TeV γ-Ray Observations and Implications for Galactic Accelerators : PWNe, SNRs and SBs

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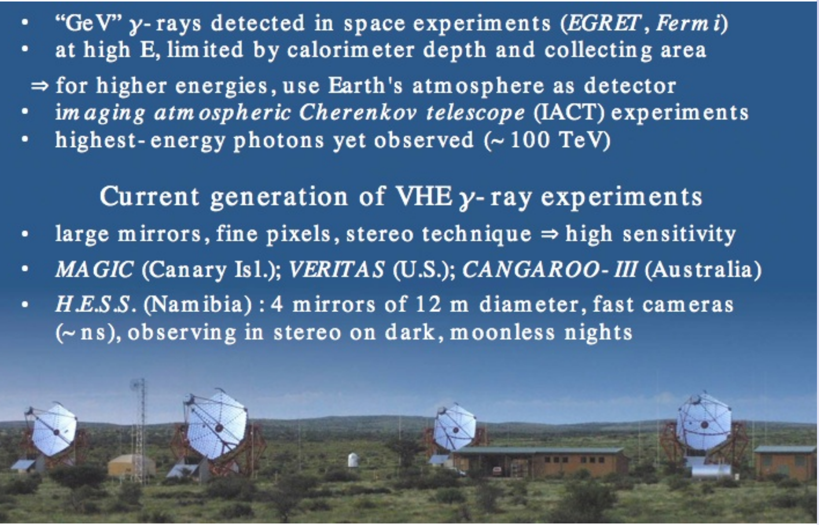
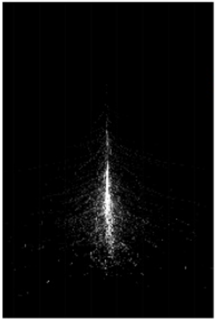
Particle Acceleration in Astrophysical Plasmas
KITP, Santa Barbara, August 12, 2009

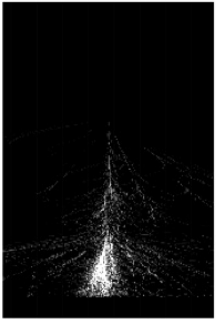
Very High Energy (VHE, 100 GeV $< E_\gamma <$ 100 TeV) or "TeV" γ-Ray Astronomical Detectors



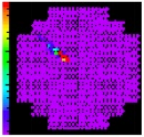
Imaging High-Energy Atmospheric Showers

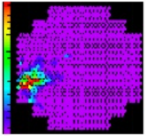


Gamma-ray showers develop quite smoothly in the atmosphere. Their camera images are lean and compact



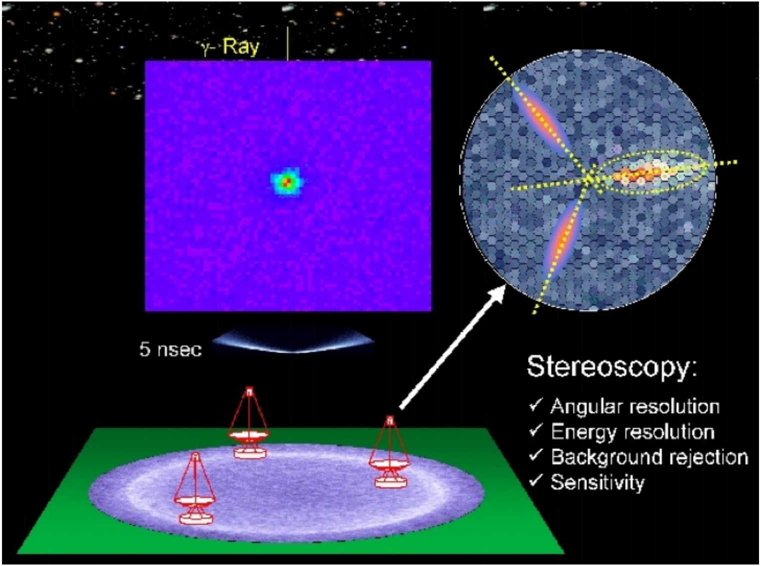
Showers from charged cosmic rays develop in an irregular way. Their camera images are broader and less compact.





Slide 5

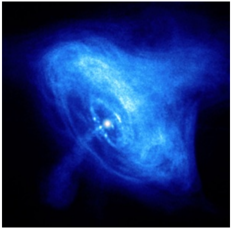
Stereo Imaging and Event Reconstruction



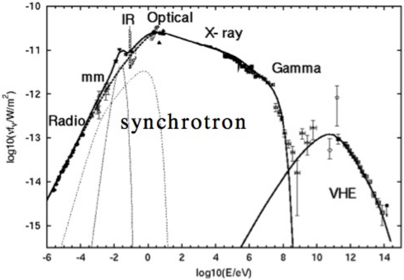
TeV γ-ray emitting Pulsar Wind Nebulae

In the beginning, there was the Crab Nebula...

