Pulsar Wind Nebulae as seen in TeV γ-rays and their Galactic environments

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TeVPA 2019, Galactic Sources session
Sydney, December 3, 2019

PWN luminosities in TeV γ-rays

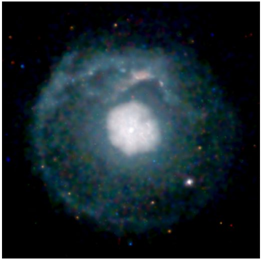
Galactic (far-infrared) interstellar radiation field

Offsets of TeV PWNe from their pulsar

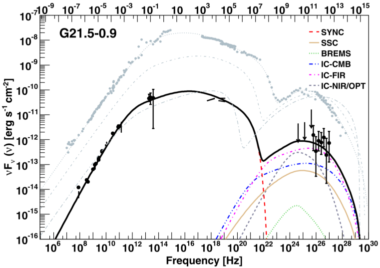
Interstellar medium (ISM) density contrasts

Pulsar Wind Nebulae and Supernova Remnants

- a **Pulsar Wind Nebula (PWN)** is a bubble of accelerated $e^{\pm}$ powered by a pulsar's relativistic wind
- when young, often surrounded by the blast wave of the birth supernova, a shell-type **Supernova Remnant (SNR)**
- SNR shell + PWN = **composite** SNR, e.g. G 21.5–0.9 :



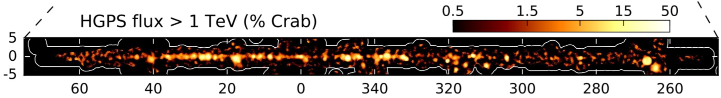
X-ray *(Chandra)* image



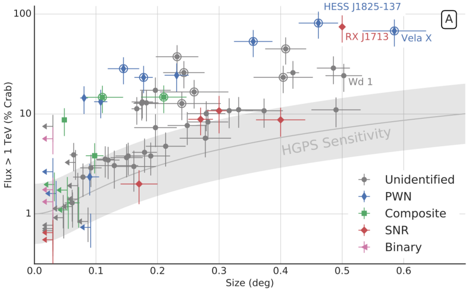
PWN model by Torres et al. (2014)

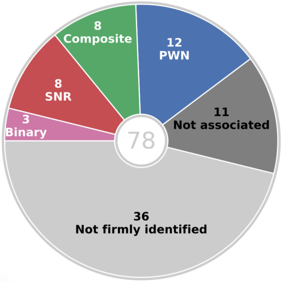
- radio to > X-rays : synchrotron emission
- gamma-rays : Inverse Compton emission

HESS Galactic Plane Survey (HGPS)



- $+75^\circ > \ell > -115^\circ$, exposure highly non-uniform (HESS Coll. 2018a)
- 78 sources in HGPS catalog, of which 40% identified
- identifications based on position, morphology and/or variability
- 90% of identifications are either PWNe, shell or composite SNRs
- 14 identified as PWNe of known pulsars, +5 outside HGPS

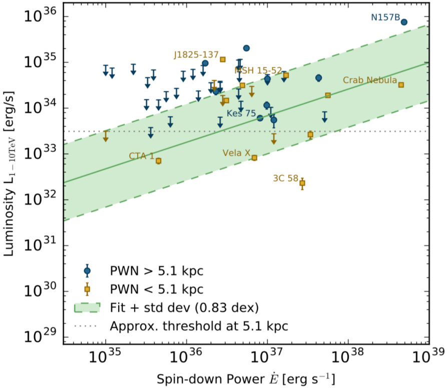




TeV γ-ray luminosity distribution of PWNe

- PWN TeV luminosities $L_\gamma = 4\pi D^2 F_{1-10\,\mathrm{TeV}}$, vs. (current) pulsar spin-down energy loss $\dot{E}$

(HESS Coll. 2018b; arXiv:1702.08280)



