OVERVIEW OF LABORATORY ASTROPHYSICS

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• Introduction
• Calibration of Observations
• Investigation of Dynamics
• Probing Fundamental Physics
• Summary

SABER Workshop
March 15-16, 2006, SLAC
National Research Council Turner Committee:  
**Connecting Quarks with the Cosmos:**  
Eleven Science Questions for the New Century  

*Laboratory Astrophysics can address several of these basic questions*

- How do cosmic accelerators work and what are they accelerating?
- Are there new states of matter at exceedingly high density and temperature?
- Are there additional space-time dimensions?
- Did Einstein have the last word on gravity?
- Is a new theory of matter and light needed at highest energies?

One of the seven recommendations made by the Turner Committee:  

**Recommendation On Exploring Physics Under Extreme Conditions In The Laboratory**

“Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high energy-density physics. The Committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field.”
Connection to Extreme Astrophysical Conditions

- Extremely high energy events, such as ultra high energy cosmic rays (UHECR), neutrinos, and gamma rays
- Very high density, high pressure, and high temperature processes, such as supernova explosions and gamma ray bursts (GRB)
- Super strong field environments, such as that around black holes (BH) and neutron stars (NS)

“Detailed understanding of acceleration and propagation of the highest-energy particles ever observed demands a coordinated effort from plasma physics, particle physics and astrophysics communities”
Three Categories of LabAstro
- Using Lasers and Particle Beams as Tools -

1. Calibration of observations
   - Precision measurements to calibrate observation processes
   - Development of novel approaches to astro-experimentation
     ➔ Impact on astrophysics is most direct

2. Investigation of dynamics
   - Experiments can model environments not previously accessible in terrestrial conditions
   - Many magneto-hydrodynamic and plasma processes scalable by extrapolation
     ➔ Value lies in validation of astrophysical models

3. Probing fundamental physics
   - Surprisingly, issues like quantum gravity, large extra dimensions, and spacetime granularities can be investigated through creative approaches using high intensity/density beams
     ➔ Potential returns to science are most significant
1. Calibration of Observations
1. Fluorescence from UHECR Induced Showers

- Two methods of detection: Fly’s eye (HiRes) & ground array (AGASA)
- Next generation UHECR detector *Pierre Auger* invokes hybrid detections
- Future space-based observatories use fluorescence detection
UHECR: Production and Detection

Cosmic Microwave Background
At 2.7 K

GZK limit on proton energy: $\sim 5 \times 10^{19} \text{ eV}$
SLAC E-165 Experiment: *Fluorescence from Air in Showers* (FLASH)

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* Collaboration Spokespersons
Motivation for FLASH

- Experiment designed to help resolve discrepancy between measured flux of ultra high energy cosmic rays (UHECR).
- Energy scale of fluorescence technique based upon fluorescence yield (number of photons produced per meter per charged shower particle).
- Provide a precision measurement of the yield.
FLASH Motivation

- At large distances of up to 30 km, which are typical of the highest energy events seen in a fluorescence detector, knowing the spectral distribution of the emitted light becomes essential due to the $\lambda^{-4}$ attenuation from Rayleigh scattering.

Bunner (1967)
Fluorescence in Air from Showers (FLASH)
HiRes-SLAC-CosPA (Taiwan) collaboration

- Spectrally resolved air fluorescence yield in an electromagnetic shower
- Energy dependence of the yield down to ~100 keV
- Aim to help resolve apparent differences between HiRes and AGASA observations

SLAC E-165 (FLASH) Experiment (2002-2004):
- Two-stage: Thin target and Thick target
- 28.5 GeV electrons, $10^7$ to $10^9$ particles per bunch
FLASH: Thin Target

- Precision total yield measurement.
- Spectral measurement made using narrow band filters.

Only small corrections to current understanding. Fluorescence technique seems to be built on stable ground!
Air Fluorescence Yield
FLASH: Thick Target

- Electron beam showered with varying shower depths.
- Particle and photon count measured at each shower depth.

Confirm long standing assumption that the total fluorescence light in air-shower is proportional to number of cascade charged particles.
FLASH: Status and Prospects

- **Publications**
  - June 2002 data: total yield, pressure dependence, effect of impurity.

- **Future Prospects**
  - The collaboration is actively assessing whether a next run is needed, pending final outcome of on-going data analysis and publication efforts.
2. Exploring New Techniques for Cosmic Neutrino Detection

- Radio Detection of UHE EAS—Askaryan effect (1962)
- Search for neutrino interactions in Lunar surface using radio
- Antarctic Ice Experiment – RICE, ANITA
- Underground Saltdome Shower Array (SalSA) for super-GZK cosmic neutrino detection
Neutrinos: The only useful messengers for astrophysics at >PeV energies

- Photons lost above 30 TeV: pair production on IR & μwave background
- Charged particles: scattered by B-fields or GZK process at all energies
- But the sources extend to $10^9$ TeV!