- "standard candle" of TeV γ-ray astronomy since its discovery



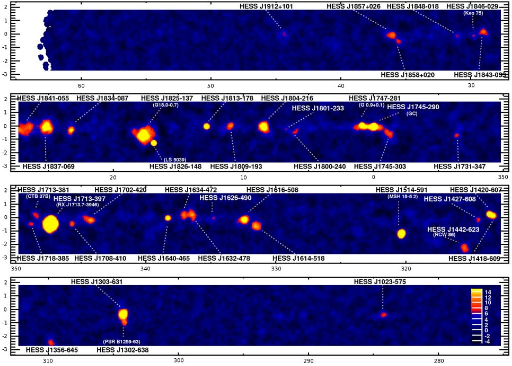
Chandra



- *synchrotron* emission in most of the electromagnetic spectrum, from $e^{\pm}$ accelerated in the pulsar, wind, termination shock
- TeV γ-ray emission results from *Inverse Compton* scattering of lower-energy photons (synchrotron, CMB, IR, starlight...)
- (hadronic contributions also proposed, e.g. Horns et al. 2007)
- for most other such *plerions*, non-thermal radiation detected only in radio and X-rays — until recently...

Galactic TeV γ-ray sources and PWNe

- much improved sensitivity of current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), inaugurated by HESS (initial 4-telescope array completed 5.5 years ago)

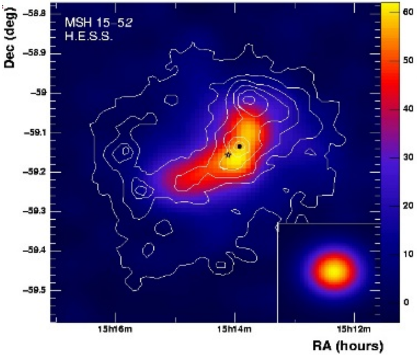


- HESS Galactic plane survey (now covering Gal. longitudes $-80°$ to $60°$)

- currently about 50 Galactic TeV sources known
- about half are identified as PWNe or candidate PWNe

I – Young PWNe (and composite SNRs)

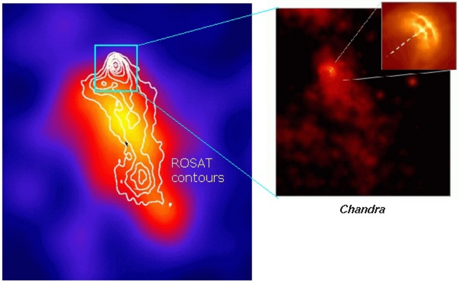
- in addition to the **Crab**, HESS discovered TeV emission from **G 0.9+0.1** (A&A, **432**, L25, 2005), **G 21.5–0.9** and **Kes 75** (Djannati-Ataï et al. 2007, ICRC, `arXiv:0710.2247`)
- **MSH 15–52** : first PWN angularly resolved in TeV γ-rays
  - A&A **435**, L17 (2005)
  - contours: ROSAT
  - X-ray thermal shell and non-thermal "jet-like" nebula
  - other composites similar in X-rays



- IC emission $\propto$ (approximately uniform) target photon density $\Rightarrow$ direct inference of spatial distribution of electrons

II – Older, “offset” PWNe

- TeV emission from the **Vela X** nebula (A&A **448**, L43, 2006)

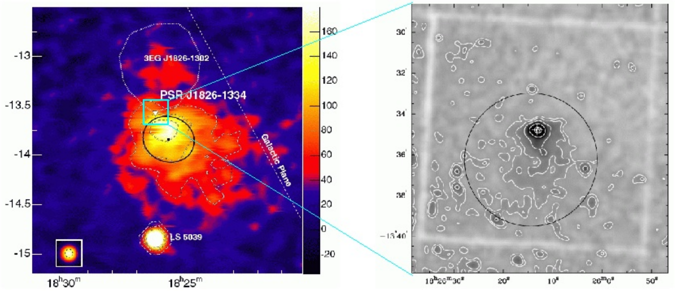


- coincident with one-sided “jet” (Markwardt & Ögelman 1995)
- compact X-ray nebula not conspicuous in TeV γ-rays $\Rightarrow$ torii and jets bright in X-rays because of higher magnetic field
- offset morphology explained by passage of anisotropic reverse shock, “crushing” the PWN (Blondin et al. 2001)?
- two TeV PWNe in **Kookaburra** appear to fall in same category

PWN established from TeV properties

- previous identifications based on positional and (when resolved) morphological match to known X-ray (or radio) PWNe

HESS J1825–137 as nebula of PSR B1823–13



HESS (A&A **460**, 365, 2006) XMM (Gaensler et al. 2003)

- large TeV source, offset from PSR B1823–13 position
- smaller X-ray extension, E–W compact nebula and cometary "tail" in the direction of HESS source centroid

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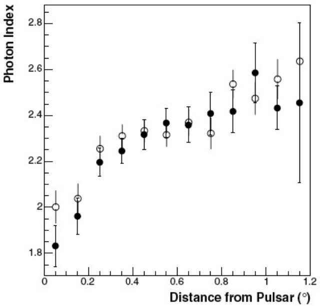
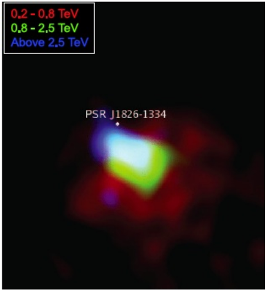


A&A **460**, 365 (2006)



