Catching Neutrinos From Orbit

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NASA/GSFC

http://owl.gsfc.nasa.gov
UHECR Flux Measurements

Douglas Bergman
Aspen Winter Conference, 2002
OWL Science

* How do cosmic accelerators work and what are they accelerating?
  * The primary goal of OWL is measurement of the Ultra-High Energy Cosmic Ray component (UECR) above $10^{20}$ eV - $10^{22}$ eV with high statistics. At present, this is presumed to be hadronic.
  * **Signature:** by measurement of the energy spectrum, point-back origin, interaction point and air-cascade development, the questions of anisotropy, point-source(s), acceleration mechanism, and particle identity are addressed.

* Do the UHECR have a “top-down” origin?
  * UHECR may produced by topological defects which are relic from the early Universe, (GUT symmetry breaking)
  * **Signature:** If UHECR result from topological defects, then the composition of events above $10^{20}$ eV will be much enriched in gamma ray and neutrino primaries, as compared with a UHECR origin which results from a bottom-up astrophysical acceleration process.

* Might matter and light behave differently at the highest energies?
  * Lorentz invariance might be weakly broken at ultra-high energies. OWL will observe the highest energy particles known in the Universe.
  * **Signature:** Lorentz invariance breaking might avoid the GZK cutoff. The absence of photomeson interactions would result in the absence of any pileup effect.

* Are there extra space-time dimensions?
  * Extra space-time dimensions may force the GUT unification scale to energies well below $10^{22}$ eV.
  * **Signature:** This “precocious unification” could induce strong neutrino interaction cross-sections above the unification scale. These in turn would result in “anomalous” neutrino-induced air-shower cascades which might be identified by their unusual properties.
Astrophysical Neutrinos: Sources and Signatures

<table>
<thead>
<tr>
<th>Test</th>
<th>GRB</th>
<th>AGN</th>
<th>TD</th>
<th>Z-Burst</th>
<th>$p_{\gamma_{2.7K}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coincidence with a GRB</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$(N_{\nu}/N_{p}) \gg 1$</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
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<td>$(N_{\gamma}/N_{p}) \gg 1$</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
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</tbody>
</table>

Characterisitic

<table>
<thead>
<tr>
<th>Energy</th>
<th>$10^{16}$</th>
<th>$10^{14}$ eV</th>
<th>$10^{21}$ eV</th>
<th>$\frac{10^{20}}{m_{\nu}}$ (eV)</th>
<th>$10^{19}$ eV</th>
</tr>
</thead>
</table>

Multiple Events

Table 1: Distinguishing characteristics of the different sources of ultra-high energy neutrinos (Cline and Stecker 2000).
### What is OWL?

#### Concept
- Air fluorescence imagery, night atmosphere
- Built on success of ground-based Flys Eye and HiRes fluorescence observations
- 300-400 nm photons induced by atmospheric cascade from E~$10^{20}$ eV cosmic rays
- Stereo viewing unambiguously determines shower height and isolates external influences (e.g., cloud effects, surface light sources)

#### Mission
- 2 identical spacecraft flying in formation
- 1,000 km, near-equatorial orbit
- 3 year design life, 5 year goal
- Designed to fit within Delta IV 5-m launch vehicle shroud
Extreme Universe Space Observatory (EUSO)
Under study for Placement On the Space Station
OWL Major Requirements Overview

* Large Aperture (effective aperture several 100,000 km²-sr)
* Mechanical structure, deployment, shielding
* Wide-angle optics (≈ 45 degree full-angle, ≈ 0.05 degree resolution)
* Photonics (single photoelectron sensitivity, large focal plane detector)
* Trigger (space-time) pattern recognition
* Ability to handle background light
* Deal with signal distortion, clouds, atmospheric conditions
* A thorough “end-to-end” performance simulation
OWL Mechanical Design

Packed for DualLaunch
Delta IV Heavy
(4050-H-19 fairing)

Rodger Farley / GSFC
NeSS, Sept 20, 2002
OWL Mechanical Design

The Jiffy-Pop solution
A compact instrument for the observation of EECRs and Neutrinos
OWL Baseline Schmidt Optics

0.06° Pixel Angular Resolution in UV
~ 10^4 away from Diffraction Limit

• F/1 System
• 3.0 m Diameter Optical Aperture formed by Single Corrector Plate
• 7.1 m Diameter Aspherical Mirror
• 2.3 m Diameter Focal Plane
• Full FOV 45°
• 3 mm Focal Plane Pixel Diameter
• ~ 1 mm, 0.1° Alignment
Capabilities of Owl Baseline

* Intrinsic energy resolution – 14% @ \(10^{20}\) eV and improves with energy

* Angular resolution – 0.2 - 1 degree

* Longitudinal profile – Locate shower max within 50 g cm\(^{-2}\)
  – Able to statistically identify protons, nuclei, and photons
  – Perform event-by-event identification of near horizontal and earth skimming neutrinos

* Detector viewing stereo aperture \(\approx 2.3 \times 10^6\) km\(^2\) sr at the energy threshold of \(10^{20}\) eV.

* \(\approx 5\) year operation with \(~10\%\) duty cycle
UHE Neutrinos via Air Fluorescence

- Large Aperture (~10^{12} tons of effective atmospheric target) opens the door for observing ultra-high energy neutrinos interactions

- Horizontal Airshowers initiated deep (> 1500 g/cm^2) in the atmosphere provide a signature of neutrino interactions which are well-separated from hadronic and electromagnetic showers, \( \lambda_\nu \sim 10^{10} \) cm, \( \lambda_p \sim 10^4 \) cm (Air, STP, \( E = 10^{20} \) eV)
Monte Carlo Simulations

Two independent Monte Carlo systems

“Grass-Roots” MC

Cascade physics, model atmosphere, photon absorption and scattering (but no clouds), detailed instrument simulation.

