In search for Extragalactic Cosmic Rays

Star Burst Galaxies (SBGs)
Luminous InfraRed Galaxies (LIRGs)
and
Galaxy Clusters (GCs)

Vladimir V Vassiliev (UCLA)
for EnB SWG
Signature of Cosmic Rays in MW

- High-energy gamma-rays are produced in cosmic-ray interactions with interstellar gas and photons.

- Cosmic-ray production is associated with sites of SNRs & colliding OB stellar winds and enhanced in the regions of massive star formation.

- This represents approximately 90% of the high-energy gamma-ray luminosity of the Milky Way (~1.3x10^6 solar).

1991-2000, EGRET; >1.4 \times 10^6 \gamma\text{-rays detected; \sim60\% of all EGRET gamma-rays were diffuse emission from the Milky Way}

From D. Torres

(Strong, Moskalenko, & Reimer 2000)
Galactic Diffuse VHE emission

Most likely will be discovered by HESS soon
Diffuse radiation from Galactic Anti-Center region may be mapped by VERITAS

Slide is courtesy of HESS collaboration

VERITAS Science Meeting: Extragalactic non-Blazars Group
Diffuse emission from external galaxies

LMC
Distance: ~55kpc

30 Doradus:
- extensive massive SFR
- and molecular clouds

F(E>100 MeV) = $(1.9 \pm 0.4) \times 10^{-7}$ cm$^{-2}$ s$^{-1}$

- Only one other external galaxy detected in the light of its diffuse emission – LMC
- The problem is distance: Milky Way at 1 Mpc would have a flux of about $2.5 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$ (>100 MeV), well below EGRET’s detection limit and $\sim 2 \times 10^{-4} F_{\text{Crab}}$ (>1 TeV), well below VERITAS’s sensitivity

From D. Torres
Scientific Drivers

- Test SNRs and CR acceleration paradigm
- CR distributions in regions of high SFR
- Implications of star burst SF mode
- CR re-acceleration at large scales (>10 kpc)
- Starburst phenomena & relative influence of central black holes (effect of central radio sources)
- **Standard (!) extragalactic steady “candle”**
  (direct implications for EBL detection)
Expected hadronic CR $\gamma$-ray fluxes (scaling to MW)

$$E \frac{dF}{dE} \sim 5.2 \times 10^{-3} \Phi_{\text{Crab}} \left( \frac{E}{1\text{TeV}} \right)^{-1.75} \frac{\tau_{\text{conf}}}{\tau_{\text{MW}}} \frac{dR/dt}{dR_{\text{MW}}/dt} \frac{M}{10^9 M_\odot} \left( \frac{1\text{Mpc}}{L} \right)^2$$

$$\Phi_{\text{Crab}} = 3.2 \times 10^{-11} \text{cm}^{-2}\text{s}^{-1}$$
(Crab Nebula EdF/dE at 1 TeV; Hillas et al. 1998)

$$\tau_{\text{MW}} \sim 2.5 \times 10^5 \left( \frac{E}{1\text{TeV}} \right)^{-0.65} \text{yrs}$$
(Gaisser 1990)

$$dR_{\text{MW}}/dt \sim 1.5 \times 10^{-2} \text{yr}^{-1}$$
(Cappellaro et al. 1999)
Three strategies to enhance $\gamma$-ray fluxes

\[ E \frac{dF}{dE} \sim 5.2 \times 10^{-3} \Phi_{\text{Crab}} \left( \frac{E}{1\text{TeV}} \right)^{-1.75} \frac{\tau_{\text{conf}}}{\tau_{\text{MW}}} \frac{d\Omega}{dt} \frac{d\mathcal{R}}{d\mathcal{R}} \frac{M}{10^9 M_\odot} \left( \frac{1\text{Mpc}}{L} \right)^2 \]

Increase density of target gas $\rightarrow$ Star Burst Galaxies

\[ n_{\text{MW}} \sim 1\text{ cm}^{-3} \rightarrow n_{\text{NGC253}} \sim 10^5 \text{ cm}^{-3} \]