Funk et al. 2007

- TeV γ-ray spectral steepening with distance away from pulsar
- consistent with radiative losses of $e^{\pm}$ accelerated near the pulsar
- electron scattering CMB to 1 TeV radiates synchrotron $\ll$ 1 keV (for typical B's) $\Rightarrow$ consistent smaller size of X-ray nebula

Latest discoveries

Young PWNe and composite SNRs

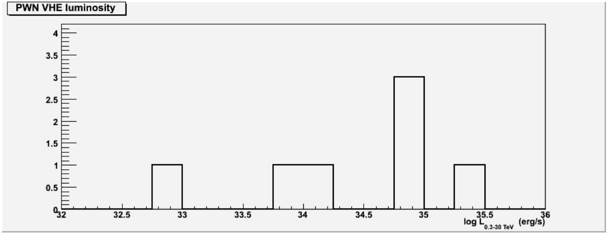
- plerion **G 54.1+0.3** (PSR J1930+1852) detected by *VERITAS* : $\Gamma \sim 2.3 \pm 0.3 \pm 0.3_{\rm sys}$, $F(>1\,{\rm TeV}){\sim}3\%$ Crab (Aliu et al. 2009)
- composite **G 292.2–0.5** (PSR J1119–6127) detected by *HESS* : flux $\sim 4\%$ Crab, Γ steeper than typical, TeV offset from pulsar (Djannati-Ataï et al. 2009)

Offset PWNe

- *VERITAS* discovery of extended emission from **G 106.3+2.7** ("Boomerang"), offset to PSR J2229+6114 : Flux $\sim 5\%$ Crab, $\Gamma \sim 2.3 \pm 0.3 \pm 0.3_{\rm sys}$ (Aliu et al. 2009)
- *HESS* evidence for spectral steepening in **HESS J1303–631** away from PSR J1301–6305 (Dalton et al., ICRC 2009)

- In G 292.2–0.5 and G 106.3+2.7, shell contribution plausible

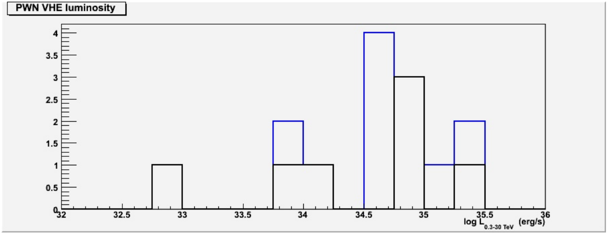
TeV luminosities of established PWNe



- PWN distances: when pulsar detected (in radio), can use dispersion measure (DM) and Galactic electron distribution (Cordes & Lazio 2002)
- "Established" PWNe with known pulsars:

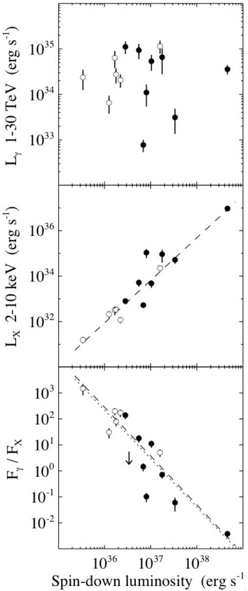
  Median luminosity : $L_{0.3-30\,\mathrm{TeV}} \approx 7 \times 10^{34}$ erg/s $\quad (\sim L_{\mathrm{Crab}})$

TeV luminosities of candidate PWNe



- “Candidate” PWNe are TeV sources coincident with an energetically plausible pulsar, but with weaker/no MWL evidence for association
- Median luminosity : $L_{0.3-30\,\mathrm{TeV}} \approx 5 \times 10^{34}$ erg/s (consistent with confirmed PWN luminosity distribution)

TeV luminosity distribution of PWNe



- $L_{\rm TeV}$ much more tightly clustered (∼2 decades) than L_X (6 decades); no correlation with $\dot{E}$ (2-3 decades)
- strong correlation of L_X with $\dot{E}$, hence correlation of $L_{\rm TeV}/L_X$ with $\dot{E}$ (ratio independent of estimate for D) (Grenier 2009, Mattana et al. 2009)
- X-rays trace recently injected particles, whereas TeV γ-rays reflect history of injection since pulsar birth

Summary on TeV-emitting PWNe

- TeV γ-rays have opened a new observational window for the study of Pulsar Wind Nebulae, giving a more direct view of the accelerated particle population
- About half of Galactic TeV sources are PWNe or candidates:
  - 11 (+1) established TeV PWNe
  - 11 TeV sources coincident with known energetic pulsars
  - 5 TeV sources coincident with non-thermal X-ray nebulae
- Two broad categories of TeV PWNe:
  - young PWNe, typically in composite SNRs
  - offset PWNe, typically with older Vela-like pulsars
- With X-ray synchrotron, yield information about B in PWNe
- Deeper X-ray and radio observations may well yield further TeV PWNe or candidates

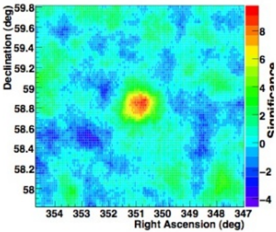
TeV γ-rays from (shell-type) SNRs and the origin of Galactic Cosmic Rays

