Astroparticle physics with Milagro
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OUTLINE:
- Very High Energy Gamma Ray Astronomy
- Origins of VHE gamma rays
- Current Paradigm for non-thermal radiation
- The Milagro Detector

Observations:
- Standard Candle – the Crab Plerion, and BG rejection
- Blazar Mrk 421 observed during its ‘hot’ period
- Galactic disc in TeV gamma rays
- TeV emission from Gamma Ray Bursts (GRB)
- Solar Energetic Particle events

1. VERY HIGH ENERGY GAMMA RAY ASTRONOMY

Milagro Energy range: Above 100 GeV
Not reachable by direct measurements with satellite instruments because of small flux.
Gamma rays produced in relativistic astrophysical environments from interactions of high energy particles with photons and/or matter.

High energy particles produced by cosmic accelerators
- Relativistic jets in AGNs and GRBs
- Supernova shocks into ISM
- Stellar wind shocks
- Dynamo electric fields in neutron stars
Stochastic processes which produce non-thermal power law spectra.

Sources of VHE gamma rays:
- Galactic Sources: The Crab Nebula and Supernova Remnants
  Galactic Cosmic Rays interacting with ISM producing pi-zeros
- Extra Galactic Sources: Active Galactic Nuclei
  Gamma Ray Bursts
- Exotic sources: e.g. WIMP annihilations in the Sun or GC
- Active Galactic Nuclei Have Super Massive Black holes at the center of a galaxy
  GRBs are thought to be mergers of n-stars, nstar and BH in galaxies at cosmological distances.
  SNRs have a n-star or BH providing energy
- Some examples are shown next
Composite picture of the Crab Nebula powered by a rapidly rotating neutron star with \( P = 33 \text{ ms} \)

Crab SN Observed in 1054

Active Galactic Nucleus

Note the disc around the BH and two jets along the rotation axis of BH

If one of the jets is pointing towards earth it is a Blazar

Electron being accelerated in jets by shocks and emitting IC and Synchrotron gamma rays

Origin of high energy gamma rays: Essential ingredients

Energy Sources: Accretion in AGNs
N-star N-star coalescing in GRBs
N-star spin in Plerions
SN shock in SNRs

How are charged particles accelerated?

Acceleration by ubiquitous SHOCKS

The Processes Involved

Central Engine
- Pulsars, SNR, AGNs: Supplies the energy

Accelerator
- Ubiquitous shocks / vacuum gaps with electric fields
- Acceleration done by changes of B field or by Electric fields
- Electrons, positrons, protons and nuclei accelerated

Gamma production
- Synchrotron radiation, Bremsstrahlung, Inverse Compton and pion production. Need B fields and ambient photons and matter to generate the photons.

Gamma absorption in source
- Gamma energy degradation by EM cascade on ambient photons

Gamma absorption in transit from source
- By collisions with either EBL or CMBR

Observed Flux
- At the earth
**Shock Acceleration**: Stochastic process of charged particles crossing and recrossing an expanding shock wave and gaining energy each time. Energy gain per cycle

- **Energy Gain proportional to Energy**
- **Cycle time independent of Energy**

Probability of recrossing depends on diffusion out of the shock region. Higher the energy more crossings are needed and a longer time. This leads to a universal power law spectrum – non thermal spectrum.

\[
dN/dE \sim \text{const } E^{-2} \quad \text{up to a maximum energy}
\]

Fermi Acceleration - “First Order” 1949 and And Bell, Ostriker, Axford in 1978

**Electrons, positrons, protons and nuclei can be accelerated by stochastic processes to high energies.**

**High Energy gamma rays can be produced by:**

- Synchrotron radiation by electrons and positrons in B fields
- Bremmstrahlung by electrons on ambient nuclei
- Inverse Compton of high energy electrons on photons
- Hadronic collisions of accelerated nuclei on ambient matter or ambient photons

This is shown in the next slide.
**CURRENT PARADIGM FOR VHE GAMMA RAY EMISSION**

1. Shocks accelerate charged particles to high energies: Non-thermal spectrum electrons, positrons, protons and nuclei.

2. Synchrotron radiation by electrons in ambient B fields: $E \propto B^3$, up to energies $E \propto Y^2 \propto B^3$, where $Y$ is the Lorentz factor of the electron.