Increase Supernovae rate $\rightarrow$ Ultra Luminous InfraRed Galaxies

\[ d\mathcal{R}_{\text{MW}}/dt \sim 1.5 \times 10^{-2} \text{ yr}^{-1} \rightarrow d\mathcal{R}_{\text{IRAS17208-0014}}/dt \sim 5.4 \text{ yr}^{-1} \]

Increase CR confinement time $\rightarrow$ Galaxy Clusters

\[ \tau_{\text{MW}} \sim 2.5 \times 10^5 \left( \frac{E}{1\text{TeV}} \right)^{-0.65} \text{ yrs} \rightarrow \tau_{\text{GC}} \sim 10^9 - 10^{10} \text{ yrs} \]

Division is somewhat artificial particularly between first two classes

November 4-6, Tucson, AZ  VERITAS Science Meeting: Extragalactic non-Blazars Group
SBGs & ULIRGs
(steady state CR density)

pp interaction time

\[ \tau_{pp} = \frac{1}{n_p \sigma_{pp} c} \approx 3.52 \times 10^4 \text{ yrs} \left( \frac{10^3 \text{ cm}^{-3}}{n_p} \right) \]

MW : \( \tau_{pp} \approx 3.52 \times 10^7 \text{ yrs} \)

light crossing time

\[ \tau_{lc} = \frac{R}{c} \approx 3.26 \times 10^3 \text{ yrs} \left( \frac{R}{1 \text{ kpc}} \right) \]

MW : \( \tau_{lc} \approx 3 \times 10^4 \text{ yrs} \)

With no magnetic field \( \gamma \)-ray flux is CR escape limited and only <10% of CRs would interact

diffusion time

\[ \tau_{diff} \approx 2.5 \times 10^5 \text{ yrs} \left( \frac{R}{R_{MW}} \right)^2 \left( \frac{B}{3 \mu \text{G}} \right)^{0.65} \left( \frac{E}{1 \text{ TeV}} \right)^{-0.65} \]

With sufficiently large magnetic fields (> \( \sim 50 \mu \text{G} \)) \( \gamma \)-ray flux is SNR rate limited and all CRs would interact producing \( \gamma \)-rays
SBGs & ULIRGs
(interaction limited confinement regime)

\[ \tau_{\text{conf}} = \tau_{\text{pp}} = \frac{1}{n_p \sigma_{\text{pp}} c} \quad (\tau_{\text{pp}} \ll \tau_{\text{diff}}) \]

No dependence on density of target gas!

\[ E \frac{dF}{dE} \sim 7.6 \times 10^{-2} \Phi_{\text{Crab}} \left( \frac{E}{1\text{TeV}} \right)^{-1.1} \left( \frac{R}{1\text{kpc}} \right)^3 \frac{d\Phi}{dt} \left[ \frac{1\text{Mpc}}{L} \right]^2 \]

All CRs interact producing maximal \( \gamma \)-ray flux
Spectrum is hard reflecting CR spectrum at the source

Several SBGs and ULIRGs might be detectable at a few percent of the Crab Nebula flux

Morphology of the starburst region(s) and the strength of magnetic field matters!
Thus detailed multi-wavelengths source geometry dependent modeling to determine magnetic fields and densities of CR electron population(s) is important!
Exposure Requirements

- \(\gamma\)-ray fluxes are consistent with non-detection by Whipple and EGRET.
- Majority of VERITAS sources should be detected by GLAST after one year.
- VERITAS will need at least 20h per source to get below EGRET flux limits.

\[
\text{Sensitivity } E^2 \frac{dN}{dE} \text{ [erg cm}^{-2} \text{s}^{-1}] \\
\text{Energy [TeV]}
\]
SBGs & ULIRGs
(diffusion limited confinement regime)

\[ \tau_{\text{conf}} = \tau_{\text{diff}} ; (\tau_{\text{diff}} \ll \tau_{\text{pp}}) \]

- Up to \(~90\%\) of CRs may escape interaction resulting in reduced \(\gamma\)-ray flux
- Spectrum becomes softer due to energy dependent escape
- Majority of VERITAS sources should have been detected already by EGRET unless the dominant mechanism of radiation at EGRET energies is different (IC or Bremsstrahlung)

The possibility of leptonic (primary or secondary) origin of VHE radiation additionally complicates the picture

Re-acceleration of CRs at large scales by collective effect of shocks was also discussed
Nearby Starbursts: EGRET Limits


10 starbursts selected by distance (<10Mpc),
Infrared luminosity (>10^9 L_\text{solar}) at latitudes |b|>10.