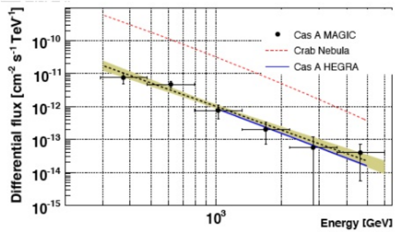
- Supernova remnants are widely considered likely sources of Galactic cosmic rays up to the "knee", $E \sim 3 \times 10^{15}$ eV :
  - well-studied shock acceleration mechanism;
  - GCR composition compatible with and SNR origin;
  - energetics require $\sim$10% of total SN energy of 10^{51} erg
- Observational evidence for accelerated e^- (synchrotron)
- For accelerated p (and ions), **hadronic** interactions with ambient matter produce π^0, decaying into two γ-rays which we observe
- On of aims of TeV γ-ray astronomy (e.g. Drury et al. 1994)
- But how to discriminate from **leptonic** (IC) emission?

(Next to) youngest Galactic SNR : Cassiopeia A

- age~330 yr (no clear SN observation)
- VHE emission discovered by *HEGRA* (Aharonian et al. 2001, *A&A* **370**, 112)
- 232 hours (!), significance 5 σ
- unresolved, centroid in Cas A

- Confirmed by *MAGIC* : 5.2 σ in 47 h (Albert et al. 2007) and by *VERITAS*





- spectra compatible
- steep spectrum : Γ=2.4±0.2
- $L_{1-10\ \mathrm{TeV}} \sim 3\times10^{33}$ erg/s ($D \approx 3.4$ kpc)

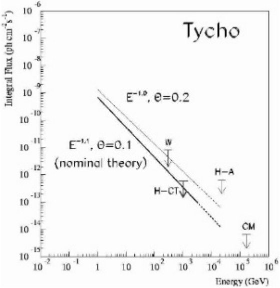
- sharp synchrotron X-ray rims, etc. $\Rightarrow$ high $B \sim$ mG
- hadronic emission favoured

Other young (historical) shell-type SNRs

Tycho (SN 1572)

- deepest upper limit: *HEGRA* 2001 (*A&A* **373**, 292) with 65 hours
- $L_{1\text{-}10\ \mathrm{TeV}} < 10^{33}\ \mathrm{erg/s}$

  (assuming $D \approx 2.3$ kpc and $\Gamma = 2$)
- synchrotron X–rays $\Rightarrow B > 22\ \mu\mathrm{G}$



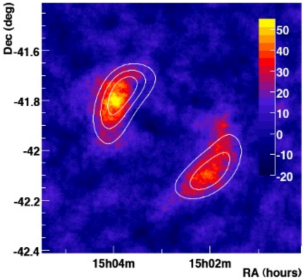
Kepler (SN 1604)

- recent *HESS* upper limit (*A&A* **488**, 219)
- $L_{1\text{-}10\ \mathrm{TeV}} < 2\times10^{33}\ \mathrm{erg/s}$ (assuming $D \approx 4.8$ kpc and $\Gamma = 2$)

  (distance uncertain by ± 1.5 kpc $\Rightarrow$ factor ~ 2 in $L_{1\text{-}10\ \mathrm{TeV}}$)

Other historical shell-type SNR : **SN 1006**

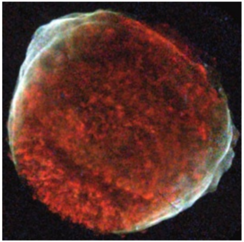
- $\sim$30' diameter shell
- *CANGAROO-I* claimed bright NE hotspot (Tanimori et al. 1998), not confirmed by *HESS* (2005, *A&A* **437**, 135) nor *CANGAROO-III*
- after 130 h, *HESS* detection! (Naumann-Godo et al., ICRC 2009)
- flux $\Rightarrow L_{1\text{-}10\ \mathrm{TeV}} \sim 6\times10^{32}$ erg/s (assuming $D \approx$2.2 kpc)



- Morphology seems to match X-ray synchrotron (contours: *XMM* map smoothed to match *HESS* PSF)
- Leptonic scenario $\Rightarrow B \sim 30\ \mu$G (lower than inferred from rims)
- Hadronic scenario : given low ($n \sim 0.05$ cm^{-3}) medium density, requires flat ($p \approx 2$) spectrum for reasonable energetics
- whether protons or electrons, shows distribution of accelerated particles in SN 1006

Bipolar morphology of particle acceleration

- SN 1006 : explosion in nearly uniform, undisturbed medium?
  - Type Ia : no stellar progenitor wind
  - High above the Galactic plane



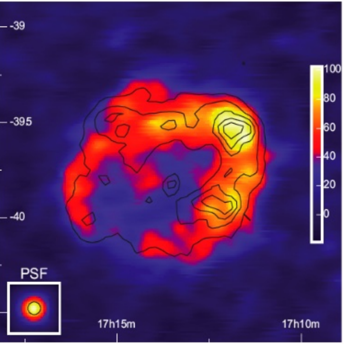
- Rothenflug et al. (2004) : X–ray image compatible with synchrotron “polar caps”, not with “equatorial band”
- Suggests that **parallel** shocks, and not **perpendicular**, are where particle acceleration is most efficient

