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Deriving Pulsar Properties from Multi-Wavelength Observations

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PWNe

- PWNe are the most numerous class of galactic gamma-ray sources at TeV energies (~40% of known emitters).
- A key question is whether emission from PWNe is purely Inverse Compton, or if there's a hadronic component.
- A key metric that determines if hadrons can escape the pulsar into the PWN is the pair-production multiplicity.

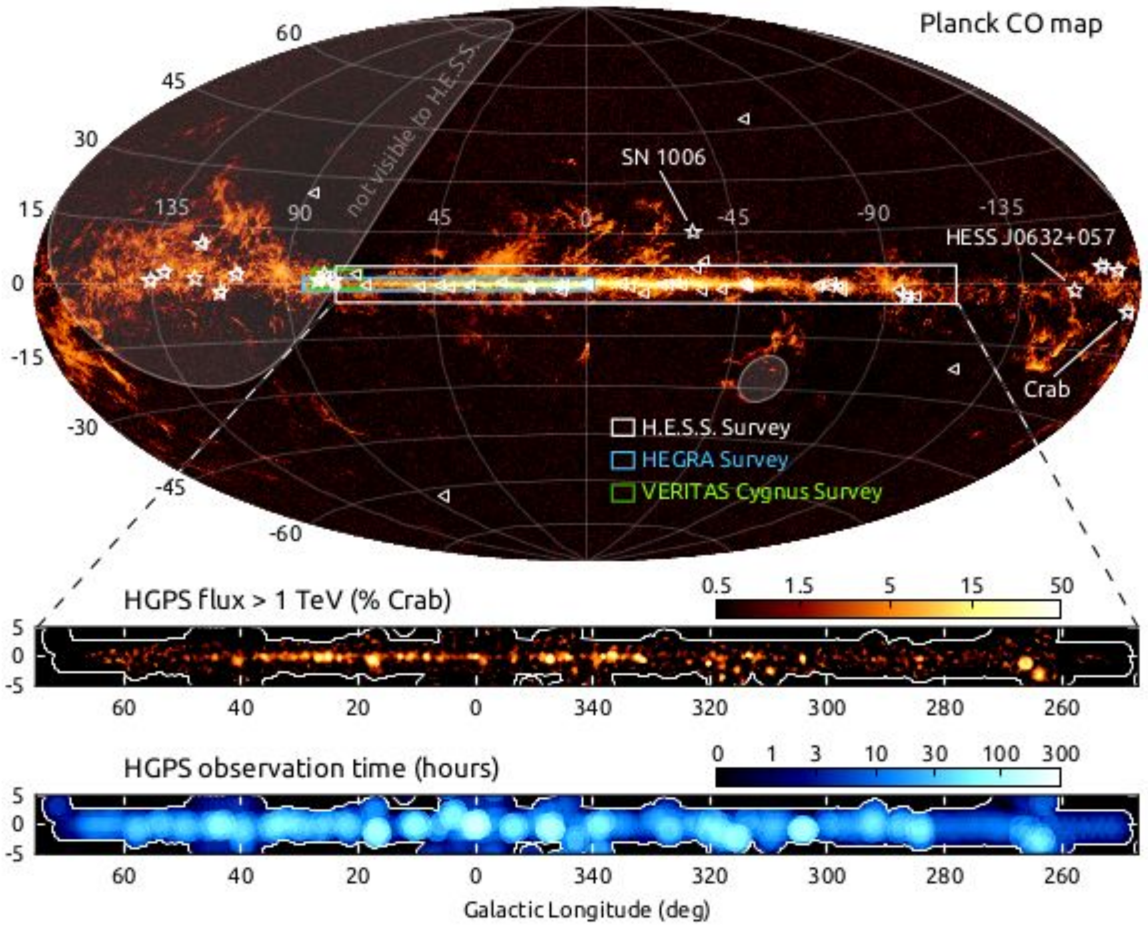


Image Credit: H.E.S.S. Collaboration

PWNe

- The pair production multiplicity (kappa) describes the number of e+/e- pairs that escape the light cylinder per electron that escapes the pulsar.
- Protons can only make up 1/kappa particles as they don't multiply in cascades in the pulsar magnetosphere.
- In this project, we aimed to constrain kappa for a population of pulsars that have been observed in the TeV and Radio.
- Built on previous work, just more sources.

