Top 10 Extragalactic Science Questions
(Thoughts On What We Need…)

- AGN+Jets
- GRBs
- Galaxies & CRs
- Clusters + Large Scale Structure
- UHECR
Jet Origin

1.) Mass Accretion onto Black Hole

- Extraction of up to 42.6% of Rest Mass Energy of Infalling Material
- Accretion Disk → Jet Matter

2.) Extraction of Rotational Energy of Black Hole

- Extraction of up to 29% of Rest Mass Energy of Black Hole
- Electron/Positron Jet

=> Different Jet Matter
Different AGN Life Time

Jet composition???

But...

Electromagnetic Formation of Jets

Strong magnetic field, generated or trapped by accretion disk induces voltage across spinning hole which drives current.

For Cygnus A:

\[ B \sim 10^4 \text{ G; } M \sim 10^9 M_\odot \]
\[ E \sim \Omega \Phi \sim 10^{20} \text{ V} \]
\[ R_{in} \sim R_{out} \sim 100 \Omega \]
\[ I \sim V/R \sim 10^{18} \text{ A} \]
\[ P \sim E I \sim 10^{38} \text{ W} \]
Hadronic vs. Electronic models of TeV Blazars

SSC or external Compton – *currently most favoured models*:  
- easy to accelerate electrons to TeV energies  
- easy to produce synchrotron and IC gamma-rays  
  recent results require more sophisticated leptonic models

Hadronic Models:
- protons interacting with ambient plasma  
  very slow process: \( t_{pp} \sim 10^{15}(n/1\text{cm}^{-3})^{-1}\text{sec} \)  
- protons interacting with photon fields  
  low efficiency + severe absorption of TeV \( \gamma \)-rays  
- proton synchrotron  
  very large magnetic field \( B=100 \text{ G} \) + acceleration rate \( c/r_g \)  

“*extreme accelerator*” (of EHE CRs) *Poynting flux dominated flow*

*detectable neutrinos from EGRET AGN but not from TeV blazars*

F. Aharonian
Infrared? (Blazejowski et al. 2000, hot dust in central 100 pc)

? Ouch! (external shock)

UV/Optical

SHOCK! (internal) = dissipation + particle acceleration

(reprocessing of disk emission)

BLR

e-p or e^+e^-

??

BH Spin?

Accretion Disk

\gamma-Sphere

The central engine of a generic gamma-ray blazar is a MESSY place!
Christmas Tree/Internal Shock Model … clearly not right for some objects

Mrk 501 X-TeV correlation STABLE over 3+ months!

Linear Axes!

Steady X-Ray Component??

Figure 1. Correlation between X-ray (RXTE) and TeV Gamma-ray fluxes. The Gamma-ray fluxes are from CAT (squares), HEGRA CT System (solid points), HEGRA CT 1 (asterisks), and Whipple (open circles). Only observation pairs with less than 6 hrs time delay have been used.

N.B. June 1997 data (after main flaring) included!

$L_{TeV} \propto L_x^2$ (naive SSC)

$L_{TeV} \propto L_x$ (ERC, SSC, hadronic model)

Key – 3 keV flux tracks TeV flux relatively poorly
Multiple Emission Components!

Krawczynski et al. 2004
In case you still thought things were simple…

Mkn 421 2002 X-ray/TeV campaign

(Dieter Horns, preliminary)
PKS 2155-304: multiwavelength coverage of flares …

Uh, oh….

\[ \Delta t_{\text{min}} / M_{BH} \]

GRB:

10^{-3} \text{ sec} / 10 \, M_\odot \quad \square \quad 10^{-4}

2155:

300 / 10^9 \, M_\odot \quad \square \quad 3 \times 10^{-7}! \quad (\Delta t_{\text{min}} < R_{\text{Schwarzschild}} / c)

Foschini et al. 2007 (astro-ph/07010868)
EBL absorption complications II: Incredibly hard gamma-ray spectra

L. Costamante
Blazar Problems…

One zone SSC models can match TeV blazars SEDs well but…

Details don’t work so well…
- Emission region very out of equipartition? (B low? Poynting dom?)
- Doppler factor >> 10
- Jet very radiatively inefficient, huge jet power?
- Very rapid variability, how to accelerate particles so fast?
  - too small/too efficient emission regions?
- Multiple emission components!

Making Compton-dominated TeV sources not so easy …
- Mess up “unified” blazar model?

Population statistics! (δ~50? But then why see M87?)
- EBL makes all problems worse 😊

[ For GLAST, don’t forget K-N effects, Γ<1.5 at hard X-rays still problematic ]
Theorist’s Wish List (for AGN)

Rule of thumb: give a theorist a spectrum consistent with a power law (e.g., due to insufficient statistics) and he can fit any model/EBL you like.