Young SNRs in TeV gamma–rays

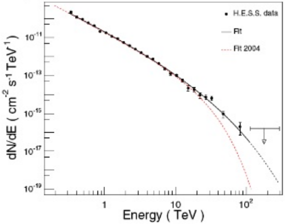
- Other historical shell–type SNRs somewhat less luminous in TeV γ-rays than Cas A
- Lower surrounding medium density(?), or less efficient particle acceleration

SNRs with shell morphology in TeV γ-rays

RX J1713.7–3947 (or G347.3–0.5)



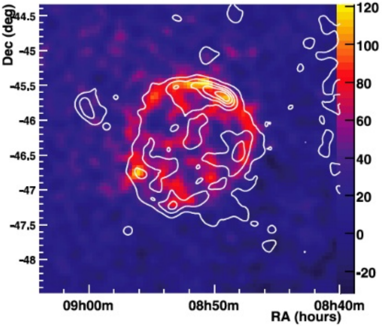
- VHE γ–ray emission discovered by *CANGAROO* (Muraishi et al. 2000)
- first resolved SNR shell in VHE γ–rays (*HESS* 2004, *Nature* **432**, 75)
- very good spatial correlation with (non–thermal) X–rays (ASCA 1–3 keV) (*HESS* 2006, *A&A* **449**, 223)
- large zenith angle observations ⇒ spectrum 0.3–100 TeV (*HESS* 2007, *A&A* **449**, 223)



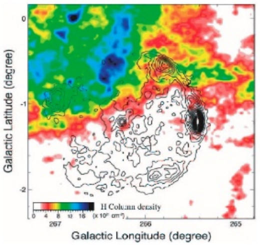
- power law $\Gamma \approx 2.0$ with cutoff or break at $E_\gamma \sim 10$ TeV (depending on model)
- $L_{1-10\,\mathrm{TeV}} \sim 10^{34}$ erg/s (assuming $D \approx 1.3$ kpc)
- leptonic emission scenario $\Rightarrow B \sim 9\ \mu$G

TeV γ-ray shells

RX J0852.0–4622 (or G266.2–1.2, "Vela Junior")



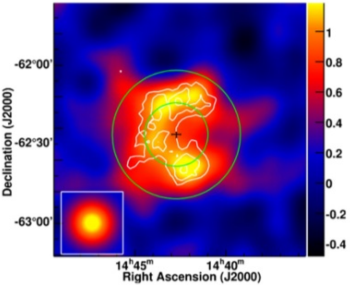
- Detection of a thin, 2° diameter shell (*HESS* 2005, *A&A* **437**, L7)
- *CANGAROO–II* detected NW rim (Katagiri et al. 2005), *–III* confirmed the shell (Enomoto et al. 2006)
- High spatial correlation with X-rays (ROSAT, ASCA); no clear correlation with CO (*HESS* 2007, *ApJ* **661**, 236)



- power law $\Gamma = 2.24 \pm 0.04_{\rm stat} \pm 0.15_{\rm sys}$ (indication of steepening at high energies)
- $L_{1-10\ \rm TeV} \sim 6 \times 10^{33}$ erg/s at "far" $D \approx 1$ kpc
- leptonic emission scenario $\Rightarrow B \sim 7\ \mu$G

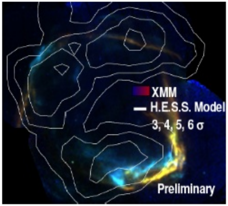
Probable TeV shell : **RCW 86** (or MSH 14–63)

(*HESS* 2009, *ApJ* **692**, 1500)



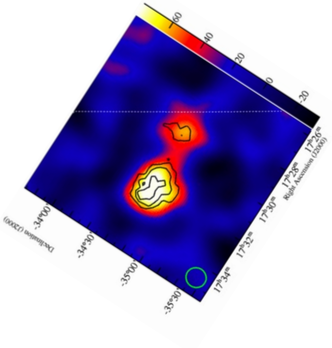
- $\sim 4\sigma$ excess earlier reported by *CANGAROO* (Watanabe et al. 2003)
- 8.5σ in 31h : clear detection
- hint of shell morphology (more data needed), like synchrotron X–ray and radio shell
- no hint of strong enhancement at SW dense interaction region

- fairly steep power law, $\Gamma = 2.54 \pm 0.12_{\rm stat}$
- $L_{1\text{–}10\ \rm TeV} \sim 7 \times 10^{33}$ erg/s assuming $D \approx 2.5$ kpc
- leptonic emission scenario $\Rightarrow B \sim 30\ \mu$G (compatible with X–ray rims, Vink et al. 2006)
- hadronic scenario : extrapolated proton spectrum too high, need $\Gamma \approx 2$ and cutoff (also compatible with spectral data)

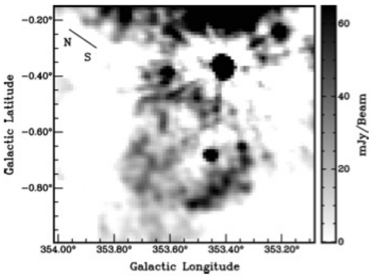


A new non-thermal shell : HESS J1731–347

- discovered in *HESS* Galactic plane survey; $\Gamma = 2.3 \pm 0.1 \pm 0.2$
- coincident radio shell discovered with ATCA data: G 353.6–0.7