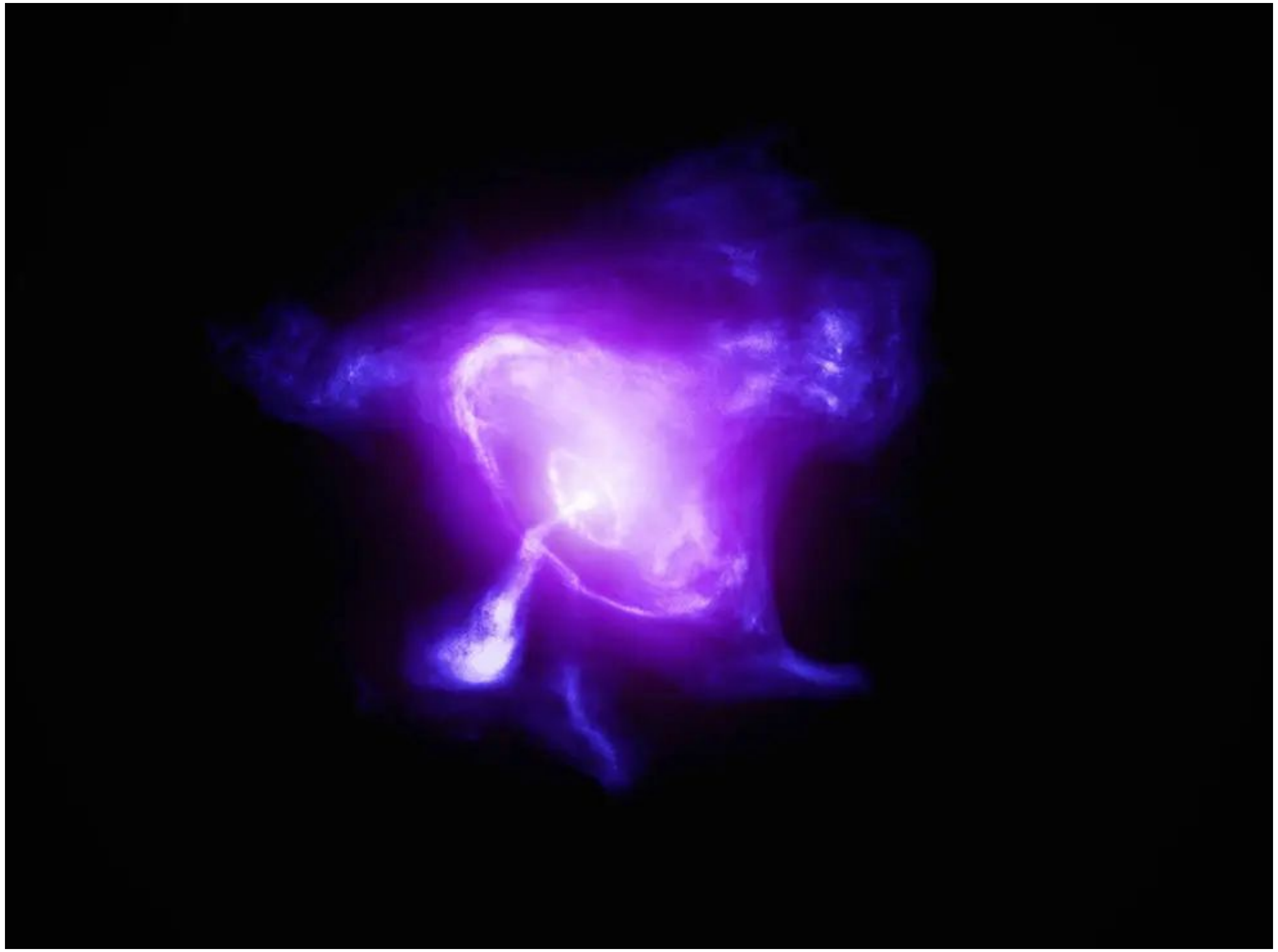


Image Credit: IXPE Collaboration

Relating Birth Period to Current Day Sizes

- Based on the simulation studies of Van der Swaluw and Wu (2001), one can estimate the birth period of a pulsar using this formula.

- Valid for spherically symmetric systems 10^3-10^4 years old.

