Discovery of a Pulsar Wind Nebula Around B0950+08

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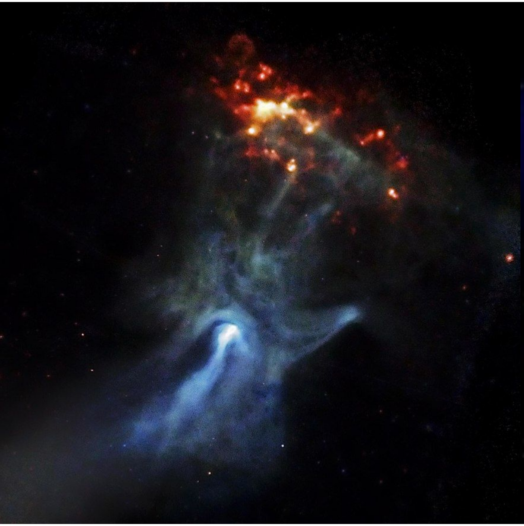


B1509-58: x-ray
(NASA/CXC/CfA/P. Slane et al.)

Crab Nebula: optical, x-ray
(NASA/HST/ASU/J. Hester et al.)

3C58: radio, x-ray
(x-ray: NASA/CXC/SAO/P. Slane et al.
radio: NCSU/S. Reynolds)

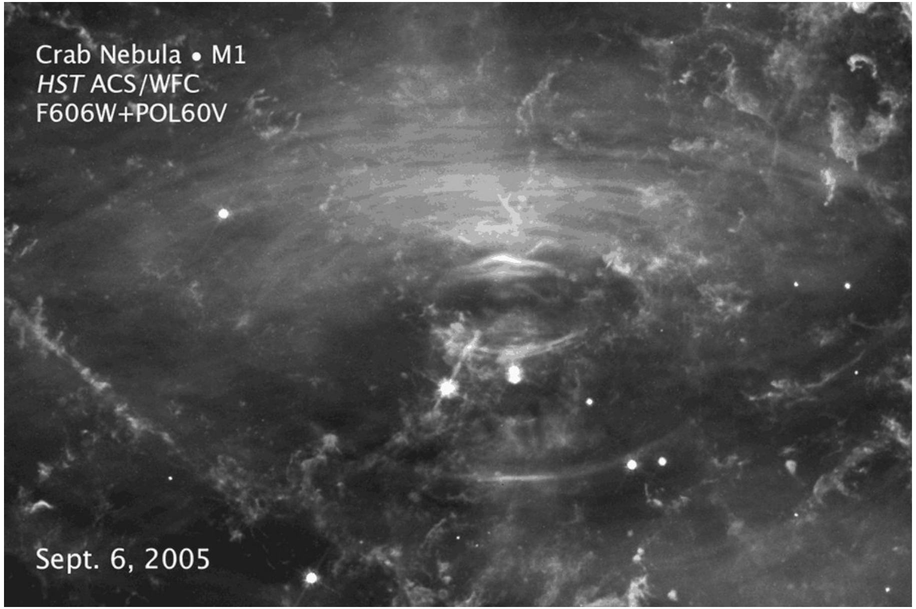
B0950+08
?

UNM
NSF

Outline

- Overview of PWNe (formation, spectra) & B0950+08
- Observation of B0950+08 with the ELWA
- Image Analysis to characterize flux density and shape
- Discussion of results with previous work
- Conclusion

Overview of PWNe - formation



Crab Nebula (optical) dissipating energy in wave-like structures.
NASA/ESA/ASU/J. Hester.

Similar to solar winds!

(Slane 2017) Ram pressure of wind balanced by PWN's pressure. Typically 0.1 - 1 pc in size