(Tian et al. 2008)



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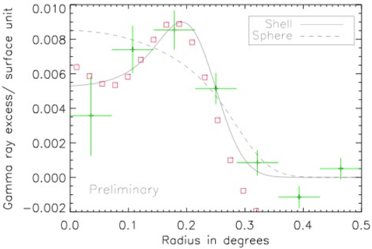

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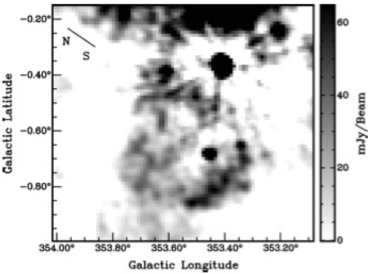

- further *HESS* observations: hint of limb-brightening ($\sim 2\sigma$ level)

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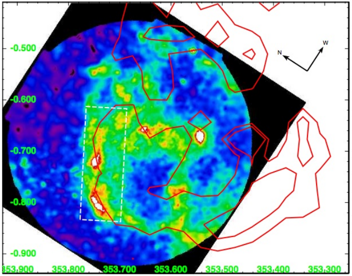
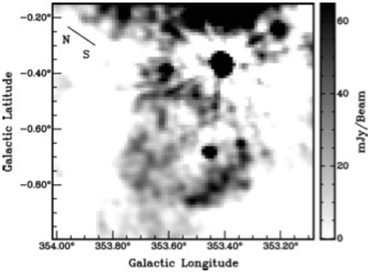




- further *HESS* observations: hint of limb-brightening ($\sim 2\sigma$ level)
- X-ray observations of (part of) shell reveal rims of emission with non-thermal spectra! (no evidence for thermal emission)
- X-ray absorption gradient suggest SNR lies behind a CO cloud
- $D > 3.5\,\mathrm{kpc} \quad \Rightarrow \quad L_{1-10\,\mathrm{TeV}} > 2 \times 10^{34}\,\mathrm{erg/s}, \quad R > 15\,\mathrm{pc}$

TeV γ-ray shells : general properties

- dominantly non-thermal X-ray emission
  (thermal only in RCW 86, SN 1006 and especially Cas A)
- weak radio synchrotron emission (except younger SNRs)
- similar TeV luminosities, $L_{1-10\,\mathrm{TeV}} \sim 10^{34}$ erg/s
  (historical SNRs $\sim 10^{33}$ erg/s)

Leptonic emission scenario

- might explain spatial correlation with synchrotron X-rays
- implies fairly low $B \sim 10\,\mu$G (in one-zone model), in apparent contradiction with evidence for turbulent B-field amplification
- TeV shell widths larger than X-ray filaments (e.g. Renaud 2009): if rapid B-field damping behind the shock, may be compatible with weak *spatially-averaged* B value
- difficult to fit TeV spectral shapes in one-zone model

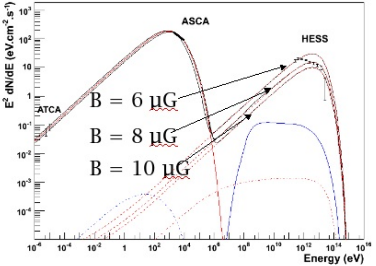
One-zone spectral modeling of **G 347.3–0.5**

Primary population: electrons ?

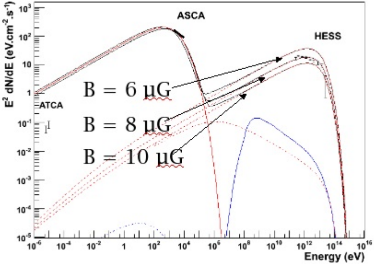
- Need about 8 μG B field to match flux ratios
- Simplest electronic models don't work well

- Simple one-zone model
- Electrons & protons injected with the same spectral shape
- Energy losses + escape of particles out of the shell taken into account

Power-law index = 2.2 at injection



Power-law index = 2.4 at injection

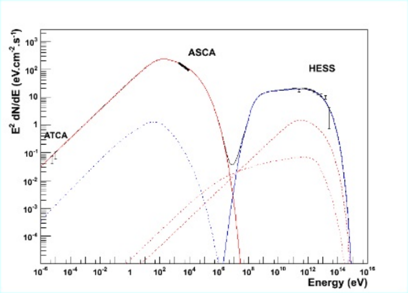


(M. Lemoine-Goumard)

One-zone spectral modeling of G 347.3–0.5

Primary population: protons ?