3. These accelerated electrons can Inverse Compton scatter with ambient photons, which can be the synchrotron photons themselves or CMB or IR in the source.

   The maximum energy of the upscattered photon is given by
   
   $$E = Y^2 E_{\text{ambient photons}}$$

   $Y$ is the Lorentz factor of the electron.

   The energies of the upscattered photons by energetic electrons are in TeV range!

4. The spectrum of the emitted gamma ray spectrum can be calculated if the spectrum of the accelerated electrons (or protons) is known.

   **Accelerated protons can also produce gammas via pion production if sufficient target material is traversed in the source.**

5. The shape of the observed gamma ray spectrum can be modified by absorption of emitted gamma rays by intervening ambient intergalactic photons - EBL.

   If EBL is known then Source spectrum can be deduced.
   If Source distance and spectrum is known then EBL can be estimated.

   A non-trivial inverse problem.
The energy spectrum of produced high energy gamma rays is also a non-thermal energy spectrum – a power law.

The yield depends on:
- Flux of accelerated particles
- Source magnetic fields
- Ambient photon distribution and density
- Density of matter in source or in the ISM

The flux of gamma rays observed at earth depends on:
- Distance of source to earth
- On absorption of gamma rays in transit from production to earth.

The Milagro Collaboration

Search for VHE Gamma Ray emission from Energetic Astrophysical Sources – both steady and transient
A Gamma Ray shower

Milagro Telescope

Milagro air shower detector detects showers produced by gamma rays or by cosmic ray nuclear particles.

Cosmic ray showers constitute the background for gamma ray detection. They occur at a rate which is about 10,000 times the expected gamma rates.

Milagro is able to reject more than 90 percent of these background showers!

Milagro High Energy All sky Telescope: The Pond and Site

The telephone poles support a grid of wires which form a Faraday Cage for Lightning protection – important in the summer.

LOCATION

Hot Dry Rock Fenton Hill Site in Jemez Mountains in New Mexico.

- Elevation of 2630m (750 g/cm²)
- 60m X 80m X 8m covered pond
- Water-Cherenkov EAS detector

Milagro detector

100% coverage, 50% eff.
Wide field of view
High duty factor (>90%)
Sensitivity above 100 GeV

Schematic

450 Top Layer 8" PMTs
273 Bottom Layer 8" PMTs
Milagro Shower Detection Method:

Use water instead of scintillators to detect EAS particles
100% of the area is sensitive (instead of 1% with scintillator).
Sensitive to electrons, gammas, hadrons and muons in shower

Milagro Properties for detection of VHE gamma rays

- Low energy threshold (100 GeV)
- Median energy ~4 TeV
- High duty cycle (~95%)
- Large field of view (~2 sr)
- Good background rejection (~90%)
- Trigger Rate 1.7 kHz

Milagro has been operating since 2000
- 0.208 Trillion Events
- Outriggers were finished in 2003
- We run with ~96% on-time
- Data rate is ~ 1700 Hz
- 8-9% deadtime
- We reconstruct in real-time
- We look for GRBs and send out alerts
- One month of raw data saved for archival analysis
- Data is sent via network to LANL & UMD
- Nearly total remote capability

Method of Measuring shower direction and shower energy with Milagro

Shower particles (electrons, positrons, gammas, muons) all move with about the speed of light and hence form a plane. They traverse the water of Milagro detector and produce Cherenkov light which is detected by the PMTs. We measure pulse height and arrival time of photons hitting the PMTs.

The distribution of arrival times is used to reconstruct the shower plane and the direction of the incident particle which generated the shower.