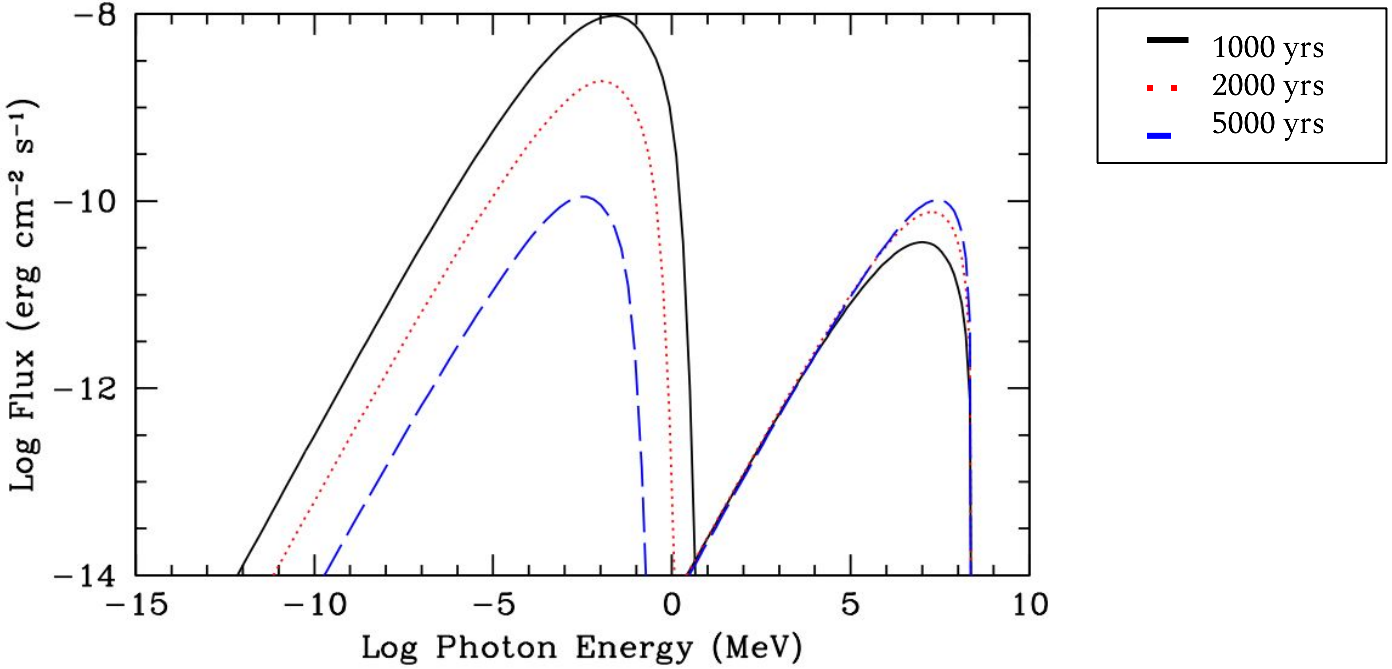
$$R_{TS} \propto \sqrt{\frac{\dot{E}}{P_{PWN}}}$$

(Chevalier 1977) Before RS interaction, evolves like:

$$R_{PWN} \approx 1.5\dot{E}^{1/5} E_{SN}^{3/10} M_{ej}^{-1/2} t^{6/5}$$

Spectra and Age of PWNe $(S_\nu \propto \nu^\alpha)$

(Weiler & Sramek 1988) 100 MHz to 10 GHz, spectral index $-0.5 < \alpha < 0$



(Slane 2017) With time, spectra shifts from synchrotron to IC dominated.

Spectra and Age of PWNe

(Zhang et al. 2008) Modeled spectrum for PWN

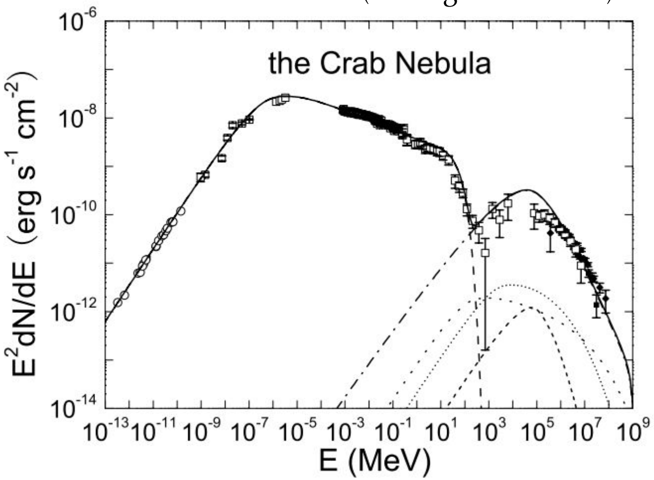
$$\frac{dN}{dE_e} = \int_0^{T_{age}} Q(E_e,t)exp(\frac{T_{age}-t}{\tau_{eff}})dt$$

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{syn}} + \frac{1}{\tau_{esc}}$$ accounting for $\frac{1}{\tau_{esc}} \propto \frac{1}{R^2_{PWN}}$

amount of injected electrons:

$$Q(E_e,t) = Q_0(t)(\frac{E_e}{E_b})^{\alpha_x}$$

(Zhang et al. 2008)



$\alpha_R \approx -0.3$

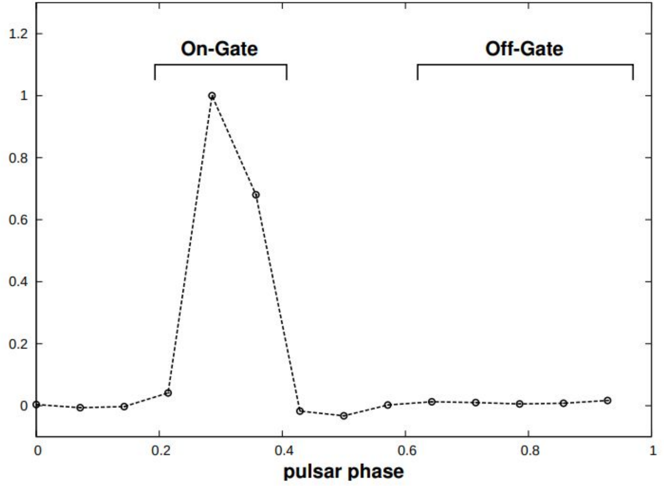
(Gaensler et al. 2000) Radio survey for PWNe with pulsars $\{t_3 < 50$ kyrs $\dot{E} > 50 \times 10^{34}$ ergs/s$\}$, concluded none observed since:

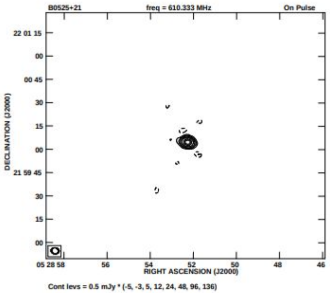
$$n_{ISM} \sim 0.003 \text{ cm}^{-3}, \eta_R = \frac{L_R}{\dot{E}} < 10^{-5}$$

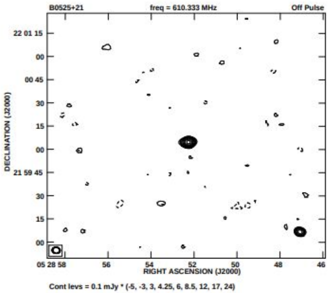
(Kargaltsev & Pavlov 2010) X-ray study, correlation of η_X and $\tau = \frac{P}{(n-1)\dot{P}}$ weakened w/ larger sample size, concluded may rely on geometric factors

Off-pulse Emission

Usually associated with young pulsars and PWNe.







(Basu et al. 2012) Detected off-pulse emission w/ GMRT ($\theta_{res} \sim 4$ ") at 325 and 610 MHz from B0525+21 and B2045-16:

Max angular size: $\theta_{max} \sim \lambda / D_r$

Utilized refractive timescale: $T_r = \frac{D_r}{v_{trans}(1-\beta)}$

$$\beta = \frac{D_s}{D_0} \approx 0.5$$

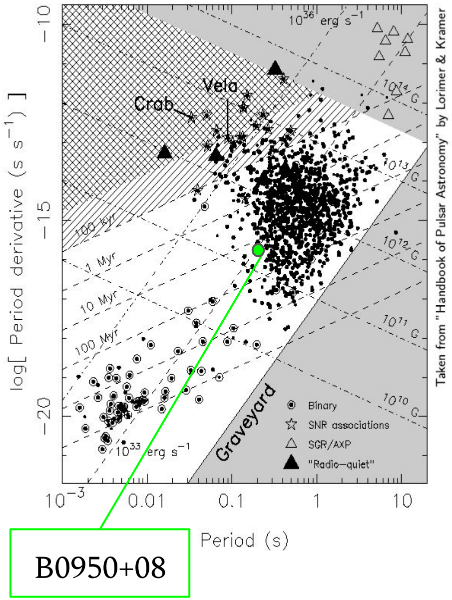
Radius of light cylinder: $R_{LC} = \frac{Pc}{2\pi}$

Concluded magnetospheric in origin:

- extends at most 14.7 R_{LC} ,
- Spectral indices $|\alpha| > 1$

B0950+08

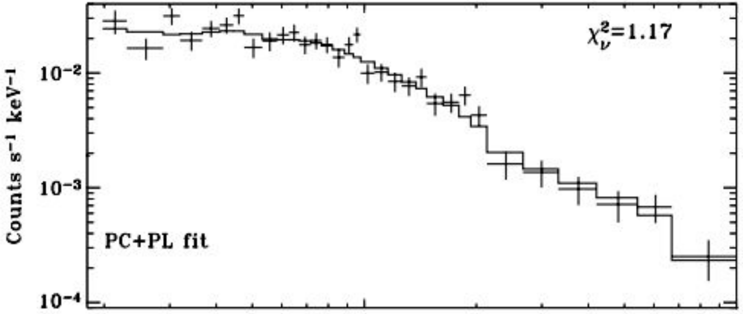
$d = 0.262\,\text{kpc}$, $P = 0.253$ s, $\dot{P} = 2.29 \times 10^{-16}$, $\tau \approx 17$ Myr



(Lorimer & Kramer 2005)

(Zavlin & Pavlov 2004) XMM-Newton observation: X-ray emission from thermal and non-thermal components, possibly H atmosphere at PCs

- BB fit to thermal component: $T \approx 1$ MK



(Rudak & Dyks 1998) Compared CGRO data w/ Sturrock pair PC model, B0950+08 and B0656+14 outliers with lower luminosity limits than predicted

(Igoshev 2018) Joint maximum likelihood for kinematic age & magnetic cooling age, found $\tau \approx 2$ Myr , $t_{dec} \approx 5$ Myr, $n \approx -2.3 \times 10^3$