- Spectral shape at injection : power–law w/exponentional cut–off E_{cut} = 120 TeV and index = 2.0
- Energy injected = 10^{50} ergs
- Electron/proton ratio = 5 x 10^{-4}
- Magnetic field = 35 μG & Density = 1.5 cm^{-3}



(M. Lemoine-Goumard)

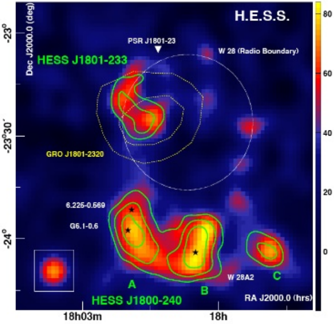
TeV γ-ray shells : general properties

Hadronic emission scenario

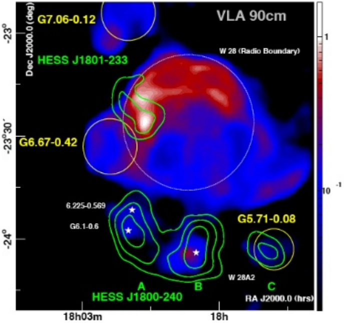
- no obvious explanation for high correlation with X-rays, and poor correlation with surrounding medium density
- **all** TeV-detected SNRs have $\Gamma > 2.0$ or cutoff at $E_\gamma \sim 10\,\mathrm{TeV} \;\Rightarrow\; E_p \sim 10^{14}\,\mathrm{TeV}$ — well short of "knee"
- spectrum must flatten to $\Gamma \sim 2$ at lower energies (as seen in G 347.3 and hinted in others), otherwise CR energetics prohibitive
- relatively high surrounding medium density ($n \sim 1\,\mathrm{cm}^{-3}$) required to explain G 347.3, Vela Jr and HESS J1731
- but upper limits on n from lack of thermal X-ray emission are a few$\times 0.01\,\mathrm{cm}^{-3}$ (assuming $k_B T \sim$ keV)
- **Caveat:** distances to these SNRs uncertain; most precise estimates often rely on unmodified shock jump conditions

SNR / Molecular Cloud interactions : **W 28**

(*HESS* 2008, *A&A* **481**, 401)

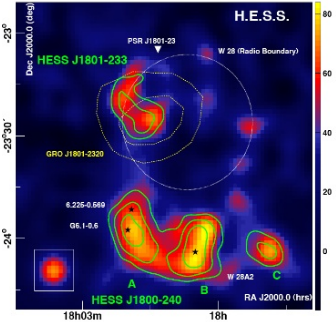


- new source HESS J1801−233 on E rim of SNR W 28, radio hot spot
- coincident with EGRET source

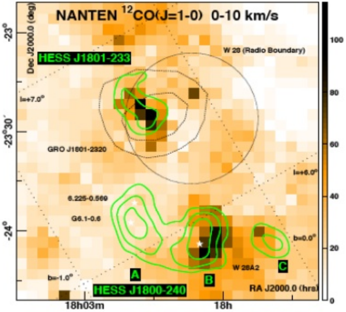


SNR / Molecular Cloud interactions : **W 28**

(*HESS* 2008, *A&A* **481**, 401)

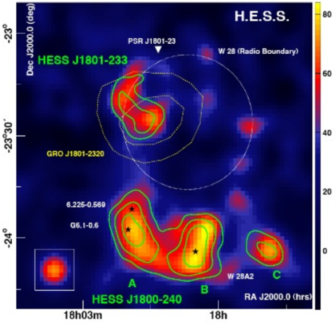


- new source HESS J1801−233 on E rim of SNR W 28, radio hot spot
- coincident with EGRET source
- morphological match to CO cloud
- 1720 MHz OH masers : signature of shock / MC interaction



SNR / Molecular Cloud interactions : **W 28**

(*HESS* 2008, *A&A* **481**, 401)



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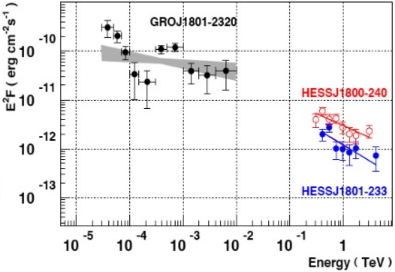
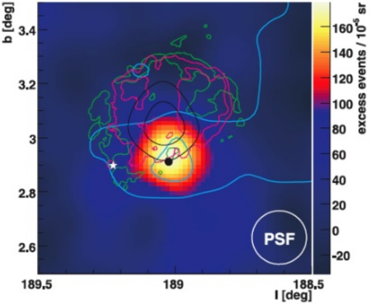


steep spectrum, $\Gamma = 2.7 \pm 0.3_{\mathrm{stat}}$
(flattening in EGRET range)

$L_{1-10\,\mathrm{TeV}} \sim 5 \times 10^{32}$ erg/s, assuming $D \sim 2$ kpc

SNR / Molecular Cloud interactions : **IC 443**



- discovery of an unresolved source in IC 443 (*MAGIC* 2007, *ApJ* **664**, L87)
- not coincident with PWN (white star)
- direct coincidence with peak CO density (blue contours), 1720 MHz OH maser (black dot)
- compatible with 3EG J0617+2238
- very steep spectrum, $\Gamma = 3.1 \pm 0.3_{\mathrm{stat}}$
- $L_{1-10\ \mathrm{TeV}} \sim 2 \times 10^{32}$ erg/s with $D \approx 1.5$ kpc

General properties

- correlation with high density ⇒ strongly suggests hadronic emission
- steep spectra, flattening in EGRET range, low 1–10 TeV luminosities
- Probe of accelerated proton spectra in SNRs?
- Caveat : passage in MC may alter shock acceleration properties

Summary on TeV-Emitting SNRs

Young (historical) SNRs

- **Cas A** confirmed, with somewhat steep spectrum : hadronic scenario favoured; high B–field
- **Tycho, Kepler** at least a few times less luminous
- **SN 1006** detected : bipolar morphology for acceleration

VHE shells : RX J1713.7, RX J0852.0, RCW 86

- Leptonic scenario disfavoured due to low implied B–fields
- Hadronic scenario fails to explain high correlation with X–rays, poor correlation with surrounding medium density
- High–energy cutoff or break $\Rightarrow$ difficult to reach the "knee"?