Need to detect *curvature!* Ideally measure both sides of low and high energy peaks, simultaneously w/good (< hour-month) continuous *time-sampling*: UV-MeV, 100 MeV-TeV coverage. 😊 [Also very good to get below IR/O absorption threshold – N.B. EBL absorption *not* dependent.]

Find *(HAWC)* and follow low duty cycle flaring activity.

Monitor synchroton peak up to ~MeV!
But every new object shows different behavior!
And same objects change classification.

Caution: *non-simultaneous* data points!
Flaring objects change class?

Donato et al 2000
But what about objects like PKS 2155?

Fig. 6. Luminosity at the synchrotron peak frequency plotted against synchrotron peak frequency.
Many Small vs. 1 Large Telescope?

Common debate in optical astronomy .... Answer would seem to be need both!

Large telescopes find furthest objects, but for those objects have marginal statistics/resolution. Understanding relevant physics can come only from studying many local objects in detail, for which small telescope sufficient.

Especially for AGN, field is very number limited (need to move up Kifune plot!). In volume currently accessible by HESS, we are probably missing most objects! = don’t need more collection area, higher sensitivity, just need more HESS telescopes!

If we’re limited to relatively nearby universe (=not that many sources), need good latitude coverage + for continuous observations, we need good longitude coverage => NETWORK!

Are “Incremental” (factor 2-3x sensitivity, medium term) Telescopes Worth Pursuing?

Yes, if are good in some particular parameter which opens new population.

3x sensitivity = ~10x decrease in integration time for known sources = non-
Two components!

Optical polarized 
⇒ Synchrotron 
⇒ TeV+ electrons!

Uchiyama et al. 2007
Another quasar jet (1136) ...
Gamma-Rays and Probing Spacetime

- Probe refractive index of vacuum giving rise to energy dependence in velocity of light
  - Quantum Gravity
  - Large extra dimensions
  - TeV to Planck scale physics
  - Lorentz invariance violation
- Best limit to date from Whipple Mkn 421 flare (Biller et al., Phys Rev Letters 1999).

Lots of controversy
-- how do you disentangle effect from INTRINSIC source evolution?
Most sources can think of, even decaying/annihilating CDM particles, trace large scale structure… look for *clustering* signal/cosmic web (anisotropy)!

The rarer/more biased the source, the stronger the clustering signal!

Bromm et al. 2003, cosmological structure formation calculation
Chandra Image of Perseus Cluster with VLA Radio Inset
Chandra Ripple Image of Perseus
Observational evidences for CRs & B in the ICM

- diffuse radio halos and relics in over 30 clusters
  radio synchrotron (CR electrons + magnetic field)
  (Govoni, Feretti, Giovannini, ..)

- hard X-ray & EUV emission *in excess of thermal radiation*
  inverse Compton scattering of CBR by CR electrons
  (Fusco-Feminao, Boywer, Lieu, Sarazin)

- Pion decay (or IC) γ-rays from clusters *yet to be observed*
  CR p + p → π⁰ decay → GeV γ-ray or electron IC
  (Scharf & Mukherejee, Colarfrancesco, Reimer)

- cluster γ-ray contribution to EGDB (extrag. diffuse γ-ray background)
  (Colarfrancesco & Blasi, Totani & Kitayama, Kesht & Loeb, Miniati, …)
Clusters with a radio halo:
CR electrons of GeV & B of 0.1-1 $\mu$G on Mpc scale are required.

Radio Halos of Clusters of Galaxies (contour) + X-ray (color)

Feb 06, Kashiwa

Slide from L. Feretti (KAW3)
Shocks in LSS: Mach Number

rich, complex shock morphology
Shocks “reveal” filaments and sheets

Location of shocks: color=Mach number

LCDM simulation with $1024^3$ cells, computational box: $(100h^{-1}\text{ Mpc})^3$, TVD: grid-based Eulerian hydro code (Ryu et al 2003)
Energies passed through and produced at shocks: integrated from $z=2$ to 0

- CR acceleration: most important for shocks with $M = 2$ to 4
  (low Mach no. internal shocks in the ICM)
- $E_{CR}$ accelerated at shocks $= \sim 1/2 \times E_{th}$ generated at shocks
  (Ryu et al 2003)
“Energy Budget of the ICM”

\[ E_{CR,p} \sim (0.1 - 1) E_{\text{thermal}} \] : AGN injection
\[ \sim (0.1 - 0.5) E_{\text{thermal}} \] : Shock acceleration
\[ \sim E_{\text{turb}} \sim 0.1 E_{\text{thermal}} \] : 2\text{nd} order acceleration

\[ E_{CR,e} \sim 0.01 E_{\text{thermal}} \] (observation)

\[ E_{\text{turb}} \sim 0.1E_{\text{thermal}} \] (subsonic turbulence, observation & simul.)