Observations with the ELWA

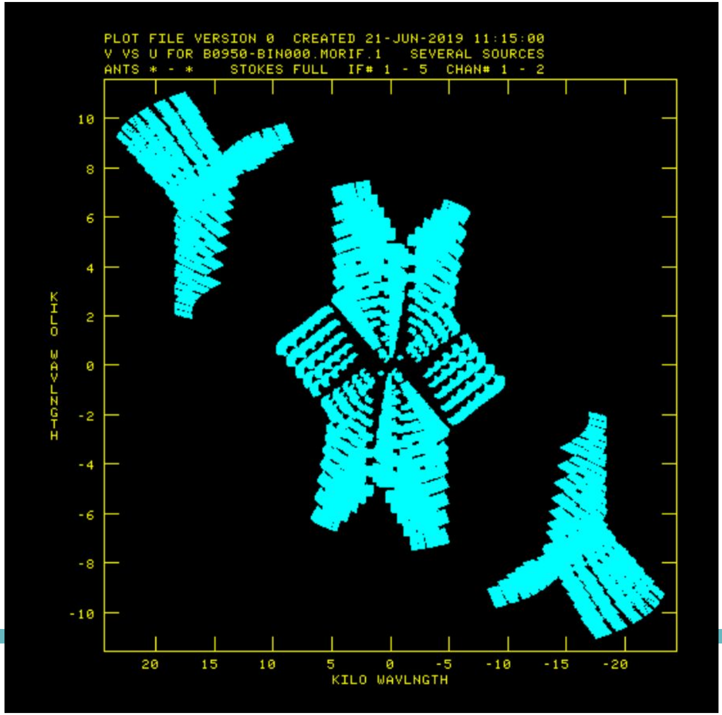
(Dowell et al. 2012) With the updated LWA Software Library:

- Heterogenous array of 2 LWA stations (LWA1, LWA-SV) and 22 VLA antennas ($b \sim 99\,\mathrm{km}$)
- Pulsar binning correlator mode

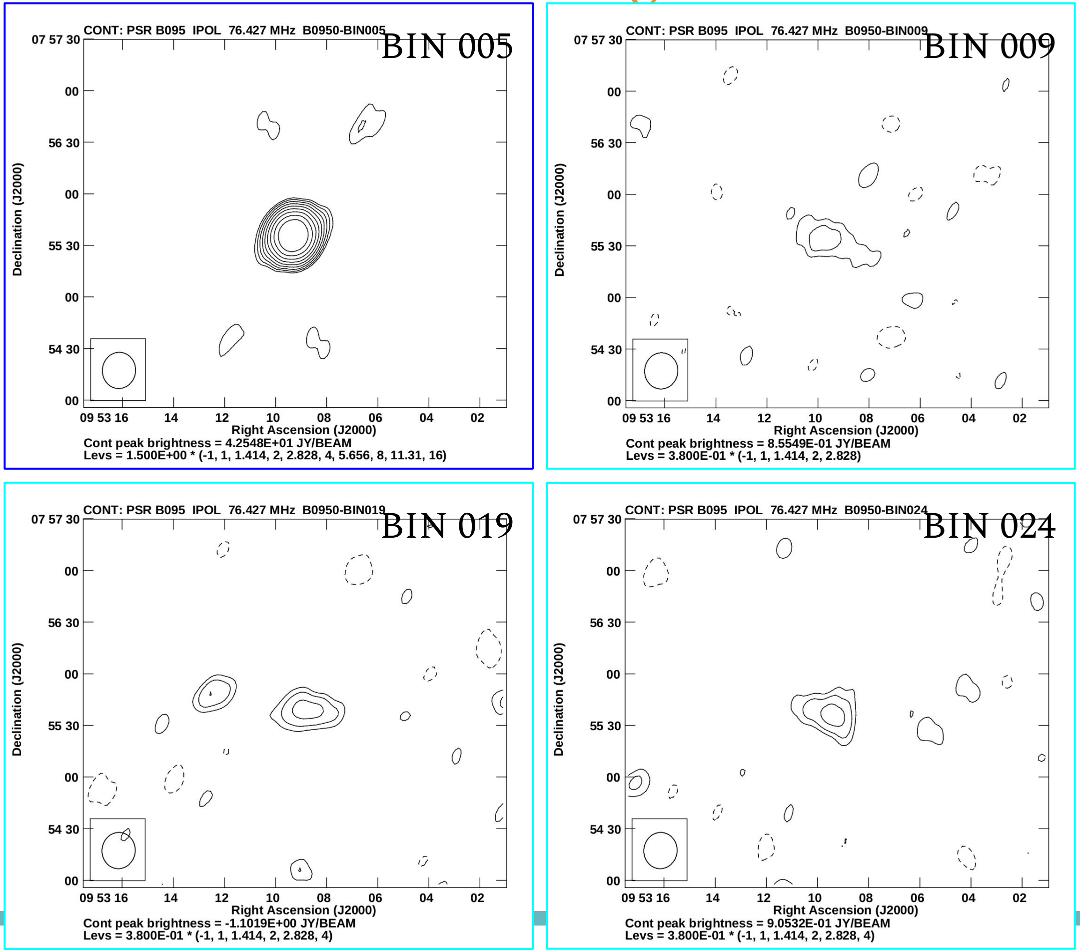
Observed at 76 MHz ($\theta_{res} \approx 8.2$ ")
31 December 2018, 6 hr run
(2.5 hr on B0950+08)
flux calibrator: 3C286
phase & bandpass calibrator: Virgo A (M87)