- Makes use of the radio PWN and SNR radii to map the true extent of the PWN.

$$P_0 = 2\pi \left[\frac{2E_0}{\eta_1 I} \left(\frac{R_{PWN}}{\eta_3 R_{SNR}} \right)^3 + \left(\frac{2\pi}{P_t} \right)^2 \right]^{-1/2}$$

Relating Multiplicity to Electrons

- The Goldreich-Julian density represents the number of electrons stripped from the pulsar caps

$$N_{GJ} = \int_{t=0}^{t=-\tau(P_0)} \frac{[6c\dot{E}(t)]^{1/2}}{e}(-dt)$$

- We then assume the spin-down luminosity of the pulsar evolves as

$$\dot{E}(t) = \dot{E}_0\left(1 + \frac{t}{\tau_0}\right)^{-\frac{(n+1)}{(n-1)}}$$

- The pair production multiplicity is then

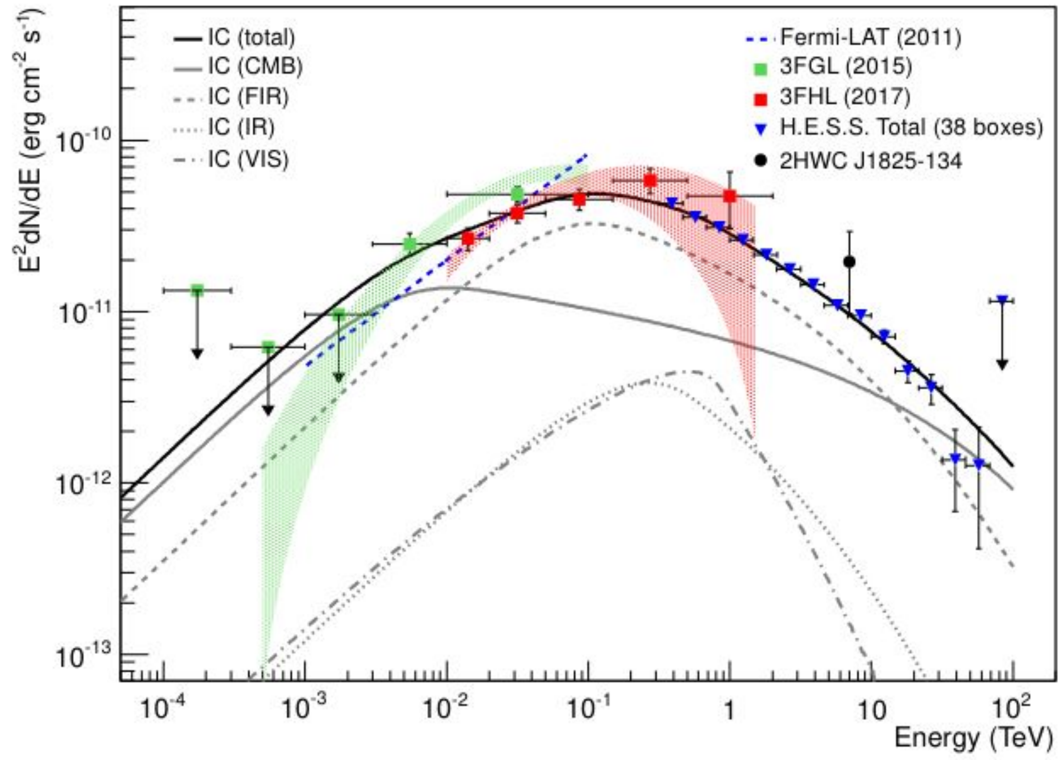
$$\langle\kappa\rangle = \frac{N_{el}}{2N_{GJ}}$$

- And the age of the pulsar is then

$$\tau(P_t, \dot{P}_t, P_0, n) = \left(1 - \left(\frac{P_0}{P_t}\right)^{n-1}\right) \times \frac{P_t}{(n-1)\dot{P}_t}$$

Obtained the Number of Electrons via Gamma-ray Data

- As the multiplicity depends on the GJ density, which depends on the pulsar age, which depends on the pulsar birth period, we can create curves of kappa as a function of P0.
- This is provided the number of electrons in the PWN is known.
- Use the previous modelling in the literature and to find this. Multiplicities are strictly lower limits because non-gamma-ray emitting electrons not considered.



