COSMIC RAY PHYSICS IN THE CTA ERA

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CHERENKOV ASTRONOMY

- VERY LOW FLUXES
- SPACE IS NOT AN OPTION
- NO ATMOSPHERIC PENETRATION
- ATMOSPHERIC SHOWERS

Galbraith & Jelley 1953

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<th>infrared</th>
<th>UV</th>
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Major Astronomical Facilities
- SKA
- ALMA
- E-ELT
- Athena
- CTA
THE FIRST GAMMA-RAY SOURCE

- 1960, COCCONI; THE CRAB NEBULA SHOULD EMIT GAMMA-RAY PHOTONS

- 1989: CRAB NEBULA OBSERVED BY THE 10 M TELESCOPE WHIPPLE (Weekes+ 89)

- FLUX FROM CRAB: 6 PHOTONS/ m²/yr
PRESENT DAY ATMOSPHERIC CHERENKOV TELESCOPES

VERITAS

MAGIC

H.E.S.S.
CTA TELESCOPES

- 4 LARGE (23 M) N/S
- 15/25 MEDIUM (12 M) N/S
- 70 SMALL (2M) S
WHAT

CTA WILL DO FOR

COSMIC RAY PHYSICS
**COSMIC RAYS**

- 98% PROTONS AND NUCLEI
  - 87% PROTONS
  - 12% He
  - 1% HEAVIER NUCLEI
- 2% ELECTRONS
- $10^{-3}$ ANTIMATTER (POSITRONS AND ANTI-PROTONS)

Very few particles but with an essential role for the workings of the entire cosmos.

$$n \approx 10^{-9} \text{ cm}^{-3}$$
THE BIG QUESTIONS

• WHAT ARE THE MAIN SOURCES OF GALACTIC COSMIC RAYS?
• WHERE ARE THE GALACTIC PEVATRONS HIDING?

• WHAT IS THE END OF THE CR LEPTON SPECTRUM?
• CAN WE USE IT TO CONSTRAIN LOCAL TURBULENCE?
• PWNe?

• IS THE CR SPECTRUM UNIVERSAL THROUGHOUT THE GALAXY?
• GALACTIC CENTRE PEVATRON AND ITS NATURE

• WHAT IS THE INTERPLAY BETWEEN CRS AND STAR FORMATION AT ALL SCALES
• IS THERE A UNIVERSAL GAMMA-RAY/IR RELATION?

• CRS AND IN OTHER GALAXIES: THE LMC

• WHAT IS THE ROLE OF CRS IN TERMS OF COSMOLOGICAL FEEDBACK?
• CR CONTRIBUTION TO GALAXY CLUSTER PHYSICS
GALACTIC COSMIC RAYS

- ASSOCIATION WITH SNRS SUGGESTED SINCE THE ‘30S (Baade&Zwicky 34)
  \[ L_{\text{CR}} \sim 3 \times 10^{40} \text{ erg s}^{-1} \sim 10\% (10^{51} \text{erg/100yr}) \]

- ACCELERATION MECHANISM SUGGESTED IN THE ‘70s (Krymski 77, Bell 78, based on Fermi 49)

- FIRST INDIRECT EVIDENCE: X-RAY OBSERVATIONS OF THIN SYNCHROTRON FILAMENTS IN YOUNG SNRs (e.g. Ballet 06, Vink 12 for a review): MULTI-TeV ELECTRONS, AMPLIFIED B-FIELD

- DIRECT EVIDENCE OF PROTON ACCELERATION IN MIDDLE-AGED SNRs: W44, IC443 (Agile, Fermi 09-10)
"PION BUMP" IN MIDDLE AGED SNRS INTERACTING WITH MOLECULAR CLOUDS

Fermi (Abdo+ 09,10; Ackerman+ 13) & Agile (Giuliani+ 10,11; Cardillo+ 14)

LOW MAX ENERGY

RE-ACCELERATION?
$\xi_{CR} \approx 2 \times 10^{-5}$

- OLD, SLOW SHOCK, LOW EFFICIENCY
- BRIGHT THANKS TO WEALTH OF TARGET

LOOK FOR EFFICIENT ACCELERATION ELSEWHERE,
  e.g. TYCHO (Molino&Caprioli 12)
TeV GAMMA-RAYS DETECTED FROM >10 SNRs:
• MOST SHOW STEEP SPECTRA
• CUTOFF/BREAK $E_Y < 10$ TEV

$E_{\text{max}} \approx 500$ TEV
$\xi_{\text{CR}} \approx 10\%$
DETECTING PEVATRON SNRS WITH CTA

