HESS Galactic Plane Survey and Implications for CTA

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$L_{\text{TeV}} \sim 10^{32-34} \text{ erg/s} \quad <d>\sim 3\text{kpc}$
TeV Milky-Way (according to HESS)
HESS TeV horizon 1% & 10% Crab flux > 1 TeV

Carrigan et al 2013
Gamma Rays from multi-TeV particles

Protons: Gamma-rays and gas targets are generally spatially correlated (need to map atomic and molecular ISM)

Electrons: Gamma-ray (IC) + X-ray, radio emission (synch.) coupled (Bremsstrahlung usually minor)
TeV gamma-ray production:

Cooling times: Excellent first-order evaluation of dominant processes in particle accelerators

\[ t_{\gamma} \equiv \gamma \frac{E}{\dot{E}} \]

Pi-zero decay: 
\[ t_{pp} = (n\sigma_{pp}f_c)^{-1} \approx 5.3 \times 10^7 (n/cm^3)^{-1} \text{ yr} \]

IC scattering: 
\[ t_{IC} \approx 3 \times 10^8 \frac{U_{rad}/eV/cm^3}{(E_e/\text{GeV})^{-1}} \text{ yr} \]

Bremsstrahlung: 
\[ t_{br} \approx 4 \times 10^7 (n/cm^3)^{-1} \text{ yr} \]

Synchrotron: 
\[ t_{sync} \approx 12 \times 10^6 \frac{B/\mu G}{(E_e/\text{TeV})^{-1}} \text{ yr} \]

For ISM, B and \( U_{rad} \) parameters in many sources, TeV gamma-ray production can be slow: \( t > 10^4 \text{ yrs} \) especially for pi-zero decay

Slower than X-ray synchrotron (\( t < 10^4 \text{ yr} \)) but similar to radio synchrotron from GeV electrons.

TeV gammas and non-thermal radio \( \rightarrow \) relic emission in old sources e.g. ancient SNRs and PWNe
**Galactic TeVatrons and PeVatrons**

What are the particle accelerators to $E \sim 10^{15}$ eV (1 PeV)?

- **Shell Type Supernova Remnants?**
  
  \[ W_{CR} \sim 10^{50} \text{ erg per SNR} \]

- **Pulsar Wind Nebulae?**
  
  Pulsar spin-down power

  \[ \dot{E} = I \omega \dot{\omega} \sim 10^{32} \text{ to } 10^{39} \text{ erg s}^{-1} \]

- **Pulsars? Rotating dipole B**

  \[ E_{\text{max}} \approx 8 \times 10^{20} Z (B/10^{13} \text{G})(\omega/3000 \text{Hz})^2 \text{ eV} \]

- **WR, O & B stars, Massive Stellar Clusters, Massive Star Formation?**

  Stellar wind KE

  \[ L_w = \frac{1}{2} \dot{M} v_\infty^2 \]

  B-star \[ L \sim 10^{34-35} \text{ erg/s} \]

  WR star \[ L \sim 10^{38-39} \text{ erg/s} \]

- **X-Ray Binaries, Microquasars, Active galaxies (AGN)?**

  Accretion power

  \[ L_{\text{acc}} = \eta c^2 \dot{M}/2 \]

  \[ \eta = 10 \text{ to } 20\% \]

  Galactic \[ L_{\text{acc}} \sim 10^{40} \text{ erg s}^{-1} \]

  AGN \[ L_{\text{acc}} \sim 10^{46} \text{ erg s}^{-1} \]
Evolved SNR without MC interaction

Evolved SNRs interacting with Molecular Clouds

Young SNRs interacting with Molecular Clouds

Young shell-type SNRs

Historical SNRs

Interaction/association with MC

Isolated

N.B. ~50% SNRs are detected at GeV (Fermi) and TeV

From M. Lemoine-Gourmard
X-Ray-Bright Shell-Type Supernova Remnants
age < few 1000 yr
GeV-TeV spectra of supernova remnants
Funk et al.
Excellent TeV & Molecular Cloud spatial match

→ **best indication for CRs from SNRs!**

CR density $k_{CR}$

~7 to 30 x local value

**HESSJ1801-233**

SNR shock/mol cloud interaction

**HESSJ1800-240**

Also CRs from W28

+ HII regions?