Self-calibration w/ nearby AGN

(Joe Craig)



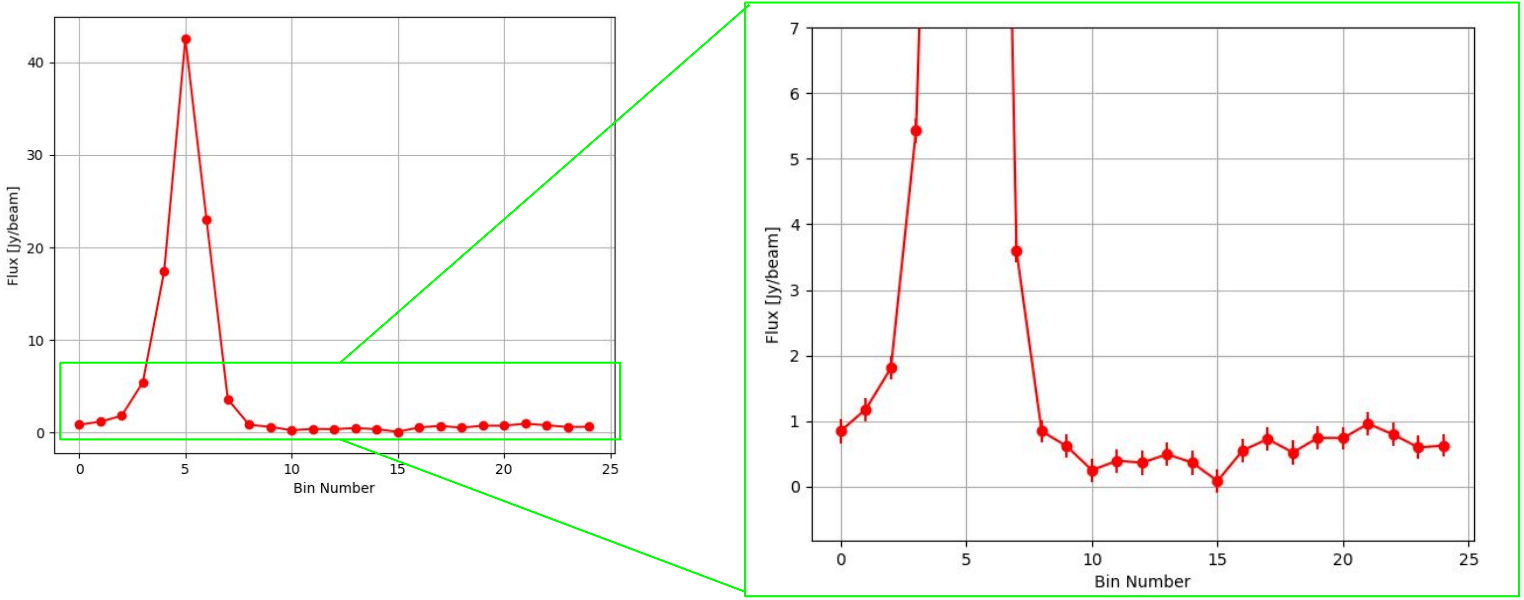
Characterizing the Flux Density



‘On’ bins: 1-7
‘Off’ bins: 0, 8-24
brightest in bin 5

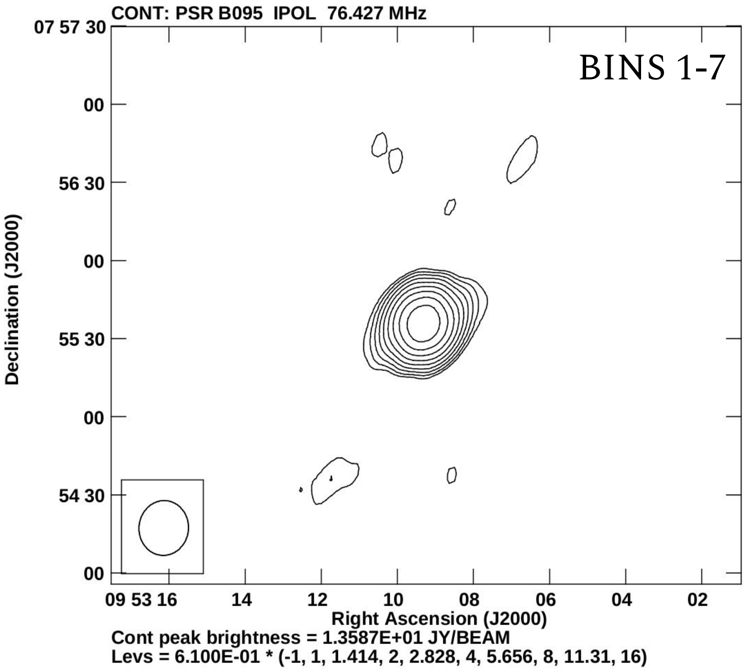
beamsize: 25 ”