- 100s OF NEW DETECTIONS OF SNRS
- COMPETING WITH RADIO WAVELENGTH DETECTIONS
MAXIMUM ENERGY IN SNRs

- MFA (Bell 04) DUE TO CURRENT OF ESCAPING PARTICLES
- GROWTH RATE PROPTO $J_{CR}$ WHICH DEPENDS ON SPECTRUM AT THE SHOCK, $P_{MAX}$ AND $V_s$ (Schure & Bell 13, Cardillo, EA, Blasi 15)

SELF-REGULATION MECHANISM

LITTLE TURBULENCE → CURRENT DECREASES → EFFICIENT ACCELERATION → LARGE ESCAPE FRACTION → TURBULENCE INCREASES → LARGE CURRENT
**PEVATRONS**

**TYPE I**

\[ E_M \approx 130 \left( \frac{\xi_{\text{CR}}}{0.1} \right) \left( \frac{M_{\text{ej}}}{M_\odot} \right)^{-\frac{2}{3}} \left( \frac{E_{\text{SN}}}{10^{51}\text{erg}} \right) \left( \frac{n_{\text{ISM}}}{\text{cm}^{-3}} \right)^{\frac{1}{6}} \text{TeV} \]

**TYPE II**

\[ E_M \approx 1 \left( \frac{\xi_{\text{CR}}}{0.1} \right) \left( \frac{M_{\text{ej}}}{M_\odot} \right)^{-1} \left( \frac{E_{\text{SN}}}{10^{51}\text{erg}} \right) \left( \frac{\dot{M}}{10^{-5}M_\odot\text{yr}^{-1}} \right)^{\frac{1}{2}} \left( \frac{v_w}{10\text{km/s}} \right)^{-\frac{1}{2}} \text{PeV} \]

**CARDILLO, EA, BLASI 15**

**RECENT B/C BY AMS-02**

**INDICATES STEEP CR INJECTION SPECTRA:**

\[ N(E) \propto \frac{Q(E)}{D(E)} \propto E^{-\gamma-\delta} \]

\[ \frac{N_{\text{sec}}(E)}{N_{\text{prim}}(E)} \propto \frac{1}{D(E)} \propto E^{-\delta} \]
WORSENING THE PROBLEM

\begin{align*}
N(E) &= Q(E) \tau_{ESC} \\
\tau_{ESC}(E) &\approx \frac{H^2}{D(E)} \propto E^{-\delta_e}
\end{align*}

\[ N_{\text{prim}}(E) \propto \frac{Q(E)}{D(E)} \propto E^{-\gamma-\delta_e} \]

\[ N_{\text{sec}}(E) \propto N_{\text{prim}}(E) \tau_{esc} \]

AMS02 DATA POINT TO
\[ \delta_e \sim 0.4 \]
\[ \gamma \sim 2.3 \]
**MAXIMUM ENERGY AND SOURCE SPECTRUM**

\[ E_{\text{max}} \propto \xi_{\text{CR}} E_{\text{SN}} \]

\[ \text{Flux} \propto \xi_{\text{CR}} E_{\text{SN}} R \]

**WITH** \( \Gamma_{\text{CR}} > 2 \),

**\( P_{\text{max}} = \text{PeV} \) REQUIRES:**

- **RARE** (<1/1000 yr\(^{-1}\))
- **EXTREME EVENTS** \( (E_{\text{SN}} > 10^{52}\text{erg}) \)
- **EXTREME EFFICIENCY** \( (\xi_{\text{CR}} > 30\%) \)

Cardillo, EA, Blasi 15
MASSIVE STAR WINDS?

\[ N_p \propto E^{-2.3} \]

Aharonian+19

\[ w_{CR} \propto 1/r \]

CR SPECTRUM AND ENERGETICS OK WITH CONTINUOUS INJECTION OVER FEW \( \times 10^6 \) YR

STRIKING SIMILARITY WITH GALACTIC CENTRE

WITH CTA:

• LOOK FOR CUTOFF
• CONSTRAIN SIZE OF EMITTING REGION (ENERGETICS)
THE GALACTIC CENTRE

- CLOSEST SUPERMASSIVE BH
- DENSE MOLECULAR CLOUDS
- MANY SNRs AND PWNe
- STAR FORMING ACTIVITY
- BASE OF LARGE-SCALE OUTFLOW