Conclusion:
- Study of the highest energy processes and particles throughout the universe requires PeV-ZeV neutrino detectors
Comparison between Cosmic EM and Neutrino Spectrum

NRC, “Neutrinos and Beyond” 2003
UHECR: "How do cosmic accelerators work and what are they accelerating?"

\[ p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^\pm \leftrightarrow \mu\nu \leftrightarrow e\nu \nu \]

- UHECR: Top-down or bottom-up?
- If bottom-up, what accelerates the cosmic particles?
- Where are the sources?
- GZK neutrino spectrum and directions indispensable

Every Neutrino points back to its source!
The Askaryan Effect

UHE event will induce an e/γ shower:

In electron-gamma shower in matter, there will be ~20% more electrons than positrons.

Compton scattering: $\gamma + e^-(\text{at rest}) \rightarrow \gamma + e^-$

Positron annihilation: $e^+ + e^-\text{(at rest)} \rightarrow \gamma + \gamma$

$\frac{dP_{CR}}{d\nu} \propto \nu d\nu$

In solid material $R_{\text{Moliere}} \approx 10\text{cm}$.

$\lambda \gg R_{\text{Moliere}}$ (microwaves), coherent

$\Rightarrow P \propto N^2$
SLAC Characterization of Askaryan Effect

- 2000 & 2002 SLAC Experiments confirm extreme coherence of Askaryan radio pulse
- 60 picosecond pulse widths measured for salt showers. Unique signal reduces background, simplifies triggering, excellent timing for reconstruction.
ANITA: Antarctic Neutrino Transient Antenna
ESTA Ice Target

ICE TARGET FOR ANITA CALIBRATION IN SLAC END STATION A

- Ice block stack
- Beamline
- Drain & hose
- Forklift slot
- Hard foam insulation 4" thickness
- Hypalon liner
- Ferrite tile layer
- 3/4" plywood
- Pair of 2"x8" sistered joists with crossmembers (not shown)
- McMaster-Carr 2467735 3000lb cap.

Ice: 10"x21"x45" carving-grade blocks, 48 total in stack, 300lbs ea
14,400 lbs total ice
Ferrite tile floor: 720 tiles, 350lbs total
Structure estimate: 3800 lbs
Total weight: 18,550 lbs est.

DIMENSIONS IN INCHES OR FEET/INCHES
relative scaling approximately correct

SalSA: Saltdome Shower Array

A large sample of GZK neutrinos using radio antennas in a 12x12 array of boreholes natural Salt Domes

SalSA sensitivity, 3 yrs live:
70-230 GZK neutrino events
2. Investigation of Dynamics
Can intense neutrino winds drive collective and kinetic mechanisms at the plasma scale?

Bingham, Bethe, Dawson, Su (1994)
Plasma Waves Driven by Different Sources

Equations for electron density perturbation driven by electron beam, photon beam, neutrino beam, and Alfven shocks are similar.

**Electron beam**
\[
\left( \partial_t^2 + \omega_{pe0}^2 \right) \delta n_e = -\omega_{pe0}^2 n_{e\text{-beam}}
\]

**Photons**
\[
\left( \partial_t^2 + \omega_{pe0}^2 \right) \delta n_e = \frac{\omega_{pe0}^2}{2m_e} \nabla^2 \int \frac{dk}{(2\pi)^3} \frac{\hbar N_\gamma}{\omega_k}
\]

**Neutrinos**
\[
\left( \partial_t^2 + \omega_{pe0}^2 \right) \delta n_e = \sqrt{2} n_{e0} G_F \frac{\nabla^2 n_\nu}{m_e} \quad \text{where } \delta n_e \text{ is the perturbed electron plasma density}
\]

Bingham, Dawson, Bethe (1993): Application to NS explosion

**Alfven Shocks**
\[
\left( \partial_t^2 + \omega_{pe0}^2 \right) \delta n_e = \frac{A}{2m_e} \nabla^2 \int \frac{dk}{(2\pi)^3} \frac{c^2 k^2}{\omega_k \omega_A} \left( E_A^2 + B_A^2 \right)
\]

All these processes can in principle occur in astro jets.
1. Supernova Electroweak Plasma Instability

- 99% of SN energy is carried by neutrinos from the core
- Single-particle dynamics unable to explain explosion
- $\nu$-flux induced collective electroweak plasma instabilities load energy to plasma efficiently*

Use laser/e-beam to simulate $\nu$- flux induced two-stream instability, Landau damping, and Weibel instability

2. Cosmic Acceleration

- Conventional cosmic acceleration mechanisms encounter limitations:
  - Fermi acceleration (1949) (= stochastic accel. bouncing off B-fields)
  - Diffusive shock acceleration (70s) (a variant of Fermi mechanism)
    Limitations for UHE: field strength, diffusive scattering inelastic
  - Eddington acceleration (= acceleration by photon pressure)
    Limitation: acceleration diminishes as $1/\gamma$