\[ E_B \sim E_{\text{turb}} \sim 0.1E_{\text{thermal}} \] (observation & simulation)
emitted flux & detectability

Coma-like cluster at $D=100$ Mpc

sensitivities for 1 deg$^2$ extended source

> TeV “absorption” by IRB+CMB

- large radiative efficiency from protons
- hard ($\Gamma \sim -1.5$) spectrum + rollover
- sensitive to $B$

\[ \text{c.f. primary IC, pp } \pi^0 \ (\Gamma \sim -2) \]
cascade emission: pair halo, background

pre-“absorbed” flux

cascade down to GeV-TeV range?

more on cascading -> Coppi
TABLE 1
PROPERTIES OF LOCAL STARBURST & STAR-FORMING GALAXIES

<table>
<thead>
<tr>
<th>Object Name</th>
<th>$D^a$ (Mpc)</th>
<th>$\Sigma_b^{\text{g}}$ (g cm$^{-2}$)</th>
<th>$S_{50\mu m}c$ (Jy)</th>
<th>$S_{100\mu m}d$ (Jy)</th>
<th>$S_{\text{TIR}}e$ (Jy)</th>
<th>$S_{1.4\text{GHz}}f$ (mJy)</th>
<th>$\nu F_\nu (\text{GeV})g$ (10$^{-11}$ GeV cm$^{-2}$ s$^{-1}$)</th>
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Eric Murphy, thesis
Mean free path for VHE photons

Absorption (pair production) and Cascading important for cosmological VHE sources.

Coppi & Aharonian 1997
Blazar Background Models, 
a la Stecker & Salamon 1996

Don’t forget cascades!

Including IR/O absorption

Coppi & Aharonian 1997
Response to Change in IR/O Background

GeV background measurement = calorimeter for VHE universe!

Key GLAST measurement

“GZK” cutoff?
Can we see cascade radiation from individual sources?

Due to likely IGMF, “No” is the standard answer, but …
If VHE source (e.g., cluster) is isotropic emitter or B field is large enough \((B>10^{-11}\ \text{G})\), pair deflection doesn’t matter! Get “Pair Halo”!

Angular size determined by *local* IR/O background

Coppi, Aharonian, & Voelk 1994, Madau & Phinney 1996
If IGMF is weak, don’t get halo but introduce *dispersion* in arrival times – probes IGMF!


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**Fig. 1.**—The distribution of arrival-time delays of greater than $10^{30}$ eV protons produced by a burst at a distance of 100 Mpc, for various IGMF structures where a fraction ~0.2 of the intergalactic space is occupied by ~1 Mpc regions of a coherent $4 \times 10^{-11}$ G field.

Waxman & Coppi 1996

**Fig. 2.**—The fluence of greater than 1 TeV secondary photons, following a GRB producing $10^{51}$ ergs as greater than $10^{30}$ eV protons at a distance of 100 Mpc. The IGMF structures are the same as those used in Fig. 1, and similar line styles correspond to the same field structure in both figures. The heavy dotted line gives the fluence obtained when a 1 $\mu$G host galaxy magnetic field is added to the field structure corresponding to the heavy solid line.
A “boring” object in the sky: the nearby elliptical galaxy M87
M 87 – evidence for production of TeV $\gamma$-rays close to BH

- Distance: $\sim 16$ Mpc
- Central BH: $3 \cdot 10^9 M_\odot$
- Jet angle: $\sim 15-30^\circ$
  $\Rightarrow$ not a blazar!
- Discovery ($>4\sigma$) of TeV $\gamma$-rays by HEGRA (1998)
  confirmed by HESS (2003)

$\Phi_{13} = 10^{-13}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$

F. Aharonian, HESS
M87: light curve and variability

X-ray emission:
- knot HST-1
  [Harris et al. (2005), ApJ, 640, 211]
- nucleus
  (D.Harris private communication)

short-term variability within 2005 (>4σ)
⇒ constrains size of emission region (R ~ 5x10^{15} δj cm)

F. Aharonian, HESS
Aside: Can use M87 [Cen A?] to probe diffuse background at MIR /FIR wavelengths with $E_{\gamma} > 10$ TeV $\gamma$-rays!

F. Aharonian
Individual UHECR Sources – Cascade Radiation
Summary

Extragalactic field still wide open!

Discovered many new phenomena,
but … more questions than answers!

More to do with AGN… ! Have only seen tip of iceberg. GLAST will need lots of help.

On threshold of observing galaxies & clusters = worth it, significantly strengthens connection to main stream astronomy.

Auger & UHECR …

Don’t throw away old telescopes … IMHOm, need diversity and network of instruments?