WITH CTA

- NATURE OF POINT-LIKE CENTRAL GAMMA-RAY SOURCE
  - HIGH SPATIAL RESOLUTION, SENSITIVITY TO VARIABILITY
- PARTICLE ACCELERATION HISTORY
  - DISTINGUISH CLOUDS FROM INDIVIDUAL POINT SOURCES, LOOK FOR CUT-OFF
- NATURE OF LARGE-SCALE OUTFLOWS
  - DETECT FBs AT 3 SIGMA IN 50 HR
- STUDY SNRs, PWNe, MCs
INDIVIDUAL SOURCES AND DIFFUSE EMISSION

SIMULATED CTA VIEW OF INNER 4°

A. Viana + in prep.
CENTRAL SOURCE AND J1741-302

**CTA CAN UNCOVER:**

- CENTRAL SOURCE EXTENSION
- CENTRAL SOURCE VARIABILITY
- SPECTRAL VARIABILITY WITH $T<30$ MIN

**CTA CAN DETERMINE:**

- J1741-302 CUTOFF (CURRENTLY UNDETECTED TO 10 TeV)
- NATURE OF EMISSION (LEPTONIC VS HADRONIC)

A. Viana + in prep.
CTA CAN UNCOVER:

- MORPHOLOGY
- SPECTRAL CUT-OFF UP TO 100 TeV (200 h observation)

SIMULATED OBSERVATIONS
COSMIC RAY ELECTRONS

- CR ELECTRONS AT \( E > 10 \text{ TeV} \) PROBE THE LOCAL CR ACCELERATION ENVIRONMENT (LOSS LENGTH \( \sim 100 \text{ pc} \))
- IACT SUITABLE FOR MEASUREMENTS (SEE H.E.S.S.)
- BROKEN POWER-LAW \([\text{SLOPE } -3(-3.8) \text{ BELOW (ABOVE) } 1\text{TeV}]\)
  DIFFICULT TO INTERPRET
- FINDING A CUT-OFF
ELECTRONS WITH CTA

3-SIGMA MEASUREMENT

Lopez-Coto+ in prep

\[ \alpha E^{-\gamma} \exp\left(\frac{E}{E_{\text{CUT}}}\right)^{\delta} \]

EXTRA COMPONENT

\[ \propto E^{\gamma} \exp\left(\frac{E}{E_{\text{CUT}}}\right)^{\delta} \]
CLUSTERS OF GALAXIES

LARGEST GRAVITATIONAL STRUCTURES IN THE UNIVERSE:
30–300 GALAXIES, R \sim FEW Mpc, M \sim 10^{14–10^{15}} M_{\odot}

30% BARYONS (10% STARS, 15–20% HOT DIFFUSE GAS)

70% DARK MATTER

ENERGY INPUT (MERGERS): 10^{64} \text{ erg/Gyr}

CLUSTER SCALE RADIO EMISSION

OPEN QUESTIONS FOR CTA

• DETECT GAMMA-RAY EMISSION FOR FIRST TIME

• DETERMINE CR PROTON CONTENT AND DYNAMICAL IMPACT

• CR ACCELERATION, PROPAGATION, CONFINEMENT

• ELECTRON ACCELERATION

• MAGNETIC FIELD DISTRIBUTION

COSMIC RAY RESERVOIRS

Brunetti & Jones 14
CTA KSP ON PERSEUS

Hitomi Coll, 16

- Nearby massive
- Brightest (ICM targets)
- AGNs sources of CRs
- Turbulence: CR transport

Mini Halo and edges in the ICM

Turbulence

- Thermal broadening
- $v_{therm} = 500$ km s$^{-1}$
- $v_{therm} = 1000$ km s$^{-1}$

Emission from XMM 100 kpc

Fe XXV

Beam

NGC 1265

NGC 1275

CR 15

IC 310

412343.9

4123436.9

18'-400 kpc
LIMITS ON CRs IN PERSEUS

MAGIC Coll: Ahnen et al 16
SUMMARY AND CONCLUSIONS

✓ MANY OPEN QUESTIONS IN CR PHYSICS
✓ CTA WILL GREATLY CONTRIBUTE TO CLARIFY SOME OF THEM
  ☐ THE NATURE OF GALACTIC PEVATRONS
  ☐ PHYSICS IN THE GALACTIC CENTRE REGION
  ☐ HELP CONSTRAIN GALACTIC PROPAGATION IN OUR NEIGHBOURHOOD THROUGH MEASUREMENTS OF MUTI-TEV ELECTRONS
    • AT THE SAME TIME CLARIFY ORIGIN OF POSITRON EXCESS
  ☐ CR CONTENT OF GALAXY CLUSTERS
    • COSMOLOGICAL IMPACT OF CRs
✓ EXCITING TIMES AHEAD