From D. Torres
M82: closest northern SBG (pessimistic estimate)

For interaction limited regime M82 would have a flux of about 5% of Crab Nebula at 1 TeV (1kpc core)

Due to incomplete VHE CR confinement in the model it may be undetectable by VERITAS but detected by GLAST
Radio spectrum constrains cosmic-ray electrons

M82 (optimistic estimate)

Model
- transport by diffusion
- escape
- energy losses by ionization,
- inelastic scattering
- bremsstrahlung
- adiabatic cooling
- radiative losses

Spectral fit
- Free-free absorption
- thick-target steady-state

Use minimum energy assumption for B estimate

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### M82 Integrated flux predictions

#### Integrated flux above 100 GeV in ph./cm²/s

<table>
<thead>
<tr>
<th></th>
<th>Primary electrons</th>
<th>Secondary electrons</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$I_p = 10^{-12} K_{0.07} (B_{45})^{-1.55}$</td>
<td>$I_p = 2 \cdot 10^{-12} (B_{65})^{-1.52}$</td>
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<tr>
<td></td>
<td>$I_b = 10^{-14} (B_{45})^{-1.55}$</td>
<td>$I_b = 10^{-15} (B_{65})^{-1.52}$</td>
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<tr>
<td></td>
<td>$I_{ic} = 10^{-10} (B_{45})^{-1.55}$</td>
<td>$I_{ic} = 10^{-11} (B_{65})^{-1.52}$</td>
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From M. Pohl

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**November 4-6, Tucson, AZ**  
**VERITAS Science Meeting: Extragalactic non-Blazars Group**
IC component dominates flux prediction up to a few TeV

Magnetic fields assumed are 45 and 65 $\mu$G respectively
LIRGs Basics

- LIRGs have $L_{\text{FIR}} > 10^{11} \ L_\text{sun}$. Some, having $L_{\text{FIR}} > 10^{12} \ L_\text{sun}$ are the most luminous local objects. Their infrared luminosity is greater than the luminosity in all other wavelengths combined.

- These galaxies possess very large amounts of molecular material (e.g., Sanders 1991; Downes et al. 1992; 1993). Consequently, they present large CO luminosities, but also a high value for the ratio $L_{\text{FIR}} / L_{\text{CO}}$, both about one order of magnitude greater than for spirals. The latter implies, in star formation models, a higher star formation rate per solar mass of gas.

- The molecular material is often found concentrated in the central regions of the galaxies, at densities orders of magnitude larger than that found in giant Galactic molecular clouds.

- LIRGs (and especially ULIRGs) are generally regarded as recent galaxy mergers in which much of the gas of the colliding objects has fallen into a common center (typically less than 1 kpc in extent), triggering a huge starburst.

From D. Torres
ARP 220: Closest ULIRG (77Mpc)

Model
- All escape and energy losses mechanisms for e, p, and γ
- Detailed morphology description
- SNR rate ~ 2 yr^{-1}(!)

Spectral fit
- Steady-state
- Multi-wavelengths
- Synchrotron radio emission from secondary electrons
- Large B ~ mG
Detecting SBGs & LIRGs

- Gamma-ray detectability is favored in starburst galaxies (Akyuz, Aharonian, Volk, Fichtel, etc)
  - Large $M$, with high average gas density, and enhanced cosmic ray density

- Recent HCN-line survey of Gao & Solomon (2004) of IR and CO-bright galaxies, and nearby spirals
  - Allows estimate of SFR (from HCN luminosity) and minimum required $k$ for detection by LAT and IACTs (from HCN + CO intensities and distance)

- Several nearby starburst galaxies and a number of LIRGs and ULIRGs are plausible candidates for detection

From D. Torres

CR Enhancement required for detectability/LAT
Galaxy Clusters

Due to the large size of these systems (>0.5 Mpc) diffusive and convective escape time of VHE CRs is larger than the Hubble time.

