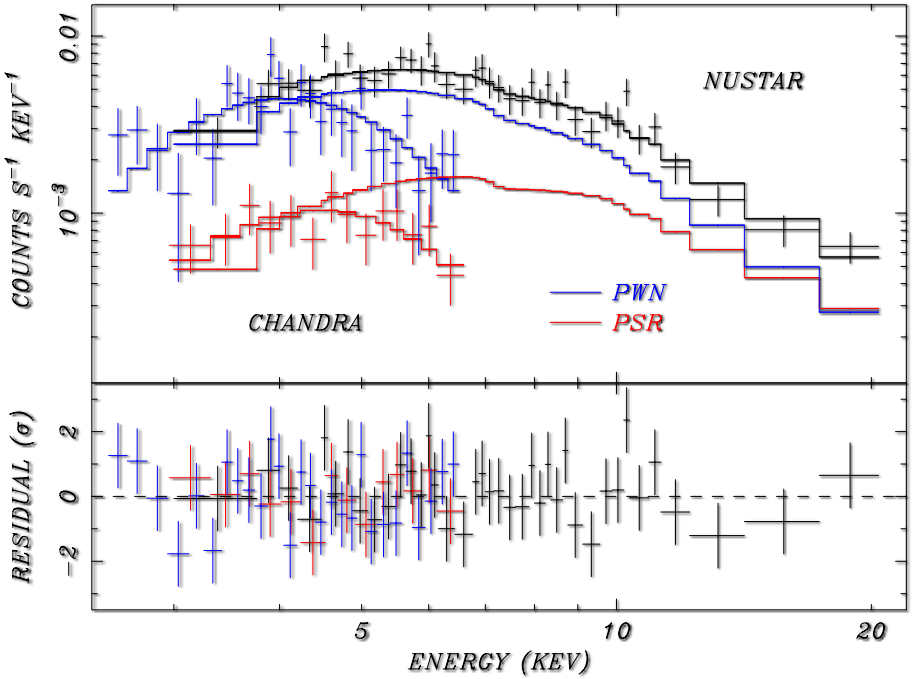
PSR J1640-4631: young, energetic pulsar sufficient to power HESS J1640-465

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.

Parameter	*Chandra* only	*Chandra* +*NuSTAR*
$N_{\rm H}$ (cm^{-2})	$(1.2 \pm 0.6) \times 10^{23}$	$(1.8 \pm 0.6) \times 10^{23}$
$\Gamma_{\rm PSR}$	$1.2^{+0.9}_{-0.8}$	$1.3^{+0.9}_{-0.5}$
$F_{\rm PSR}$ (2–10 keV)	$1.9^{+0.2}_{-1.4} \times 10^{-13}$	$(1.8 \pm 0.4) \times 10^{-13}$
$\Gamma_{\rm PWN}$	$2.3^{+1.2}_{-1.0}$	$2.2^{+0.7}_{-0.4}$
$F_{\rm PWN}$ (2–10 keV)	$5.4^{+0.6}_{-2.3} \times 10^{-13}$	$(5.5 \pm 0.8) \times 10^{-13}$
χ^2_ν (dof)	1.0 (56)	0.82 (79)

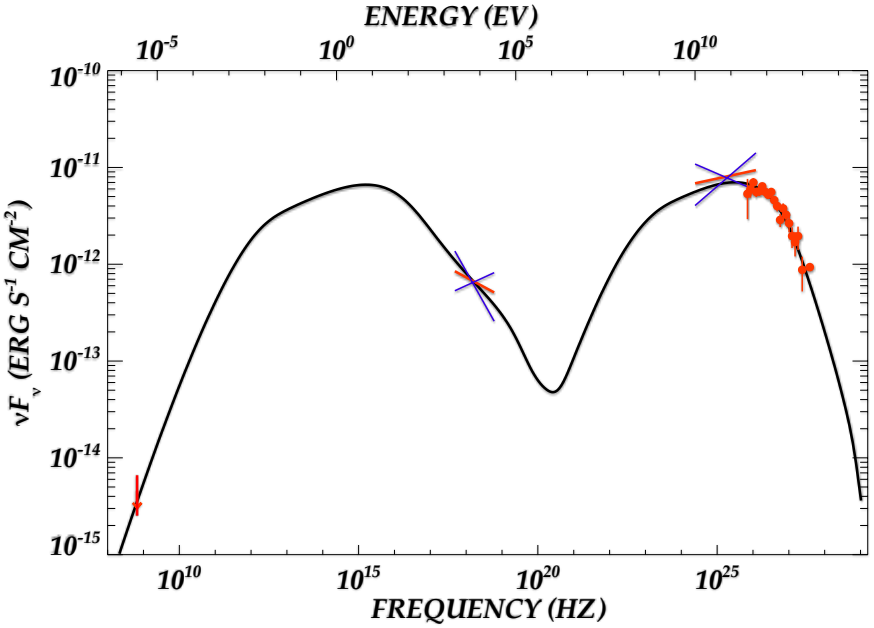
F(0.2-10 TeV) / F(2-10 keV) = 13

IC losses now dominate over synchrotron emission (for leptonic model)

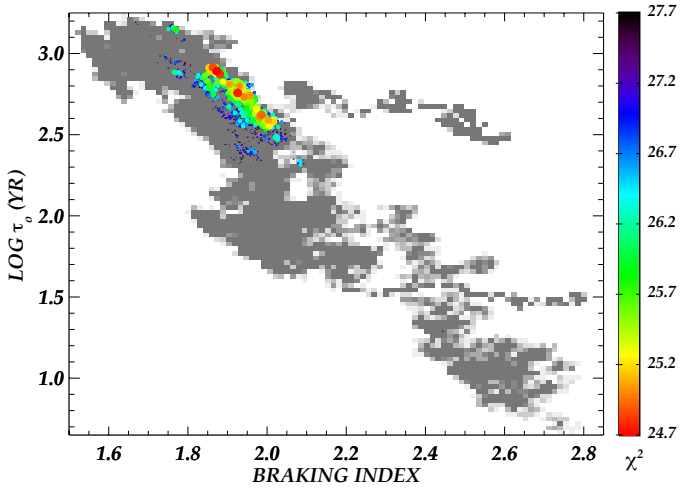
Latest SED Modeling of HESS J1640-465

(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*



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

Fit results:
E_{min} = TeV
E_{max} = 1.3 PeV
α = 0.017

Initial values:
P_o = 15 ms
$\dot{E}_o$ = 10^{40}
E_o = 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 ~2 and initial P_o ~ 15 ms

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

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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