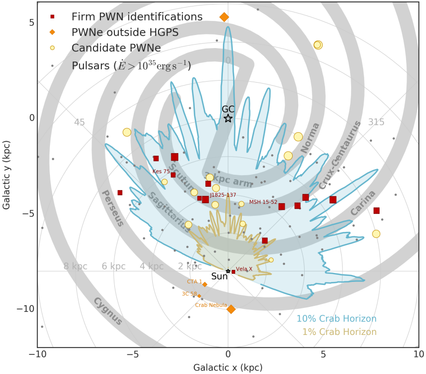
- relatively narrow range of L_γ ($\gtrsim$1 decade, with outliers)
- weak correlation with $\dot{E}$, unlike L_X (Grenier 2009, Mattana+ 2009)
- add HGPS upper limits $\Rightarrow$ significant faintening as $\dot{E}$ decreases

Galactic distribution of TeV PWNe

- PWNe trace recent massive star formation (spiral arms)

(Klepser et al. 2017, HESS ;

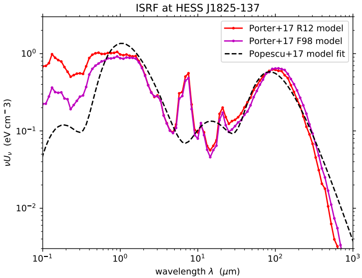
symbol size $\propto L_\gamma$)

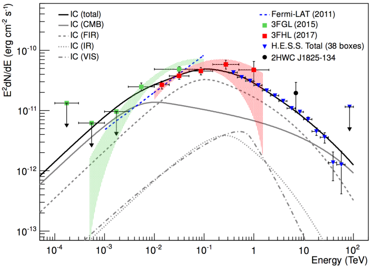


- HGPS detectability quite good to **Scutum-Crux** (Centaurus) arm
- deficit of TeV-emitting PWNe in Sagittarius-Carina arm ?
- PWNe in outer Galaxy (Vela X, 3C 58...) have low luminosities
- consequence of PWN parameters or of Galactic environment ?

Galactic photon distribution and IC emission

- e.g. HESS J1825–137 in Scutum-Crux arm (talk by A. Mitchell)
- self-consistent models of Galactic (interstellar) radiation field (ISRF) by Porter et al. (2017) and Popescu et al. (2017) yield very similar results at HESS J1825–137 position (left panel)

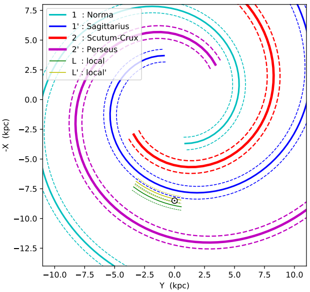


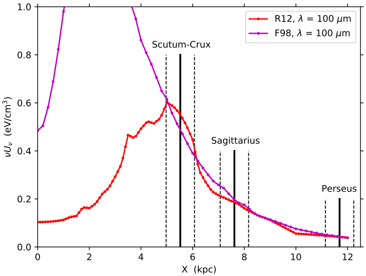


- inverse Compton γ-ray emission model (HESS Coll. 2019) shows that far-infrared (FIR) is dominant target photon component
- stellar photon contribution suppressed by Klein-Nishina effects at TeV energies (UV component even more so)

Spiral arms and Galactic photon density

- Porter et al.'s R12 includes spiral arm model of Robitaille et al. (2012)
- 4 arms, but 2 dominant : 2 and $2'$, i.e. **Scutum-Crux** and Perseus which have enhanced stellar emissivity (young, newly formed stars)



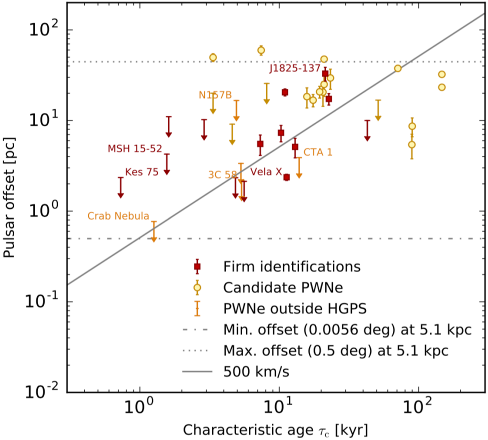


energy density vs. $R_{\rm Gal}$ at $Y = Z = 0$

- Porter et al.'s calculations show mild arm-interarm contrast
- but large decrease in FIR density (factor $\gtrsim 4$) between $R \approx 5\,$kpc (Scutum-Crux) and $R \gtrsim 8.5\,$kpc (outer Galaxy)
- a sufficiently large and deep TeV PWN sample (as obtained by CTA) could probe FIR photon density throughout the Galaxy ?