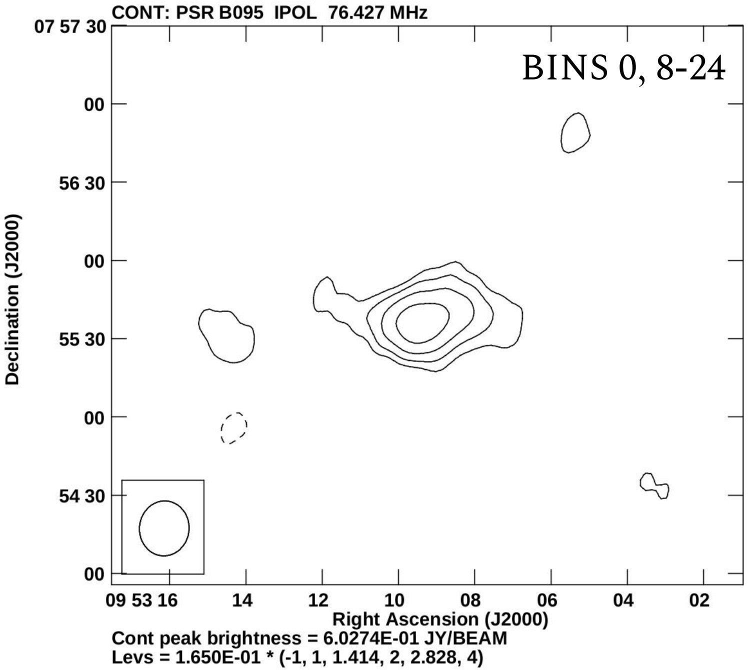
Characterizing the Flux Density



Peak flux: 42.3 ± 0.26 Jy/beam
Avg off bin flux: 0.59 ± 0.05 Jy/beam

Total Intensity Images

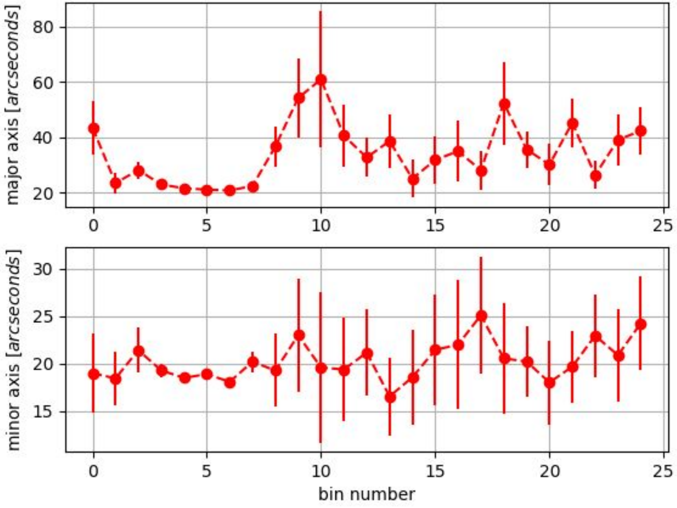


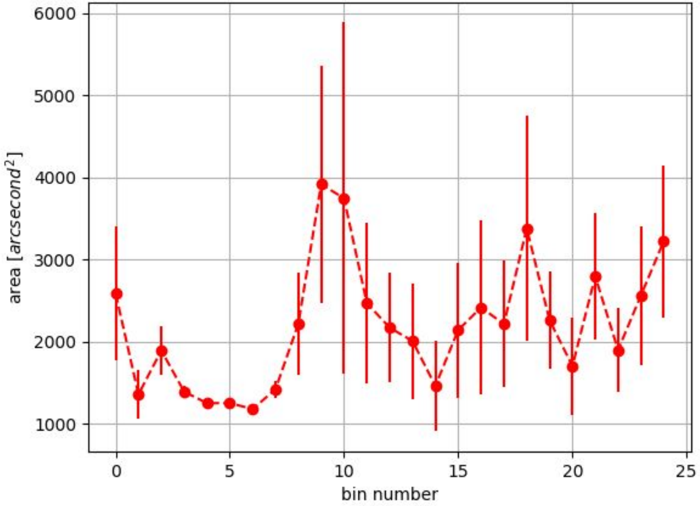


major: 21 ± 0.16 ”
minor: 19 ± 0.14 ”

major: 61 ± 6 ”
minor: 30 ± 3 ”

