The $\gamma$-ray sky seen by H.E.S.S.

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On behalf of the H.E.S.S Collaboration
THE HESS experiment

- Operating since 2003
- Energy threshold: 100 GeV
- Energy resolution: 20%
- Field of view: ~ 5 deg
- Angular resolution: <0.1 deg
- Sensitivity: 1 Crab in 30 sec
Selected results

The Galactic Survey
• SN1006 + HESS J1731-347: new shell type SNRs
• Other sources (PWNs, massive stellar clusters)

The new extragalactic detections
• TeV blazars and MWL campaign on radio galaxies
• Starburst galaxy in VHE $\gamma$-rays
The galactic survey

The initial TeV galactic plane survey (2004)
- Exposure ~95h scan mode + ~135h follow-up/dedicated
- Discovered 14 Galactic sources of TeV radiation

The extended H.E.S.S. Galactic plane survey (2005-2009)
- A much deeper exposure: 1400 h scan mode + dedicated observations
- A more uniform exposure
- Discovered a total of 56 Galactic sources
- Very narrow distribution (RMS(b) ~0.3°)

Aharonian et al. 2005 Science, 307
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The galactic plane survey

Most of the revealed sources are mildly extended (D > 3' to 4')

Population: PWN, SNRs, Binary systems, Dark sources, Interacting stellar winds

-80° < long < 60°

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Shell-type SNRs

- Supernova remnants (SNRs) are suspected to be the main accelerators of galactic cosmic-rays up to the knee
  - Diffusive shock acceleration
  - 10% of the mechanical energy of supernovae can account for the injection of CR's in the Galaxy.

- Thin filaments seen in non-thermal (synchrotron) X-rays prove that electrons are accelerated up to 100 TeV and indicate the shock position.

- SNRs are often extended sources → no clear detection by EGRET (the source does not stand out over the diffuse γ-ray flux)

- H.E.S.S. provided resolved images of several large shell-type SNRs

SN1006, X-rays Chandra

Particle acceleration in SNR

- Two possible processes:
  - Inverse Compton scattering of VHE electrons on ambient photons (mainly CMB)
  - Hadronic interactions of accelerated protons or ions in the interstellar medium

- Cut-off above 10 TeV + significant γ-ray flux (4.8 σ) above 30 TeV

- Primary particle energies:
  - Hadronic scenario
    \( E_{\text{proton}} \sim 200 \text{ TeV} \)
  - Leptonic scenario
    \( E_{\text{electron}} \sim 100 \text{ TeV} \) because of KN losses.

- Both scenarios explain the γ-ray emission.
  No conclusive proof

RX J1713-3946
Young (TeV) bright SNRs

- 5 shell-like sources detected in the TeV by HESS
- 4 are young (< $10^4$ years) historical SNRs
  - RXJ 1713.7-3946
  - Vela Junior
  - RCW 86
  - SN 1006 (last year)
  - HESS J1731-347 (most recent)

- All show rather clear correlation with non-thermal X-ray emission
SN 1006

- 2.2 kpc distance
- Type Ia supernova
- Non-thermal X-ray emission observed from the rims
- Suggests shock accelerated electrons >100TeV

- Rather uniform, low density environment (0.05 – 0.08 cm$^{-3}$), above Galactic Plane (clean, easier tests to models)
SN 1006 @ TeV

HESS observations
- Bipolar morphology, rim thickness compatible with PSF
- Faint TeV source: 1% of Crab Flux
- Morphology strongly correlated with non-thermal X-rays
  Suggests a common origin
- Ambiguity between leptonic and hadronic acceleration scenarios
SN 1006

Pure electron population

Electron+proton population

- Fails to reproduce the slope of the VHE spectrum

- $W_p \sim 12\% W_{SN}$
- Reproduce all multiwave data!
  - In any case energy budget dominated by protons

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HESS J1731-347

Originally a source with no counterparts

HESS J1731-347

Tian et al., arXiv:0801.3254

15h observation

Aharonian et al. (2008)

RADIO image by ATCA of G353.6-0.7

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HESS J1731-347

Tian et al., arXiv:0801.3254

15h observation

Aharonian et al. (2008)

More HESS observations!!
HESS J1731-347

With 60 h observation from 2007 and 2009
Identifying a new TeV shell

60 h observation

Shell morphology!