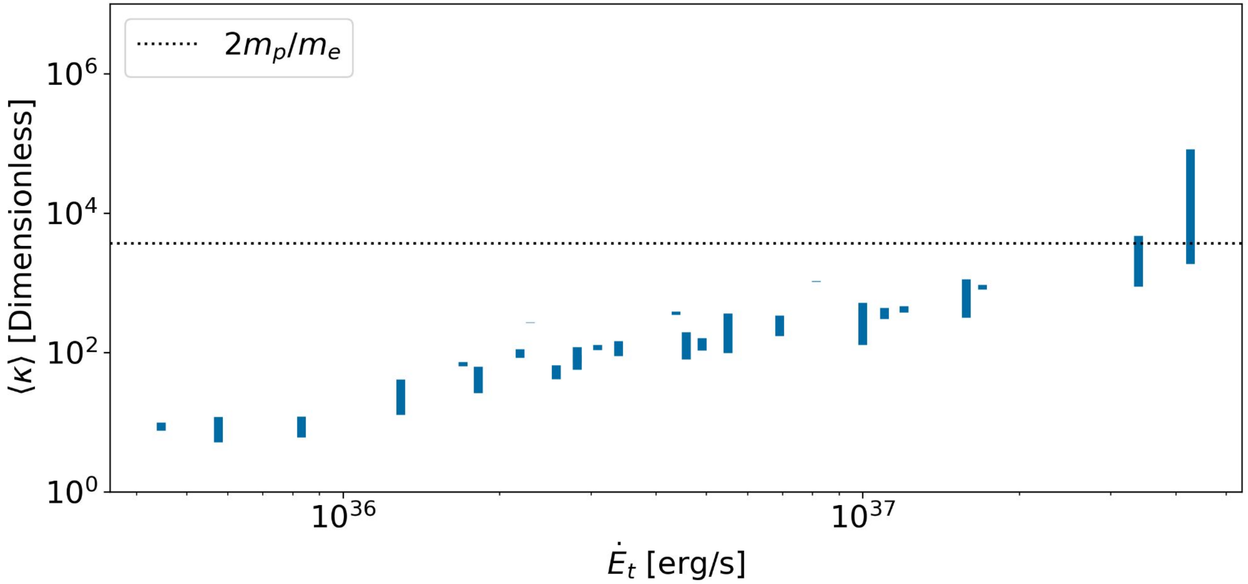
PSR J1826-1334, form H.E.S.S. Collaboration A&A 621, A116 (2019)

The Australia Telescope National Facility (ATNF) Catalogue

- As a first limit, we can estimate ranges of values for the lower limit of kappa for sources in the ATNF pulsar catalogue and the H.E.S.S. Galactic Plane Survey (HGPS).

- Assume birth period in the range 10-50ms.

- All sources in this sample have ranges that are compatible with hadrons escaping into the PWN (needs to have kappa below 2m_p/m_e (3672).



Giacinti et al. 2020

System	Crab	MSH 15-52	G21.5-0.9	G0.9+0.1	Vela X	G327.1-1.1	J1825-137	Geminga
Age (kyr) [(a)]	0.94	1.56	4.85	5.31	11.3	18	21.4	342
PSR [(b)]	B0531+21	B1509-58	J1833-1034	J1747–2809	B0833-45	[(c)]	B1823-13	J0633+1746
$\log(\dot{E})$ (erg s^{-1})	38.65	37.23	37.53	37.63	36.84	36.49	36.45	34.51
Distance (kpc)	2	4.4	4.1	8.5	0.28	9	3.93	0.25
R_{SNR} (pc)	? [(d)]	38.4	2.98	19.8	19.5	22	120	?
R_{PWN} (pc) [(e)]	2.8	19.2	0.8	2.5	12.2	10.5	?	0.01
$v \times t$ (pc) [(f)]	0.27	0.45	1.4	1.5	3.3	5.2	6.2	100
R_{TeV} (pc) [(g)]	<3	11	<4	<7	2.9	3	50	16.2
R_{X-ray} (pc)	0.24	10.2	0.8	4.9	3.08	13	9.1	0.15
Stage [(h)]	1	1	1b	1b	2	2	2b	3
Refs.	I	II	III	IV	V	VI	VII	VIII