Being trapped hadronic VHE CRs may or may not reach steady-state distribution

$$n_p \sim 8 \times 10^{-3} \ \text{cm}^{-3} \left( \frac{0.5 \text{ Mpc}}{R_{GC}} \right)^3 \frac{M_{GC}}{10^{14} M_\odot}$$

$$\tau_{pp} = \frac{1}{n_p \sigma_{pp} c} \approx 4.4 \times 10^9 \text{ yrs} \left( \frac{R_{GC}}{0.5 \text{ Mpc}} \right)^3 \frac{10^{14} M_\odot}{M_{GC}}$$

CRs from billions of SNRs which escaped host galaxies are accumulated through the Universe history
Observation of Galaxy Clusters

\[
E \frac{dF}{dE} \sim 0.1 \times \Phi_{\text{Crab}} \frac{\delta_{\text{escape}}}{0.01} \left( \frac{E}{1 \text{TeV}} \right)^{-1.0} \left( \frac{R}{0.5 \text{ Mpc}} \right)^3 \frac{<dR/dt>}{dR_{MW}/dt} \left( \frac{1 \text{Gpc}}{L} \right)^2
\]

- Even if only 1\% of CRs escape from host galaxies into inter-cluster medium, GCs may still be observable by VERITAS even at moderate cosmological distances (no $\gamma$-$\gamma$ absorption assumed)

- Merging activities within the cluster may substantially increase supernovae rate averaged over CR confinement time (pp interaction time) or cluster evolution time
Additional scientific motivations

- Interaction of intercluster medium with bubble inflating radio galaxies
- CR re-acceleration in large scale shocks
- Prominent Dark Matter search sources
- Potential sources of cosmological VHE diffuse backgrounds
- Source of UHE Cosmic Rays
- May become standard candles for VHE astronomy around ~100 GeV

Perseus A

Hydra A X-ray and Optical
Coma cluster: Modeling

Expected flux from the Coma Cluster (Voelk 2003).

From J. Perkins

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Coma-like cluster: general remarks

Due to extended apparent size of clusters the detection sensitivity of IACTs will be reduced

Prospects of detecting TeV $\gamma$s from ICS of ultra-relativistic $e^-$ in clusters of galaxies is not promising

Arguably only massive, nearby clusters could be detected by future IACTs

(Gabici & Blasi 2003)

Distance $\sim$ 100 Mpc
with & without IR absorption

From R. Mukherjee

There is no fundamental limit which would indicate that distant clusters cannot be detected by IACTs

Under the assumptions of maximum $\gamma$-ray flux production the more distant cluster among two with the same angular size will have larger flux

Careful modeling is required
Keshet et al. (2002) predict that IACTs may be able to resolve $\gamma$-rays from nearby ($z < 0.01$) rich galaxy clusters, perhaps in the form of a $\sim 5$-10 Mpc diameter ring-like emission tracing the cluster accretion shock, with luminous peaks at its intersections with galaxy filaments detectable even at $z \sim 0.25$.

From R. Mukherjee & J. Perkins
Summary

- The $\gamma$-ray radiation produced by CR interactions in galaxy clusters, luminous infrared galaxies, and starburst galaxies should be detectable by VERITAS.

- Multi-wavelength observations and extensive theoretical modeling will be required to determine critical parameters of these systems, such as magnetic field and so on, to select most promising targets.

- At the moment M82, NGC6946, ARP220, NGC 2146, NGC1068, IC342, M51, NGC1365, Coma, and Perseus are the best targets for observations during first year of VERITAS operation.
A source with differential spectral index $\sim 2.1$ can be detected around 1 TeV with the flux of 5% of the Crab Nebula for $\sim 3$-4 hours ($\sim 2\%$ for 20 h; 1% for 100h).

To avoid EGRET upper limit we need $> 20$ h per “classical” source.

Select 5-10 most promising sources and conduct observations during first year with exposure $\sim 20+$ hours per source.

Conduct guided by GLAST deep search for GCs and nearby SBGs and ULIRGs.

Survey “non-classical” sources with positive carefully modeled predictions based on multi-wavelengths observations.
Exposure: 50 hours

Required spectrum resolution: 20% (equivalent to $5\sigma$ above background or > 25 photons in each energy bin)

Analysis energy resolution: $\Delta E/E = 0.58$ (4 bins per decade)

Array Energy resolution: $\Delta E/E \sim 0.12$