Shape by phase





$$\frac{major_{OFF}}{major_5} \approx 1.84 \pm 0.45$$

$$\frac{area_{OFF}}{area_5} \approx 2.0 \pm 1.4$$

$R_{LC-B0950} = 1.2 \times 10^4\,\text{km}$

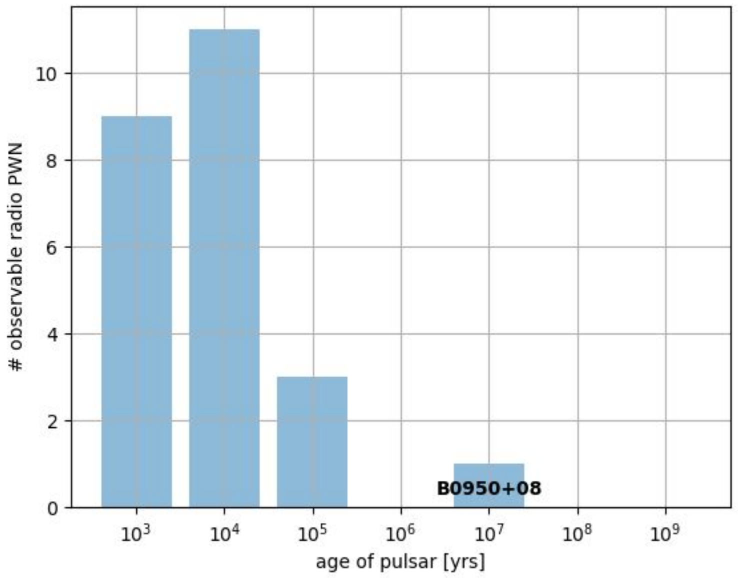
Major axis of off-pulse emission:

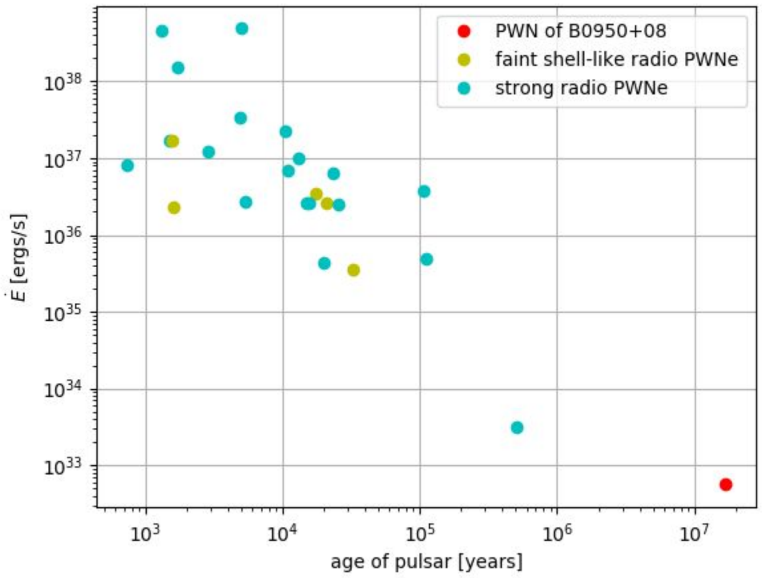
$2.4 \pm 0.24 \times 10^{12}$ km $(10^8 R_{LC})$

$0.08 \pm 0.008\,\text{pc}$

Based on the flux $(0.59 \pm 0.05$ Jy/beam) and size $(10^8 R_{LC})$, conclude this emission is from a PWN!

Observed Radio PWNe





(ATNF and the Pulsar Wind Nebula Catalog)

Electron density of local ISM

(Gaensler et al. 2000) If any PWNe, not observable in radio if low transverse motion and $n_{ISM} \sim 0.003 \text{ cm}^{-3}$

(Cordes & Lazio 2002, Paper I) Model for electron density of local ISM

- contributions from local superbubble (LSB), local hot bubble (LHB), loop I, low density region (LDR)

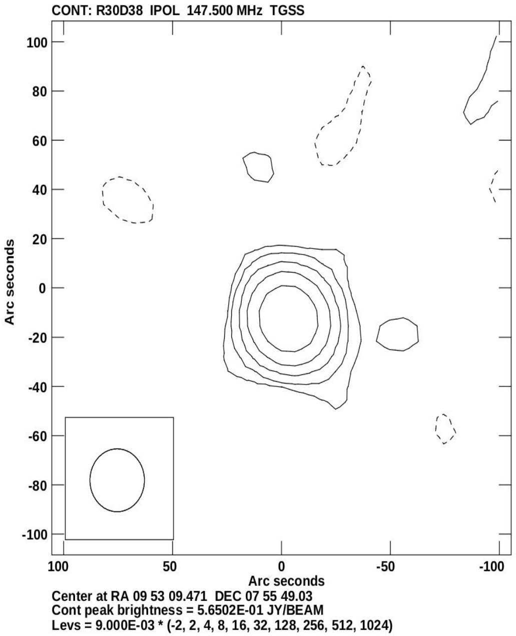
$$n_{lism}(x) = (1 - w_{lhb})\{(1 - w_{loopI})[(1 - w_{lsb})n_{ldr}(x) + w_{lsb}n_{lsb}(x)] + w_{loopI}n_{loopI}(x)\} + w_{lhb}n_{lhb}(x)$$