We can do this to about 0.5 degrees accuracy. Knowing the time of the event we can find the celestial direction of the incident particle – RA and DEC or Galactic Latitude and Longitude.
The Outrigger Array of water tanks

1. Determination of the Core position: Where the incident particle would have hit if it reached the earth.
2. Improving the angular resolution
3. Estimating the energy of the particle creating the shower

The outrigger array of water Cherenkov detectors – in red

Some outrigger water tanks in the winter

4 square meter in area and 1 meter deep with 1 PMT looking down
Shoup and Yodh

Diamond Energy estimates **with** and **without** outriggers

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<thead>
<tr>
<th>With</th>
<th>Without</th>
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<tr>
<td><img src="image" alt="Energy Resolution with outriggers" /></td>
<td><img src="image" alt="Energy Resolution without outriggers" /></td>
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Estimated Energy TeV

Yodh

Rejection of Cosmic Ray triggers: Gamma Hadron Separation

Muon (Bottom) layer response
\[ X_2 = \frac{N_{B2}}{P_{\text{Emax,bot}}} \]

- \( N_{B2} \): Number of bottom layer tubes > 2 PE
- \( P_{\text{Emax,bot}} \): Maximum PE in bottom layer

Optimal cut \( X_2 > 2.5 \):
- Removes \(~90\%\) of background
- Preserves \(~50\%\) of \(\gamma\)-ray events
- Increases sensitivity to \(\gamma\)-ray sources by a factor of \(~1.7\)

Yodh, Shoup and Sinnis

Gamma rays simulated on a 'standard' spectrum: \(E^{-2.4}\)

Milagro Sensitivity to Gammas

- Effective area vs Energy
- Median Energy vs zenith angle

Shadow of the moon in cosmic rays

- Geomagnetic field deflects the position of the shadow.
- The average deflection gives a "MC" independent determination of our energy calibration.

Moon subtends an angle of radius 0.25 degrees at the earth – the same as that by the sun.
Moon Shadow: Energy Scale Calibration

Proton Response

\[ E = 640 \pm 70 \text{ GeV (MC 690 GeV)} \]
\[ \sigma_\theta = 0.9^\circ \]

Detection of Discrete TeV Sources by Milagro:

Source: Galactic standard Candle – The Crab nebula
Extra-Galactic Sources: Flaring nearby Blazars

Mrk 501 by Milagrito in 1997-98 (not shown)
Mrk 421 by Milagro in 2001 and 2004

Milagro Results for the observation of the Crab and Mrk 421

X2 cut applied to reduce cosmic ray background

CRAB

Mrk 421

TeV emission from the Crab Nebula:

Crab is known to be a standard candle in TeV range. The emission is not pulsed.

We detect the Crab in 1 year at six sigma. The flux detected for 1 Crab can be used to estimate the Luminosity of the Crab in TeV gamma rays – Crab is 2 Kpc distant from the earth. (We detect about 20 photons/day from the Crab)

\[ L_{\text{ Crab}} = 3.14 \times 10^{34} \text{ ergs per second} \]

This can be compared to total energy radiated by the crab, which is

\[ L_{\text{total}} = 5 \times 10^{38} \text{ ergs/sec} \]

So Crab emits \( 10^{-4} \) of its radiated energy into TeV gamma rays

Let’s do a similar estimate for the AGN Mrk 421, which is at a distance of 150 Mpc \( (z = 0.035) \)

About 20 gammas from Crab per day detected

TeV emission from AGN Mrk 421:

A 3 sigma signal was seen from Mrk 421 in about 3.5 months. This was
during flaring of Mrk 421 with an average flux about 3 times that of the
Crab. A calculation of the Luminosity emitted by Mrk 421 into TeV gamma
rays can be carried out to obtain:

\[ L_{\text{Mrk421}} = 6 \times 10^{46} \text{ ergs per second} \]

Typical values for total energy radiated by BL lac objects is about

\[ L_{\text{total}} = 10^{48} \text{ ergs per second} \]

So in this case about 0.01 fraction of the energy radiated is in TeV gamma
rays – a much larger fraction than in the Crab.