TeV PWN offsets vs. age

- older TeV PWNe have **large** offsets from their pulsar



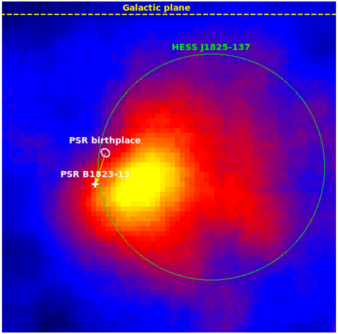
(H.E.S.S. Coll. 2018b; `arXiv:1702.08280`)

- cannot be explained solely by typical pulsar proper motions (observed distribution implies $v_\perp < 500$ km/s for most)

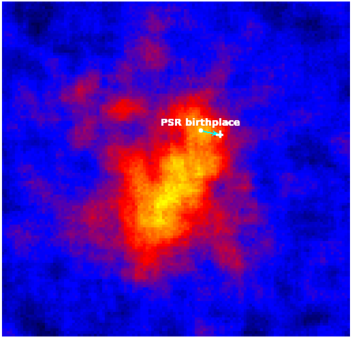
Pulsar proper motions don't explain the offsets

- 8 significantly offset TeV PWNe in population study
- from these, 2 pulsars have **measured** proper motions :

HESS J1825–137



Vela X



HGPS (public) significance maps

- velocity not only too small, but not in the right direction !
- alternative/complementary effect of asymmetric environment ?
- no systematic trend relative to Galactic plane. . .

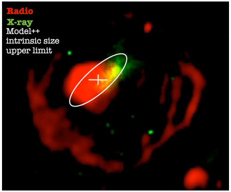
Offsets from asymmetric medium around SNR

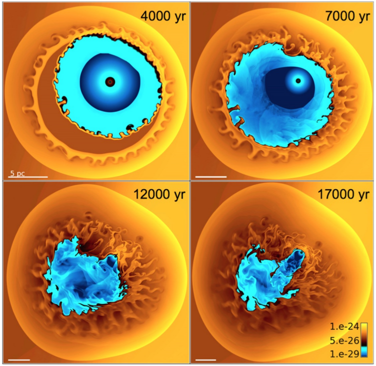
- proposed to explain offset of **Vela X** (Blondin et al. 2001)

G327.1–1.1

simulations →
(Temim et al. 2015)

multiwavelength image
(Acero et al. 2011) ↓

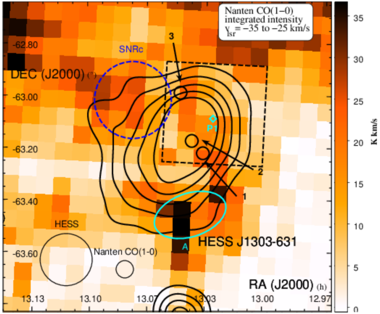




- Temim et al. simulations have pulsar moving 400 km/s toward top (N), higher density to the right (W)
- asymmetric reverse shock interaction “crushes”, displaces PWN
- what evidence supports asymmetric medium surrounding SNR ?
- consistency with SNR shell and PWN geometry ; but only 2–3 composites with TeV offsets (G327.1–1.1, Vela X, maybe MSH 15–52)

Issues and prospects on TeV PWN offsets

- SNR no longer visible around older offset PWNe…
- MWL (CO, HI, …) search for clouds, opposite to the offset



HESS J1303–631
(Voisin et al. 2019)

velocity range :
Scutum-Crux arm,
$D \approx 6.6\,\mathrm{kpc}$

- TeV PWN offset away from CO clouds nearest to pulsar
- but medium clumpy, other clouds : not a simple gradient

Prospects

- (2D) relativistic MHD simulations in progress with Z. Meliani, (AMR-VAC shock-capturing simulation code)
- address question for population : how to reproduce large offsets

Summary

H.E.S.S. Galactic Plane Survey

- 78 sources, 40% identified (most as PWNe or SNRs)
- $\gtrsim 30\%$ of detected sources are PWNe or candidates

PWN TeV luminosities

- weak trend of decreasing TeV luminosity with pulsar $\dot{E}$
- higher luminosities in inner Galaxy : FIR main IC target
- modelled FIR photon density contrast could explain trend
- deeper PWN sample (with CTA) could sample FIR in Galaxy ?