weighting factors $(w_{lsb}, w_{lhb}, w_{loopI}, w_{ldr})$ ranging from 0 to 1

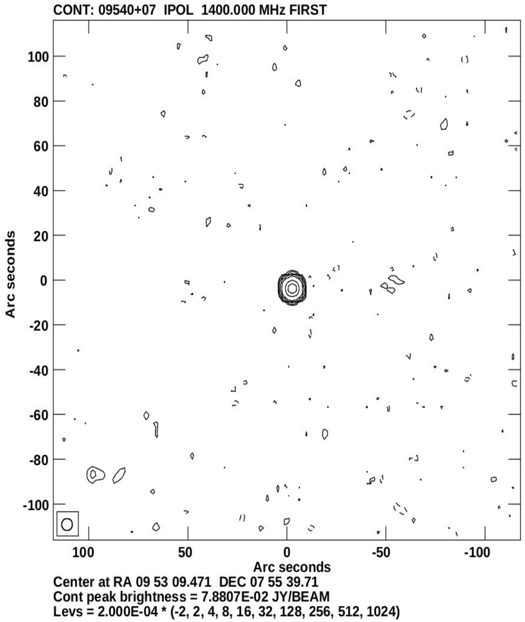
(Cordes & Lazio 2003, Paper II) Estimated the dominant components in LOS to B0950+08: LSB and LHB, let $w_{lsb} = w_{lhb} = 0.9$

$$n_{lism} \approx 0.0061 \text{ cm}^{-3}$$

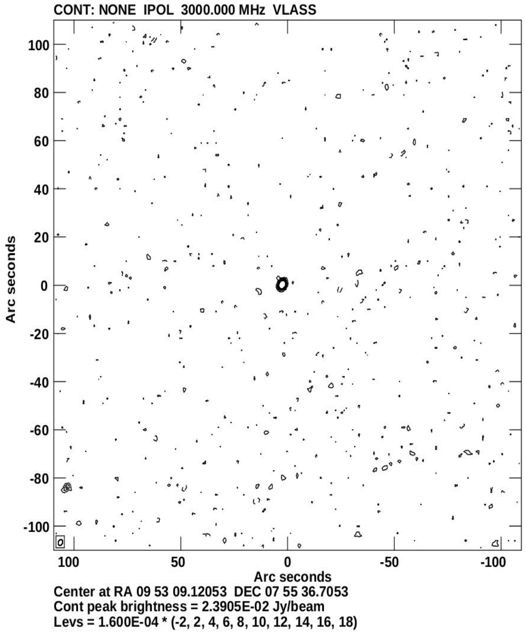
Radio Surveys with B0950+08



TGSS (Intema et al. 2016)
beamsize: 24 ”
size: 30 ”

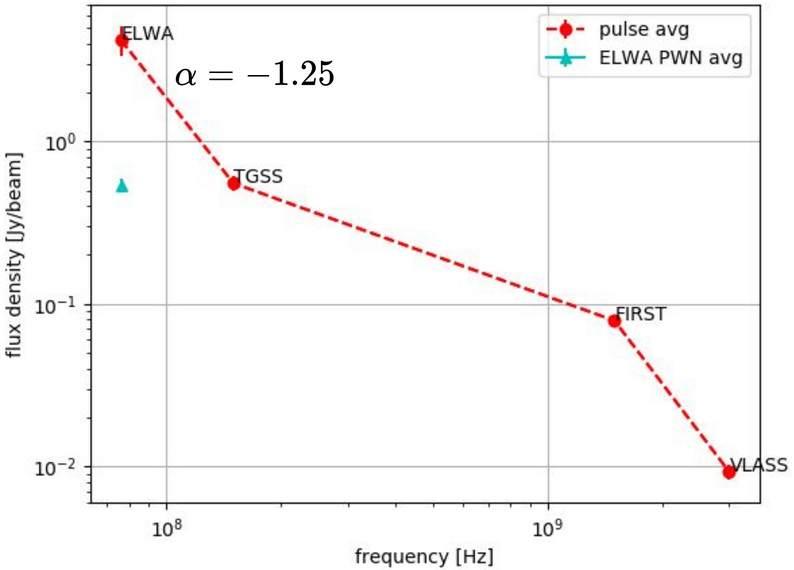


FIRST (Becker et al. 1994)
beamsize: 6 ”
size: 5 ”



VLASS (Lacy et al., in prep)
beamsize: 5 ”
size: 3 ”

survey	frequency [GHz]	resolution ["]	pulse average [Jy/beam]	σ_{err} [Jy/beam]
ELWA	0.076	8.2	4.22 ± 0.11	0.13
TGSS	0.15	16.5	0.60 ± 0.008	0.056
FIRST	1.5	3.72	0.083 ± 0.0002	0.0039
VLASS	3	2.79	0.0094 ± 0.0013	0.0010



$$\sigma_{err} = \sqrt{\sigma_{sys}^2 + \sigma_{noise}^2}$$

System noise percentages:
ELWA: 20 %
TGSS (Intema et al. 2016): 10 %
FIRST (Thyagarajan et al. 2011): 5%
VLASS (version 1.1, T12t15): 11%

Summary & Future Work

B0950+08 has off-pulse emission associated with it, observable at 76 MHz with imaging analysis and pulsar binning techniques. Due to the average off-pulse flux density and size, conclude PWN.

Gives new range on age of pulsars with radio PWNe
($10^3 - 10^7$ yr)

- Gated observations at higher frequencies for B0950+08 to confirm this detection AND find accurate spectral index
- Radio surveys of other older pulsars with PWNe
- X-ray / Gamma ray observations could also confirm