Evidence for CR escape: γ-Cygni
the GeV to TeV Morphology
with
MAGIC and Fermi-LAT

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Gamma-ray supernova remnants

- $\pi^0$ Cutoff → Evidence for hadronic CRs
- Interaction region bright
- Matured SNRs ($\approx 10^4$ yrs)

- Shell bright
- Leptonic / hadronic?
  - $\approx 1-5 \times 10^3$ yrs
Age: 5 – 10 kyr

SNR clearly in Sedov phase: → reverse shock hit centre 1.5 kyr ago [Hui+‘14]

Remnant of a core-collapse SN (PSR at the centre)

Distance: 1.5 – 2.6 kpc

Extend: $\approx 0.56^\circ$ radius, ($\approx 17$ pc at 1.7 kpc)
\(\gamma\)-Cygni in \(\gamma\)-rays

- Detected at TeV by VERITAS using 21 h obs. time
  - extended emission (\(\sigma=0.23^\circ\)) towards north-west
  - power-law spectrum (\(\Gamma=2.37\pm/-0.14\))
  - integral flux 3% Crab Units

- \textit{Fermi}-LAT observes emission all over shell at GeV energies

- < 10 GeV emission dominated by PSR J2021+4026
  - only known \(\gamma\)-ray variable PSR
Situated at the Observatorio Roque de los Muchachos @ 2200 m a.s.l.

Stereo system of 2 x 17m telescopes

Energy range from 50 GeV – 50 TeV

Obs. time 80 h

Data selection: aerosol transmission (>80%) measured with LIDAR system
Extended, multi-component source in the north-west of SNR

Emission can be well described by multiple component model:

- Disk matching radio shell
- Extended Gaussian source
- Arc structure outside shell

Simultaneous 2D-Likelihood fit with novel SkyPrism program (inspired by Fermi-tools)

- $6.2 \, \sigma$ for disk
- $13.7 \, \sigma$ for Gaussian
- $7.4 \, \sigma$ for arc

◆ : PSR 2021+4026
★ : Sadr (mag. 2.2)
─ : 408 MHz Cont. (CGPS)
Energy dependent morphology

- > 50 GeV emission concentrated towards northwest, compare [Fraija+’16]
- > 450 GeV emission outside shell
Likelihood fit of several components (Disk + Gaussian + Arc)

Fermi and MAGIC results of the disk match

Gaussian source needs to have flatter spectrum if MAGIC and Fermi see same source [Fraija+16]

Arc seen by MAGIC only → more peaked spectrum than the other components
Shock precursor or CR escape?

- Emission outside shell suggests CR escape or precursor scenario

**Precursor scenario**

- Spectrum at the arc should be harder than the one of the disk

- Diffusion coefficient based on size of the Arc ($\sim 0.15^\circ \triangleq 30\% R_{\text{SNR}}$, 5pc at 1.7kpc)

  $\lambda_p = D/u_{\text{sh}}$ leads to acceleration time of $\sim 4 \times 10^4$ yrs ($5 \times t_{\text{SNR}}$)

- Unlikely that we see the shock precursor
Escape scenarios of γ-Cygni

Damping of magn. waves
(due to e.g. ion-neutral friction)

- Also low energy CR should escape
- Disagrees with Fermi observations

\[ l_{\text{diff}} = \sqrt{4Dt} \]
\[ \Leftrightarrow D = \frac{l_{\text{diff}}^2}{4t} \approx \frac{(R_{\text{SNR}}+\Delta_{\text{arch}}-R_{\text{ST}})^2}{4(t_{\text{SNR}}-t_{\text{ST}})} \]
\[ = 2.8 \times 10^{26} \text{ cm}^2 \text{ s}^{-1} \]

\((n_0 = 0.3 \text{ cm}^3, T_{\text{SNR}} = 8 \text{ kyr}, E_{\text{SN}} = 10^{51} \text{ ergs}, M_{\text{ej}} = 10 M_{\odot})\)

- 280 times lower than average \( D_{\text{gal}} \) (20 TeV)

\[ D_{\text{gal}} = 3 \times 10^{28} \left( \frac{E}{\text{GeV}} \right)^{\frac{1}{3}} \text{ cm}^2 \text{ s}^{-1} = 8 \times 10^{29} \left( \frac{E}{20 \text{ TeV}} \right)^{\frac{1}{3}} \text{ cm}^2 \text{ s}^{-1} \]

- Compatible with CR amplifying local turbulences e.g. [Malkov+13] [Nava+16]

- Turbulences locally enhanced by other mechanisms (Cygnus Cocoon)

- Projection effects may effect size of the arc (factor 2x → D increases by ~1.7)
ISM around the SNR

- Soft X-rays show shock heated gas in north → denser medium, but no Maser found
- AGN close to SNR, but no counterpart where TeV emission is found
- CO emission next to MAGIC emission region
- Hint for a HI shell surrounding the SNR, cavity wall created by progenitor [Ladouceur+'08]
Summary

- MAGIC observations revealed multi-component morphology

- Energy dependent morphology:
  - LE confined in shell
  - HE extending beyond

- Evidence for CR escape
  - diffusive escape
  - diff. coefficient lower than $D_{\text{gal}}$

- Synergy between IACT and Fermi
  - identification of src. components
  - triggered development of new analysis tools

Thank you for your attention and interest!