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Old SNR ($>10^4$ yr) W28 + Molecular Gas

Aharonian et al 2008

**Nanten2 $^{12}$CO(J=2-1) image** -10 to 25km/s

(Nakashima et al 2008)
Dense ($>10^4 \text{ cm}^{-3}$) Cores of W28 Molecular Clouds (Nicholas et al. 2011a, 2011b)

$\text{NH}_3$ (23 GHz) & CS(1-0) (48 GHz) with Mopra

→ probe for cloud disruption and connection with W28
→ cosmic-ray diffusion properties (ala Core C in RXJ1713)
→ star formation properties of southern cores.
CR Diffusion \textit{Into} Molecular Clouds

R = distance CR travels into molecular cloud core

\[ R = 0.62 - \sqrt{6D(E_P, B)[1600 - t_0]} \text{ [pc]} \]

\[ D(E_P, B(r)) = \chi D_0 \left( \frac{E_P/\text{GeV}}{B/3 \mu \text{G}} \right)^{0.5} \text{ [cm}^2 \text{s}^{-1}] \]

\[ B(n_{H_2}) \sim 100 \sqrt{\frac{n_{H_2}}{10^4 \text{ cm}^{-3}}} \text{ [\mu G]} \]

\( \chi \) = diffusion suppression

→ Low energy CRs can't reach cloud core.
→ Expect harder TeV spectra from cores.
→ \textit{Don't expect electrons to penetrate!!} (due to sync. losses)
→ Need to map dense cloud cores
NE Shocked Cloud

Mass of dense core \( \sim 10^4 \, M_{\odot} \)

→ Gamma-rays from CS clumps (\( 10^{-14} \) to \( 10^{-13} \) ph/cm\(^2\)/s)

→ Detectable & maybe resolvable by CTA

<table>
<thead>
<tr>
<th>Region</th>
<th>( k_{\text{CR}} )</th>
<th>Expected flux ( F(E \geq 1 \text{ TeV}) ) (photons cm(^{-2}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE shocked cloud</td>
<td>13</td>
<td>(&lt; 5.1 \times 10^{-13})</td>
</tr>
<tr>
<td>G5.89 – 0.39 H( \text{II} ) region</td>
<td>18</td>
<td>(7.0 \times 10^{-13})</td>
</tr>
<tr>
<td>G5.89 – 0.39 NW arm</td>
<td>18</td>
<td>(5.4 \times 10^{-14})</td>
</tr>
<tr>
<td>G5.89 – 0.39 SE ridge</td>
<td>18</td>
<td>(1.6 \times 10^{-13})</td>
</tr>
<tr>
<td>G6.1 – 0.6 region</td>
<td>14(^a)</td>
<td>(6.5 \times 10^{-14})</td>
</tr>
<tr>
<td>G6.225 – 0.569 region</td>
<td>14(^a)</td>
<td>(1.6 \times 10^{-14})</td>
</tr>
<tr>
<td>HESS J1800 – 240 C</td>
<td>35(^b)</td>
<td>(4.7 \times 10^{-15})</td>
</tr>
</tbody>
</table>
RXJ1713.7-3946: Molecular Cloud Cores (Mopra Obs.)

Mopra observations CS(1-0) (N. Maxted)

- dense gas $10^{4-5}$ cm$^{-3}$
- mass $50 - 100$ M$_{\odot}$
CR diffusion into 'Core C'

2D Slices of CR diffusion depth vs E and $\chi$

Assume average B $\sim$ 17 $\mu$G

→ For $\chi \leq 10^{-3}$, can expect exclusion of $>1$ TeV CRs from centre

→ Similar trends for gamma-rays ($E_\gamma \sim E_p/10$)

→ Need <2 arc-min gamma-ray observations to resolve inner and outer regions.

→ New way to determine CR vs. electron nature of gamma-rays!

Deeper obs. With HESS (2015/2016)

→ many SNRs with CTA
Angular Resolution (HESS, CTA..) Acharyara et al 2013

CTA MST-SCTs with small pixels and/or hi-res cuts → resolve cloud cores!

>= 10 tels

HESS hi-res cuts e.g. DeNaurois et al 2009

ISM cloud core at few kpc
Typical radius

e.g. Cameron et al 2012
Arc-min Angular Resolution

0.004° XMM 10 keV

0.1° Simulation with current IACT

0.02° CTA @ few TeV

- sub-structure of SNR shock fronts will become visible at TeV energies;
- source morphologies
HESSJ1641-463
A Galactic PeVatron?
Acceleration of CRs above the knee ($10^{15} \sim 10^{18}$ eV)

A Major Mystery in High Energy Astrophysics...

- Diffusive Shock Acceleration Theory $E_{\text{max}} \sim \text{few } 10^{15}$ eV
  

Some ideas..... eg.