- New thinking:
  - Zevatron (= unipolar induction acceleration) (R. Blandford)
  - Alfvén-wave induced wakefield acceleration in relativistic plasma
  - Weibel instability-induced induction and wakefield acceleration
    (Ng and Noble, Phys. Rev. Lett., March 2006)
  - Additional ideas by M. Barring, R. Rosner, etc
Alfven-Shock Induced Plasma Wakefield Acceleration

(Chen, Tajima, and Takahashi, PRL, 2001)

- Generation of Alfven waves in relativistic plasma flow
- Inducing high gradient nonlinear plasma wakefields
- Acceleration and deceleration of trapped $e^+/e^-$
- Power-law ($n \sim -2$) spectrum due to stochastic acceleration
3. Relativistic Jet-Plasma Dynamics

- Relativistic jets commonly observed in powerful sources
- A key element in models of cosmic acceleration
- An understanding of their dynamics is crucial.
3D PIC Simulation Results: Overview

1. Transverse dynamics (same for continuous and short jets):
   - Magnetic filamentation instability: inductive $E_z$
   - Positron acceleration; electron deceleration

2. Longitudinal dynamics:
   - Electrostatic “wakefield” generation (stronger in finite-length jet)
   - Persists after jet passes: acceleration over long distances.
Particle Acceleration and Deceleration

Longitudinal momentum distribution of positrons and electrons for a finite-length jet at three simulation time epochs.

$t$ in units of $1/\omega_p$

~ half of positrons gained >50% in longitudinal momentum ($p_z$

(For details see my talk in Working Group C)
3. Probing Fundamental Physics
1. Event Horizon Experiment
Chen and Tajima, PRL (1999)

EVENT HORIZONS: From Black Holes to Acceleration

A stationary observer outside the black hole would see the thermal Hawking radiation.

An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.
A Conceptual Design of an Experiment for Detecting the Unruh Effect

Schematic Diagram for Detecting Unruh Radiation
2. Probing Extra Spacetime Dimension?

- In standard theory of gravity, the Planck scale is at
  \[ M_p \sim 10^{19} \text{ GeV}, \text{ or } L_p \sim 10^{-33} \text{ cm}. \]
- Assuming large extra dimensions, then
  \[ M_p^2 \sim R^n M_*^{n+2}, \text{ and } R \sim (M_p/M_*)^{(n+2)/n} L_p. \]
- If \( M_* \) is identified with the electroweak, or TeV, scale, then
  \[ R \sim 10^{32/n - 17} \text{ cm}. \] (For \( n=6 \), \( R \sim 10^{-12} \text{ cm.} \))
- Distance from accelerating detector and the event horizon,
  \[ d \sim c^2/a, \]
  can probe extra spacetime dimension.
- State-of-the art laser can probe up to \( n=3 \).
SUMMARY

• History has shown that symbiosis between direct observation and laboratory investigation instrumental in the progress of astrophysics.
• Recent advancements in Particle astrophysics and cosmology have created new questions in physics at the most fundamental level.
• Many of these issues overlap with high energy-density physics.
• Laboratory experiments can address many of these important issues.
• Laser and particle beams are powerful tools for Laboratory Astrophysics.
• Three categories of LabAstro: Calibration of observations, Investigation of dynamics, and Probing fundamental physics. Each provides a unique value to astrophysics.
LabAstro Working Group Program

March 15 (Wed.)

WG Parallel Session 1 (11:00-12:00)
Pierre Sokolsky (Utah), "Some Thoughts on the Importance of Accelerator Data for UHE Cosmic Ray Experiments"
Pisin Chen (KIPAC, SLAC), "ESTA: End Station Test of ANITA"

WG Parallel Session 2 (13:30-15:00)
Robert Bingham (RAL, UK), "Tests of Unruh Radiation and Strong Field QED Effects"*
Anatoly Spitkovsky (KIPAC, SLAC), "Pulsars as Laboratories of Relativistic Physics,"
Eduardo de Silva (KIPAC, SLAC), "Can GLAST Provide Hints on GRB Parameters?"

WG Parallel Session 3 (15:30-17:00)
Robert Noble (SLAC), "Simulations of Jet-Plasma Interaction Dynamics"*
Johnny Ng (KIPAC, SLAC), "Astro-Jet-Plasma Dynamics Experiment at SABER"*
Kevin Reil (KIPAC, SLAC), "Simulations of Alfven Induced Plasma Wakefields"*
March 16 (Thur.)

WG Parallel Session 4 (08:30-10:00)
  Bruce Remington (LLNL), "Science Outreach on NIF: Possibilities for Astrophysics Experiments"
  Bruce Remington (LLNL), "Highlights of the 2006 HEDLA Conference"
  **Round Table Discussion**, "Considerations of Laboratory Astrophysics"

WG Summary Preparation (10:20-12:00)

*Tentative title*