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HESS J1731-347A

Flat Azimuthal profile (different than SN1006 and RXJ 1713-3946)

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• Non-thermal shell seen in radio, X-rays... and γ-rays
• X-ray observations of (part of) shell reveal rims of emission with non-thermal spectra! (no evidence for thermal emission)
• X-ray absorption gradient suggests SNR lies behind a CO cloud
• $D > 3.5$ kpc, $L_{1-10 TeV} > 2 \times 10^{34}$ erg/s very luminous, $R > 15$ pc
MC & SNRs

- MCs are ideal targets to amplify the emission produced by CRs accelerated by nearby sources.
- Main idea: SNRs are PeVatrons up to $\sim 1000$ yrs and later the high energy CR escape and can illuminate local molecular clouds.
- CRs contribution (at the location of the cloud) from:
  - Galactic background: steep spectrum, steady in time, peaks at GeV energy region
  - Runaway from SNR: hard spectrum, variable in time
  - Superposition of both: concave spectra, variable in time
W 28

- W28: an old SNR (~35-150 kyrs) and molecular clouds seen in NANTEN CO (J=1-0); This association strongly indicates a hadronic origin for HESS J1801-233 and HESS J1800-240

- Presence of 1720 MHz OH masers: molecular clouds are perturbed by SNR. Three other sources: HESS J1745-303, HESS J1714-385 & HESS J1923+141

- Hadronic origin favoured -> bright in GeV domain

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about half (29) HESS Galactic sources are PWNe or candidates
PWNe

Objects powered by a relativistic particle outflow ($e^-/e^+$) from a pulsar- confined by SNR of pulsar progenitor

- Efficient conversion of rotation power into relativistic particles
- Associated with young pulsars – high spin-down power
- Expansion in a non-uniform medium may lead to complex morphology
- VHE $\gamma$-rays can be generated by IC scattering of relativistic electrons accelerated in the termination shock of the PWN.
Young pulsar wind nebulae (and composite SNRs) like Crab Nebula, G0.9+0.1, G21.5–0.9, Kes 75, MSH 15-52...
- compact, generally unresolved by H.E.S.S.

MSH 15–52:
- first PWN angularly resolved in TeV $\gamma$–rays
- X-ray thermal shell and non-thermal “jet-like” nebula

- Assuming (approximately) uniform target photon density, IC directly infers of spatial distribution of electrons

Evolved PWNe

**Older** pulsar wind nebulae

huge nebula ~few tens of pc, “offset” pulsar wind nebulae : Vela X

-offset from pulsar can be due to reverse shock (Blondin et al. 2001)

-VHE emission extends as far as the radio PWN (2° diameter)

Electron cooling observed ->HESS J1825 –137

- ✔ Spectral steeping away from pulsar
- ✔ ⇒ First observation of radiative cooling of electrons
- ✔ Gamma Flux: ~1% of pulsar rotational energy
Other sources
Dark TeV sources

Seem to shine in gamma rays
No plausible counterparts in radio, X-rays

- 50% of TeV source
- Old PWN, not seen in other wavelengths?
- Old SNRs, interacting with molecular clouds?

Gabici et al, 2008
Binary systems

• Compact object orbiting around a massive star. Scaled down versions of AGNs

- LS 5039: spectral modulation at orbital phase (3.9 days)

- Interpreted as pair creation on stellar photon field of the companion

- Other cases: PSR B1259-63 and HESS J0632+057
Massive star clusters

- Most massive compact young star cluster
  - 24 WR stars, >70% in binary systems
  - 80 blue SG stars, 3 red SG
  - 4-5 kpc, age $5 \times 10^6$ yrs, $6 \times 10^4$ $M_{\odot}$
  - Dissipated power in kinetic energy in the wind $10^{39}$ erg/s
  - Possible acceleration mechanisms: colliding wind binaries, collective stellar winds, supernovae explosions, Pre SN winds might blow superbubbles.

- HESS observation 2004-2008 (34h), 680 GeV energy threshold
- $2^\circ$ extension of VHE emission, partially correlated with HI shell $\Rightarrow$ Evidence for hadronic acceleration?
Massive star clusters

Westerlund 2

- Host >24 massive stars + 2 WR stars

- Origin of the emission from this source
  - WR binary WR20a
  - Cluster itself
  - CR accelerated in bubble interacting with environment
  - PWN and their synchrotron nebulae, Supernova explosions and their expanding remnants.
Massive star clusters

**Westerlund 2** reobserved this region (total 46h)

- Confirmed HESS J1023-575 - low X-ray emission + molecular clouds, Fermi possible counterpart the recently discovered PSR J1022-5746
- Second peak towards the pulsar PSR J1028-5819 coincident with HESS J1026-582 (suppressed at lower energies)
- Energy dependent morphology

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The extragalactic sky

TeV blazars
Radio galaxies
Starburst galaxies
## HESS TeV AGN

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<td>Cen A</td>
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http://tevcat.uchicago.edu
### Latest Addictions

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announced

✓ **1ES 0414+009**  \( z=0.287 \)  (one of the furthest AGN)
Atel#2293
~0.5% Crab flux level. Also FERMI source with an average flux above 1 GeV of \( (0.67 \pm 0.21) \times 10^{-9} \) photons cm\(^{-2}\) s\(^{-1}\), and a hard spectral index of \( (1.78 \pm 0.23) \).