- Magnetic field modification $B>100 \, \mu G$ (Bell & Lucek 2001)
  → Young SNRs

- Re-acceleration of Galactic Cosmic Rays (Jokipii & Morphill 1985, Voelk & Zirakashvili 2001)

- Acceleration by Galactic GRBs – Hypernovae
  (Wick, Dermer, Atoyan 2004)

- Large-scale galactic shocks from Superbubbles via multi SNR, multi stellar winds from OB assoc.
Mopra CO(1-0)

Mopra CS(1-0)

HESS J1641-463

HESS J1640-465

Colour: Radio view (MOST 843 MHz)

Oya et al. (2013)
Parkes SPLASH 1720 MHz OH
(data courtesy Jo Dawson)
Simulated TeV gamma-ray emission (units GeV/cm$^2$/s/sr) from CRs escaping SNR RXJ1713.7-3946 (Acero et al. 2013)

Based on Casanova et al. 2010 (with Nanten CO(1-0) data)

$$D = 10^{28}(E/10\text{GeV})^{0.5} \text{ cm}^2/\text{s}$$

$$E_{\text{escape}} \sim 500 \ (t/100 \text{ yr})^{-0.43} \text{ TeV}$$
CTA 50h Observation - CRs escaping SNR

SNR age 2000 yr

Cloud mass $10^5 \, M_{\odot}$

d = 1 kpc

$D=10^{28}(E/10\text{GeV})^{0.5} \, \text{cm}^2/\text{s}$

PeV CRs escape first and arrive at the cloud first!

Ideal way to probe CR PeVatrons
CR propagation along B flux tube

→ Nearby clouds will see different CR densities

→ Need detailed maps of ISM gas + B-field direction

CR diffusion – not necessarily Isotropic!

Malkov et al. 2013
Nava & Gabici 2013
Pulsar Wind Nebulae (PWNe)
PWN HESS J1825-137
Energy-resolved morphology → particles are electrons (+ HESSJ1303-631)
Dense molecular cloud to north

> 2.5 TeV
1 – 2.5 TeV
< 1 TeV

TeV spectral evolution consistent with electron origin: Synchrotron & IC cooling vs. distance from pulsar!

Can search for hadronic pulsar winds!
- CTA will provide Galactic Plane TeV Gamma-ray maps on ~1-3 arc-min scales
  (~0.5 arc-min possible – high quality cuts)

- >3 sources per deg$^2$ $|b|<0.2^\circ$ $|l|<30^\circ$ (Dubus et al 2013)

- Diffuse TeV components visible?
  from CR 'sea' – maybe
  local CR accelerator enhancements – yes

Confusion guaranteed (same as for Fermi-LAT at GeV energies!)

- Mapping the ISM on arc-min scales over the plane will be essential
  Mopra (CO, CS), Nanten2 (CO), ASKAP (HI, OH), THz (CI, C+)
We need to map the interstellar gas to discriminate hadronic vs. leptonic gamma-rays!

<table>
<thead>
<tr>
<th>Gas species</th>
<th>Gas density</th>
<th>Imaging tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI (atomic H), OH</td>
<td>$\sim 10^1$ to $2 , \text{cm}^{-3}$</td>
<td>ATCA</td>
</tr>
<tr>
<td>CO</td>
<td>$\sim 10^3 , \text{cm}^{-3}$</td>
<td>Parkes</td>
</tr>
<tr>
<td>CO, NH$_3$, CS, SiO...</td>
<td>$&gt;10^3$ to $4 , \text{cm}^{-3}$</td>
<td>HEAT – THz telescope (Antarctica) [CI] + [CII]</td>
</tr>
</tbody>
</table>

$\rightarrow$ tracing the complete C budget!

**Team Members**
Gavin Rowell (lead, Adelaide), Michael Burton (UNSW), Yasuo Fukui (Nagoy), Bruce Dawson (Adelaide), Andrew Walsh (Curtin), Felix Aharonian (DIAS/MPIK), Stefan Ohm (Leicester)
Adelaide PhD students: Brent Nicholas (now at DSTO), Nigel Maxted (now at Montpellier), Phoebe de Wilt, Jarryd Hawkes, Fabien Voisin, Jame Lau, Rebecca Blackwell, Stephanie Pointon (MPhil student).

**Targets**
Since 2012 observed over ~40 TeV gamma and high energy sources, > 1500 hrs.

**Student Projects**
Phoebe deWilt – ISM survey of unidentified TeV sources, TeV+HII regions
Jarryd Hawkes – Outflow sources (e.g. XRBs) and magnetars
Fabien Voisin – Pulsar Wind Nebulae
James Lau – SNR/MC associations / G328 filament
Rebecca Blackwell – CMZ
Stephanie Pointon – Two bright unidentified TeV sources
First “Mono” Results from New 28metre Telescope

~30 GeV threshold

Vela Pulsar: 1\textsuperscript{st} Detection of pulsed Gammas from the Ground
Assume Crab-like power law extension

→ ~40% of Fermi 1PC pulsars potentially detectable
CTA Sensitivity vs. Time (HESS-II is similar!) Funk et al.

CTA (& HESS-II) >1000 times more sensitive than Fermi-LAT
→ GRBs, giant pulses, PWNe variability, FRBs, SGR bursts.
Thank you..