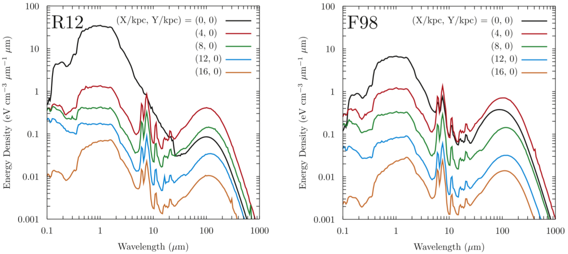
TeV PWN offsets

- older TeV PWNe have large offsets from their pulsar
- larger than can be explained by pulsar proper motion alone
- density inhomogeneities around SNR can also contribute
- limited MWL evidence for required density contrasts
- relativistic MHD simulations in progress

Supplementary slides

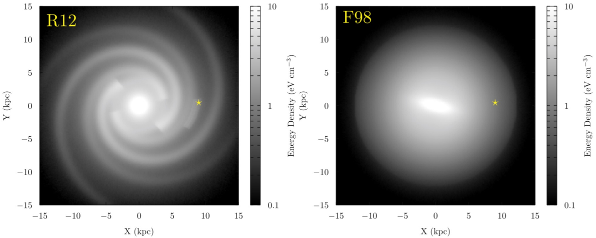
Radiative transfer models of the Galaxy

(e.g., Porter et al. 2017)



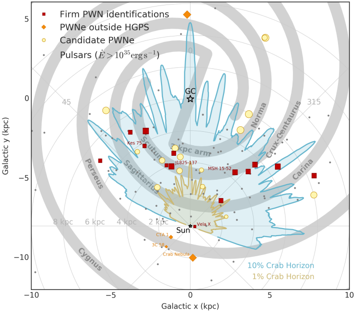
- self-consistent model : stellar radiation absorbed by dust, which re-emits in FIR according to its equilibrium temperature
- stellar emissivity and dust spatial distribution prescribed

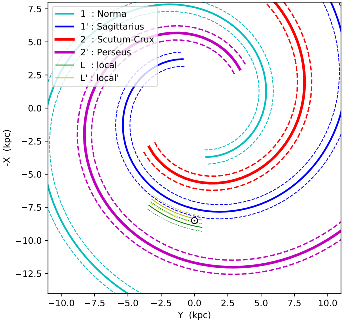
(Porter et al. 2017)



Spiral arm structure of the Galaxy

- Porter et al.'s R12 model includes the Galactic spiral arm model of Robitaille et al. (2012)
- 4 arms, but 2 dominant : 2 and 2′, i.e. **Scutum-Crux** and Perseus which have enhanced stellar emissivity (young, newly formed stars)

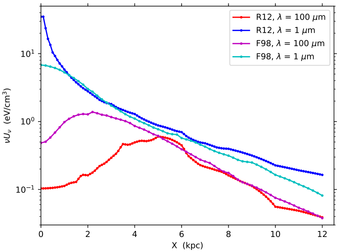


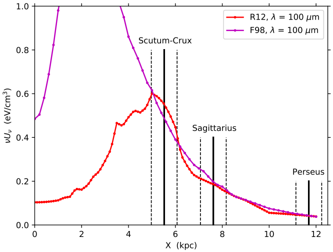


- also enhanced FIR density could explain more luminous PWNe
- in Porter et al.'s R12 model, dust is in an axisymmetric disk. . .

Galactic photon density distribution

- Porter et al.'s calculations show low arm-interarm contrast
- but large decrease in FIR density (factor $\gtrsim 4$) between $R \approx 5\,\text{kpc}$ (Scutum-Crux) and $R \gtrsim 8.5\,\text{kpc}$ (outer Galaxy)
- enough to explain PWN luminosity contrast ? To be continued. . .





energy density vs. R_{Gal} at $Y = Z = 0$

- large discrepancy between models for FIR at $R \lesssim 4\,\text{kpc}$ (and in central bulge for stellar photons)
- a sufficiently large and deep TeV PWN sample (as should be obtained by CTA) would likely help resolve the FIR discrepancy