A Systematic Search for TeV Halos associated with known pulsars

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University of Maryland, College Park
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HAWC Collaboration (Mexico, USA, Germany, Poland, Costa Rica and Italy)
300 close-packed optically isolated water Cherenkov detectors
Construction began early 2012
Full detector inaugurated March 2015
Funding from a combination of US and Mexican agencies
High energy extension: Outrigger array, since summer 2018
Pulsar Halos Ubiquitous?

- ‘Mature’ pulsars have VHE ‘halos’ from interaction accelerated electrons diffusing into the ISM.

- Halo geometry can be used to assess the charged particle diffusion rates vs in the vicinity of pulsars.

- Are halos ubiquitous and if so, are accelerated electron populations similar for all halos?

- Does not include sensitivity vs size, declination.

- Would also like to observe younger pulsars.

Linden, T. et al PHYSICAL REVIEW D 96, 103016 (2017)
Search Method

• Assume a single position, at pulsar.

• Assume a Gaussian morphology.

  • A Gaussian is more compact than a full energy dependent diffusion model, leading to less confusion with neighboring sources.

• Use Geminga as a baseline to predict the size of each pulsar candidate, the search can be done taking only a single trial for each.

• Use the known distance and age to predict the size of each candidate.

• If you want to hear about understanding diffusion in the vicinity of PWNe, see contributions by: Hao Zhou and Chad Brisbois

• Data set used: 1128d of HAWC Live Time.
Search Method (2)

• Many candidates not ‘mature’, defined as 100ky by Linden et al, so they won’t have grown to their nominal Geminga-like size

• Need a simple model for evolution.

• Use Geminga as a baseline. Apparent size (S) is just the predicted size (based on age) divided by the ratio with the size of Geminga, scaled with distance (d)

\[ S_{PWN} = S_{Geminga} \times \frac{d_{Geminga}}{d_{PWN}} \times \text{Size(Age)} \]

• And similarly with flux (F)…

\[ F_{PWN} = F_{Geminga} \times \frac{\dot{E}_{PWN}}{\dot{E}_{Geminga}} \times \frac{d_{Geminga}^2}{d_{PWN}^2} \times \text{Luminosity(Age)} \]
Pulsar Evolution

- Want to predict the properties of young pulsars (not reached full luminosity or size.

- Assume pulsar halos evolve and asymptotically approach Geminga-like halos as they mature.

- Use $\tau = 20$ky

- Full time dependent evolution model is better, but this gets the job done. (see M. Di Mauro et al for details of how to do this)

\[
\text{Luminosity} \propto 1 - e^{-\text{age}/\tau_{e+e^-}}
\]

\[
\text{Size} \propto \sqrt{1 - e^{-\text{age}/\tau_{e+e^-}}}
\]
ATNF Catalog

• ATNF Catalog (v1.6) identifies 2702 pulsar locations

• 450 have measured spin down power (E-dot) and distances and measured age<1My

• 177 are within the HAWC field of view declination in [-16°,+54°]
Confused Regions

- Many of these pulsars are in complex regions, where source confusion may be an issue.

- Multi-source fit required for most targets.

- Exclude plane: |b|<4 and l in [0,100] for this analysis.
May be able to see out to about ~here
Results:

Size indicates size of target
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Look more closely at theses
**PSR J1740+1000**

- Age: 114 ky
- Distance: 1.23 kpc
- Pred Size: 0.276 deg
- Signif: $3.0\sigma$ ($12.8\sigma$ pred)
- Meas / Pred Flux = 0.24
- $b=20.3^\circ$, ejected from the plane? may have a large proper motion?
- Unusual emission: Radio quiet, absorption lines possibly due to an anomalously small B-field.
- VERITAS limit of <1% Crab, consistent with this observation considering extension, spectrum…

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J0729-1448
(in outer galaxy, poor declination)

- Age: 35.2 ky
- Distance: 2.68 kpc
- Pred Size: 0.115 deg
- Signif: 1.7\(\sigma\) (1.3\(\sigma\) pred.)
- Measured/Expected Flux = 1.35
J0631+1036 (South of Geminga)

- Age: 43.6 ky
- Distance: 2.10 kpc
- Pred Size: 0.153 deg
- Signif: 3.3σ (3.9σ pred.)
- Meas/Pred Flux = 0.81
**J0631+1036**

(South of Geminga)

- **Age:** 43.6 ky
- **Distance:** 2.10 kpc
- **Pred Size:** 0.153 deg
- **Signif:** $3.3\,\sigma$ ($3.9\,\sigma$ pred.)
- **Meas/Pred Flux:** 0.81

**Point source map**

**0.5 deg map**

**Preliminary**
J0614+2229 (near IC443)

- Age: 89 ky
- Distance: 1.74 kpc
- Pred Size: 0.194 deg
- Signif: 1.9σ (2.2σ pred.)
- Meas / Pred Flux = 0.84
- Fits model well, but is clearly confused region with IC443.
Conclusions

• Indication of possible emission from several candidates.

• Source confusion is a problem for all but a handful of targets.

• Need to do multi-source fits to isolate source contributions.
Backup
Crab
(this is an extreme case for my evolution model, so don’t take it too seriously)

- Age: 1.26ky
- Distance: 2.00kpc
- Pred Size: 0.042° (HESS measures extent at 0.014°)
- Signif: 162σ
- Meas./Pred Flux = 0.22
- Sub-luminous

HESS measures Crab as 52" = 0.014°