✓ **1ES 0447-439**  \( z=0.2 \)
Atel #2350
Coincident with 0FGL J0449.7-4348, one of the brightest FERMI extragalactic source. Also associated with a Seyfert 1 galaxy located at a redshift of \( z=0.107 \).

✓ **PKS 1510-08**  \( z=0.36 \)
announced HEAD conf. 2010
broad-line Quasar, MWL campaign

✓ **AP Lib**  \( z=0.049 \)
Atel #2743
Fermi source 1FGL J1517.8-2423 (hard gamma-ray photon index of 2.1\(+/-0.1\)).
~2% Crab nebula flux
Fast variability in blazars

Short timescale variability (~ few minutes for PKS2155-304 in July 2006) → constraint on the size of the emission zone
Understanding the TeV blazars: PKS 2155-304

Detailed multi-wavelength observations to constrain models (HESS-Chandra simultaneous observations during flares)

Correlated spectral and flux variability, consistent with $\frac{F_\gamma}{F^3_X}$.

Incompatible with one-zone SSC model, need two components.

Flaring component Compton dominant; must be either very compact or external Compton.

Aharonian et al. (2009)
Monitoring PKS 2155-304

Abramowski et al 2010

New features:

- Quiescent state
- Flux-rms correlation observed in many accreting systems (Cyg X-1 type, some Seyfert-1s)
- Variability described as a lognormal stochastic process (multiplicative)

Challenging how to reconcile lognormality with rapid variability.

- New trend of the spectral index vs flux
MWL campaign on PKS 2155-304

SED described by SSC model

"Blob" $R \sim 10^{17}$ cm
Doppler factor $\delta \sim 3$
Field $B \sim 0.02$ G

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M 87: joint campaign

2007-2008: VERITAS/MAGIC/H.E.S.S./CHANDRA/VLBA campaign - 50 nights (>120 h)
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- VHE flare accompanied by radio flare from BH vicinity
- X-ray core (Chandra) fluxes increases
- HST-1 unlikely source of VHE emission
- VLBA (43GHz) resolves jet formation with 30 x 60 Schwarzschild radii

Acciari et al. 2009, Science

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In 2010 new MWL campaign, source in high state. Ongoing analysis

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Starburst galaxies: NGC 253

• New class of sources: NGC 253 (HESS)
• Very deep observations (100h), detected flux: 0.3% Crab
• Compact starburst region (a few 100pc) at nucleus, \( \sim 0.03 \) SN/yr
• Very high cosmic ray and gas density \( n \sim 600/150 \text{ cm}^{-3} \) vs \( \sim 1 \) in Milky Way
The future: HESS phase II

28 m diameter telescope under construction at the center of the array

- Mirror area: 600 m²
- Energy threshold: $\approx 30$ GeV
- Focal length: 36 m
- Weight: 500 tonnes
- FoV: 3.2°
- Sensitivity: $\times 2$ for $E > 200$ GeV
Conclusions

✓ Galactic sky bright in TeV, major discoveries since 2003:
  - Imaged supernova remnant shells, old SNR strongly indicate CR acceleration
  - Galaxy is full of VHE pulsar-wind-nebulae
  - Binary Systems: VHE modulation, laboratories for testing models
  - Diffuse gamma rays from interacting molecular clouds and star-forming regions

✓ Extragalactic sky: 17 extra-galactic sources: blazars, radio-galaxies and the new starburst galaxy.
  - Variability in blazars studied at the limit of the temporal sensitivity
  - MWL campaign very effective to test emission models

✓ Still exciting discoveries ahead with HESS .... and H.E.S.S. II should usefully complement satellite observations in the GeV range, particularly on variable sources (e.g. AGN).
Thanks
Backup slides
HESS J1731-347 A:
spectrum

Index = 2.3 ± 0.1_{stat} ± 0.2_{syst}

Flux(1-10 TeV) =
1.91 ± 0.17_{stat} ± 0.41_{syst} \times 10^{-12}

9% of Crab flux