GRBs are also supposed to produce energetic jets where particles are accelerated
to high energies and with high energy gamma production. GRBs typically radiate

\[ 10^{53} \text{ ergs during their burst} \]

Hence one might expect substantial emission of TeV gamma rays. If the GRB
was close enough – that is z less than about 0.1 then Milagro should be able
to observe that GRB in TeV energies. I will describe Milagro results for GRBs
a little later in the talk.
Improvements with Outriggers

Crab in one year

- 12 months of recent data on the Crab
- ~3 times faster to get same signal
- Another factor of ~1.5 for the Crab is expected from yh sep

Observation of Diffuse TeV Gamma rays from the Galactic Disc

Cosmic rays are mainly confined to the Galactic Disc. In their propagation in the disc their life time before escape is about 10 million years. In this time they traverse a substantial amount of Inter-stellar matter and interact with protons in ISM producing neutral pions which decay into two gamma rays. This generates a diffuse source of gamma rays which should be confined to the disk in the direction of the galactic center.

Milagro is sensitive to TeV gamma rays and should see an enhancement from a region defined in galactic coordinates given by:

- Galactic latitude with 2 degrees of the galactic plane
- Galactic longitude between 20 and 100 degrees.

First I show the results from CGRO, which clearly saw this emission at energies up to about 1 Gev.

Observations by EGRET

- Detailed measurements of flux of gamma rays from galactic plane:
  - $E > 1\text{GeV}$, ~5-10 degree wide emission region
  - Maximum at galactic center
  - Brighter inner galaxy region
- Truly diffuse emission also found (isotropic):
  - Extragalactic in origin
  - Unknown source
**Why Use Milagro to look for Emission from the Galactic Plane?**

- **The task:**
  - Detect the gamma ray flux from the galactic plane where the cosmic ray background outnumbers the gamma rays by ~10,000 to 1.
- **Milagro has:**
  - Wide field of view
  - Good background rejection
  - Low energy threshold

**Selection of Data**

- **Data taken:**
  - July 00 – Jan 04 (1000 d)
  - Reconstruction done online
- **Cuts applied:**
  - $X_2 > 2.5$
  - Quality Cuts
  - $10 < \text{DEC} < 60$
- **Look for excess in**
  - Inner Galaxy Region (IG)
  - Outer Galaxy Region (OG)
  - 10 degree wide band

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**Map of Galaxy in TeV gamma rays as seen by Milagro**

*5 $\sigma$ excess for the “inner galaxy” - Flux fraction $\sim 8 \times 10^6$ of CR*

This is the first detection of the galactic plane at these energies ($\sim$TeV)

Nemethy, Fleysher, Blaufuss

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**Galactic Plane as seen by Milagro in TeV gamma rays**

As Fraction of Cosmic Rays

Fleysher, Nemethy
TeV emission from GRBs:

Milagrito Observation
Milagro search and capabilities

Two types of Searches:
Triggered searches for GRBs within our field of view
Untriggered searches for transients

Evidence for a TeV signal from GRB970417a was seen by Milagrito (a smaller, single layer prototype of Milagro)

- 18 signal events with an expected background of 3.46 ->
  Poisson prob. 2.9e-8 (5.2σ).
  Prob. after correcting for size of search area: 2.8e-5 (4σ).
  Chance prob. of this excess in any of the 54 GRB examined for TeV emission by Milagrito: 54x2.8e-5 = 1.5e-3 (3σ).

Thesis research: Isabel Leonor UCI
Luminosity of GRB970417a

More luminosity at TeV energies than MeV energies. But the GRB must be close due to TeV-IR absorption, so the total energy released is not unusually large.

If $z \approx 0.1 \Rightarrow E_{\gamma} < 700\text{ GeV} \Rightarrow L < 5 \times 10^{51}\text{ ergs}$

If $z \approx 0.03 \Rightarrow E_{\gamma} < 10\text{ TeV} \Rightarrow L < 1 \times 10^{49}\text{ ergs}$

Red shift not known

VHE Instrument Sensitivity

For observations of the prompt phase of GRB, current and future high energy gamma-ray instruments (GLAST and Milagro) are very complementary.