SNR / MC interactions : W 28, IC 443, CTB 37A...

- Correlation with CO density strongly suggests hadronic
- Relatively steep spectra, low luminosity in 1–10 TeV band
- Passage through MC may alter shock acceleration properties

Superbubbles as the Main GCR Accelerators?

- core-collapse supernova progenitors (massive stars) are typically formed not in isolation but in giant molecular clouds (**GMCs**), becoming **OB associations** (open star clusters)
- combined energy input of powerful **stellar winds** and/or successive **supernovae** blow a bubble of hot gas in the medium
- $\sim$**75%** of all SNe may occur in such "superbubbles"; explains lack of other radio SNRs like Cas A? (Higdon & Lingenfelter 2005)

Particle acceleration in superbubbles

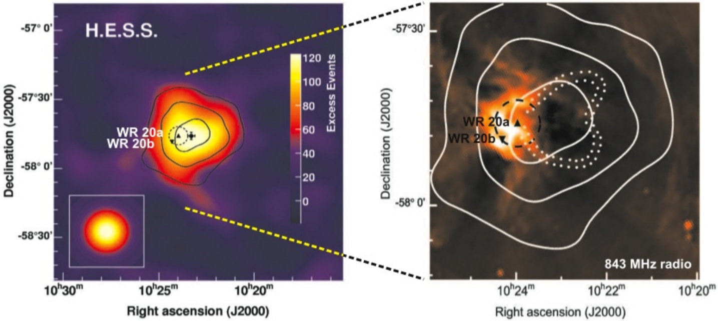
- SNRs in superbubble gas $\approx$ "hot" phase of interstellar medium ($n \sim 0.003\text{cm}^{-3}$, $T \sim 10^6$ K)?
- (colliding) winds of massive stars (e.g. Cassé & Paul 1980)?
- turbulent and multiple shock acceleration (e.g. Parizot et al. 2004)?

- relative paucity of observational evidence for acceleration to very high energies in these objects — until recently…

Discovery of TeV γ-rays from Westerlund 2

(*HESS* 2007, *A&A* **467**, 1075)

MOST (843 MHz)

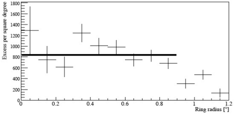


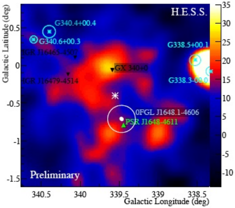
- significantly extended source (Gaussian width 0.18°)
- steep spectrum : $\Gamma = 2.53 \pm 0.16 \pm 0.10_{\rm sys}$ (380 GeV – 20 TeV)
- $D = 6.0 \pm 1.0$ kpc (Dame 2007) $\Rightarrow$ $L_{1-10\,\rm TeV} \sim 4 \times 10^{34}$ erg/s ($\sim L_{\rm Crab}$), more luminous than any shell SNR
- emission consistent with radio “blister” blown into medium (Whiteoak & Uchida 1997); $R \sim 20$ pc

The TeV-emitting superbubble of Westerlund 1

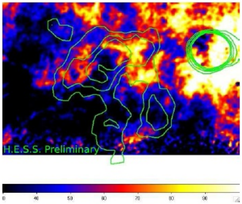
- extremely massive star cluster: 24(!) Wolf-Rayet stars (versus 2 in Westerlund 2), 80 blue supergiants. . .

(Ohm et al. for *HESS*, ICRC 2009)





HI (SGPS)



- very extended TeV γ-ray emission, up to 0.9° from Westerlund 1
- hint of shell morphology, but limb-brightening not significant

- at $D = 4\,\mathrm{kpc}$, fills region of $R \sim 60\,\mathrm{pc}$ (!)
- matches HI shell around Westerlund 1 (Kothes & Dougherty 2007)
- more than enough power in stellar winds ($L \sim 10^{39}$ erg/s, + SNe, Muno et al. 2006) to explain a superbubble of this size

- spectral analysis in progress. . .

Discussion : TeV γ-rays from superbubbles

Observations

- Westerlund 1 and 2 supported by match to MWL blister or shell
- unidentified source TeV J2032+4130 (confirmed by *MAGIC* 2008, *ApJ* **675**, L25) proposed association with Cygnus OB2
- HESS J1614–518 may be associated with Pismis 22

Interpretation

- direct evidence for $\sim 10^{14}$ eV particles in superbubbles
- **hadronic** emission? Mass in surrounding (HI) shell, interacting molecular cloud ($7 \times 10^4 M_\odot$ in Wd 2); but limb-brightening?
- **leptonic** emission? Intense photon fields for IC scattering: stellar photons, HII region, cloud IR emission...

Open questions

- in principle, most of Galactic SN energy deposited inside SBs
- what is the efficiency of SNR shock acceleration in hot medium?
- can other mechanisms (stellar winds, turbulence) be more efficient?