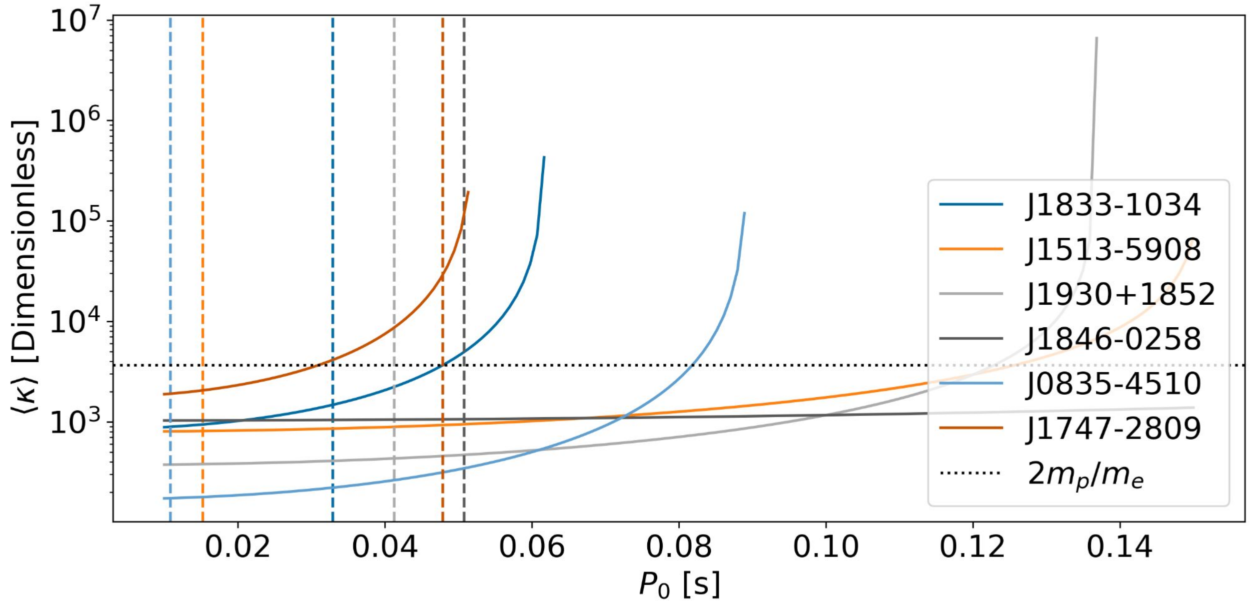
Collated table from Giacinti et al. 2020 (A&A 636, A113). Uses data from e.g. VLA to give us radii of SNR and PWN counterparts.

H.E.S.S. Sources

- Then for the six sources with measured PWN and SNR radii in both the radio, and seen by H.E.S.S., can calculate curves of kappa as a function of P0.

- Using the radio data, we can then estimate P0. Intersection point gives us (a lower limit for) kappa.

- For all except PSR J1747-2809, cannot exclude presence of hadrons in the PWN.



H.E.S.S. Sources

- For all except one source (PSR J1833-1034) we derive birth periods in the range 10-50ms that are broadly consistent with previous estimates (Helfland+ 2001, Camillo+ 2009).

- The value of 55ms we obtain for PSR J1833-1034 disagrees with Camillo+ 2009 who obtain 33ms, this is possibly because the system is too young for the Van der Swaluw+ approach to be valid.

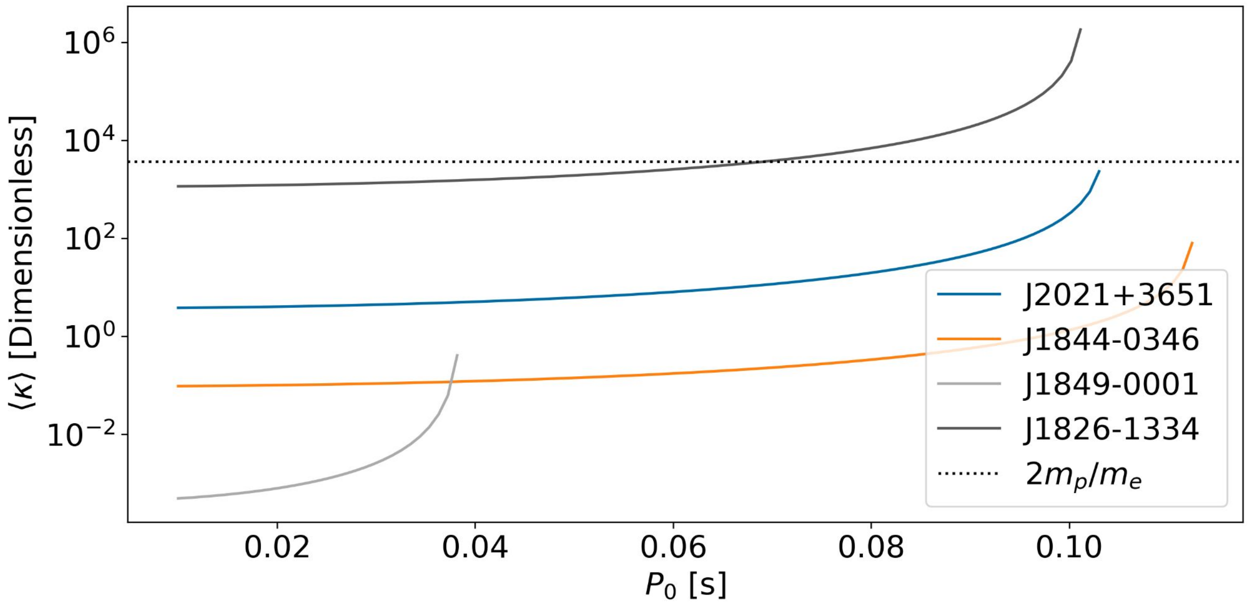
- We don't find any sources with ms birth periods, these have been proposed as potential PeVatrons in the past (Kotera+ 2015).