Milagro and GLAST Sensitivity

For a 1 second observation, Milagro becomes more sensitive than GLAST at ~100 GeV.

How many GRB will we see at TeV energies?

(Boettcher and Demer 1998) 9% with $z \approx 0.3 \Rightarrow 9\text{ year}$

(Schmidt 1999) 0.6% with $z \approx 0.3 \Rightarrow 0.6\text{ year}$

These predictions are only for long duration bursts and are very uncertain at low redshifts.
Milagro GRB Observations (triggered)

- ~30 satellite detected GRBs have been within Milagro’s field of view of 45 degrees from zenith
- No high energy emission is detected from any of the 30 bursts
- One of the bursts is in a Galaxy of redshift of 0.45

**GRB3921, z = 0.45**

- HETE detected burst
  - Fluence (8-50 keV) = 1.5 x 10^{-5} ergs/cm²
- Milagro 99% confidence upper limits
  - Fluence (> 4 TeV) < 2 x 10^{-7} ergs/cm²
  - Fluence (100-150 GeV) < 4 x 10^{-5} ergs/cm²

Milagro as a Solar Energetic Particle Event Monitor

Milagro sensitive to energies above 10 GeV

Has seen Coronal Mass Ejections and Forbush Decreases

Thesis Abe Falcone UNH 1997
Published in Ap J.

1. Search for simultaneous increase(decrease) of singles trigger rates in PMTs
2. Search for rate increase(decrease) in triggered events

Must account for rate variations due to atmospheric conditions of P and T

Coronal Mass ejection from the Sun : CME

Solar Wind can cause decrease in galactic cosmic ray flux – Forbush Decrease
**Breaking Results on Mrk 421 (Preliminary)**

- Mrk421 is flaring now - (~3 crab)
- With just 8 days of data ~3.3 $\sigma$ (more coming)

**Conclusions**

- Moon shadow determines energy scale to ~10%
- Background Rejection Demonstrated (90%)
- Detected 3 known sources
  - Crab nebula
  - Mrk 421 and Mrk 501 with Milagrito
- Surveying the TeV Sky
- Preliminary detection of galactic diffuse emission
- Trigger upgrade complete (5/2002)
- Real-time GRB search
- Outriggers improve:
  - sensitivity ~2-fold
  - energy resolution to ~50%
Published Milagrito and Milagro Papers

TeV Gamma-Ray Survey of the Northern Hemisphere Sky Using the Milagro Observatory
Accepted for publication in the Astrophysical Journal; astro-ph/0403097

Limits on Very High Energy Emission from Gamma-Ray Bursts with the Milagro Observatory

Observation of TeV Gamma Rays from the Crab Nebula with Milagro Using a New Background Rejection Technique

Observation of GeV Solar Energetic Particles from the 1997 November 6 Event Using Milagrito

The High-Energy Gamma-Ray Fluence and Energy Spectrum of GRB 970417a from Observations with Milagrito

Milagro Papers in Preparation

Observation of TeV Gamma Rays from the Galactic Plane

Observation of a Forbush Decrease at High Energies from the Solar Event of 29 October 2003

First Constraints on Very High Energy Emission from Galaxy Clusters

Constraints on Very High Energy Emission from a z>0.45 Gamma-Ray Burst and 29 Others

Search for TeV Gamma Rays from Short Duration Gamma-Ray Bursts and Evaporating Primordial Black Holes

Detection of the Moon’s Cosmic Ray Shadow to Determine the Energy Scale of Milagro

Search for Very High Energy Emission from Nearby Blazars

Search for Very High Energy Gamma-Rays from WIMP annihilations near the Sun with the Milagro Detector

Observation of a Large Scale Cosmic Ray Anisotropy at TeV Energies