- Pair production multiplicity limits also reasonable, theoretical cap at 10^5 (Timokhin+ 2019).

LHAASO Sources

- Can utilise the same approach for sources recently observed by LHAASO.

- Again cannot exclude the possibility of hadronic escape for reasonable P0 values.



Conclusions

- Pulsar properties can be constrained using a mixture of radio and TeV data.

- We looked at a sample of 26 pulsars observed by ATNF, H.E.S.S. and LHAASO.

- For a subset of these sources, mostly reasonable estimates of P0 and kappa were found. But more radio measurements would allow for the properties of more systems to be constrained.

- PSR J1747-2809 is the only source for which we can exclude the possibility of hadronic escape into the associated PWNe.

Backup

Giacinti et al. 2020

Table 1. Properties of selected well-known PWN systems in different evolutionary stages, ordered according to the system age.

System	Crab	MSH 15-52	G21.5-0.9	G0.9+0.1	Vela X	G327.1-1.1	J1825-137	Geminga
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$\upsilon \times t$ (pc) [f]	0.27	0.45	1.4	1.5	3.3	5.2	6.2	100
R_{TeV} (pc) [g]	<3	11	<4	<7	2.9	3	50	16.2
R_{X-ray} (pc)	0.24	10.2	0.8	4.9	3.08	13	9.1	0.15
Stage [h]	1	1	1b	1b	2	2	2b	3
Refs.	I	II	III	IV	V	VI	VII	VIII

Notes. [a]The pulsar characteristic age is used for the age of the system, except where historical values are known. [b]Associated pulsar (PSR). Pulsar properties are taken from Manchester et al. (2005). [c]Putative pulsar candidate identified without pulsed emission detected by Temim et al. (2009). [d]Unknown quantities are marked by "?". [e]R_{PWN} is the size of the PWN in radio (as opposed to the radio SNR shell). [f]$\upsilon \times t$ is the pulsar kick velocity multiplied by the age of the system, where a value of 300 km s^{-1} is adopted for the velocity, corresponding to the average of known values (Hansen & Phinney 1997). [g]R_{TeV} is the one sigma radius taken from Abdalla et al. (2018b) for sources within the H.E.S.S. Galactic Plane Survey (HGPS), unless a reference is provided. [h]Stage of system evolution is assigned loosely based on age, which corresponds to Fig. 1.

References. I: Frail et al. (1995), Kargaltsev et al. (2015), II: Caswell et al. (1981), Du Plessis et al. (1995), Trussoni et al. (1996), Mineo et al. (2001); III: Matheson & Safi-Harb (2010), Safi-Harb et al. (2001); IV: Green (2014), Green (2017), Dubner et al. (2008), Porquet et al. (2003); V: Duncan et al. (1996), Dwarakanath (1991), Tibaldo et al. (2018); VI: Ma et al. (2016), Temim et al. (2015); VII: Stupar et al. (2008), Duvidovich et al. (2019), Pavlov et al. (2008), Uchiyama et al. (2009); VIII: Pellizzoni et al. (2011), Abeysekara et al. (2017a), Posselt et al. (2017), Caraveo et al. (2003).

Collated table from Giacinti et al. 2020 (A&A 636, A113). Uses data from e.g. VLA to give us radii of SNR and PWN counterparts.