John Krizmanic

“HiRes Tool-kit” MC

Powerful analysis, geometric reconstruction, concentrating on clouds / scattering / atmospheric effects

Tareq Abu-Zayyad
OWL $10^{20}$ eV $\nu_e$ Simulated Event
1000 km Orbits, 500 km Satellite Separation
Depth of Shower for Triggered Events
Schmidt Baseline, 1000 km Orbits, 500 km Satellite Separation

$10^{20} \text{ eV } \nu_e$, Trigger selection

89% $\geq 1500 \text{ g/cm}^2$

88% with $> 1500 \text{ g/cm}^2$ Selection for Both Eyes

$10^{20} \text{ eV } \nu_e$, Trigger selection

88% with $> 1500 \text{ g/cm}^2$ Selection for Both Eyes
OWL Electron Neutrino Aperture

1000 km Orbits, Schmidt Baseline, Instantaneous Aperture

\[ \sigma(\nu N) = \sigma(\nu \bar{N}), E_\nu > 10^{16} \text{ eV} \]

For UHE \( \nu_\lambda N \rightarrow \lambda N' \), on average 80% \( E_\nu \) deposited into lepton.

For UHE \( \nu_e N \rightarrow e N' \), 100% \( E_\nu \) deposited into airshower.
OWL Nominal Electron Neutrino Event Rates
1000 km Orbits, 10% Duty Cycle, Schmidt Baseline

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Stereo</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 km Sat. Sep.</td>
<td></td>
</tr>
<tr>
<td>$p\gamma_{2.7K}$ (6)</td>
<td>0.1 – 0.4 Events/Year</td>
</tr>
<tr>
<td>Topological Defects (3)</td>
<td>12 Events/Year</td>
</tr>
<tr>
<td>$Z_{Burst}$ (4)</td>
<td>11 Events/Year</td>
</tr>
<tr>
<td>$E_{Threshold}$</td>
<td>$\lesssim 10^{20}$ eV</td>
</tr>
</tbody>
</table>

550 km orbits will yield reduction in energy threshold by factor of $> 3$

References:
1 Stecker & Salamon, Space Sci Rev 75 (1996)
2 Stecker, Done, Salamon, & Sommers, PRL 66 (1991)
3 Sigl, Lee, Bhattacharjee, & Yoshida, Phys Rev D 59 (1998), $m_X = 10^{16}$ GeV, $X \rightarrow q+ q$, SuperSymmetric fragmentation
4 Yoshida, Sigl, & Lee, PRL 81 (1998), $m_n = 1$ eV, Primary $F_n \sim E^{-1}$
5 Waxman and Bahcall, PRL 78 (1997)
Is ‘double-bang’ of UHE $\nu_\tau$ interaction and subsequent $\tau$ decay observable?

- $\tau$ energy loss not a large effect in the atmosphere($\sim 18\%$ for $E_\tau = 10^{20}$ eV, 1000 km in STP air; Dutta et al., hep-ph/0012350v1)
Tau Neutrino Regeneration

• The diameter of the Earth becomes opaque to neutrinos for $E > 40$ TeV

• However, tau neutrinos traverse the Earth albeit with degraded energy due to regeneration (Halzen & Saltzberg (1998), PRL 81)

• Cosmological long-baseline muon $\rightarrow$ tau neutrino oscillation appearance experiment

• Results of upward airshower simulation based upon Hillas with angular dispersion parameterization (J.Phys. G: Nucl.Phys 8, 1982; similar results, D. Kieda, ICRC Hamburg)

Upward Airshower, $E=10^{15}$ eV, 1000 km altitude

Corresponds to $\sim 3 \times 10^{15}$ eV neutrino energy
Upward Airshower Flux Sensitivity

The Earth's crust is a huge neutrino target

(Ice Cube:

1 km$^3$ of ice $\sim 10^{10}$ ton-ster $\nu$ Aperture
$E_{\nu}^{\text{Thres}} \sim 1$ TeV)

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### Tau Energy $\gamma c \tau_d$ $\nu$ Aperture

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Distance (m)</th>
<th>Effective Aperture (ton-ster)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{14}$</td>
<td>5</td>
<td>$5 \times 10^8$</td>
</tr>
<tr>
<td>$10^{15}$</td>
<td>50</td>
<td>$5 \times 10^9$</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>500</td>
<td>$5 \times 10^{11}$</td>
</tr>
<tr>
<td>$10^{17}$</td>
<td>&lt; 5 km</td>
<td>$\sim 10^{12}$</td>
</tr>
</tbody>
</table>

* 10% Duty Factor Included
**Upward Airshower Signal Detection**

Cherenkov signal delivered in <100 ns

Dark sky UV background 400 γ/(ns m² ster) ==> 0.2 PE/µs in each OWL pixel

\[
\begin{align*}
\text{Prob}(\text{PE} \geq 10 \mid 0.2) & = 2.3 \times 10^{-14} \\
\text{Prob}(\text{PE} \geq 20 \mid 0.2) & = 3.6 \times 10^{-33}
\end{align*}
\]

For 1 year observation time at 10% duty cycle with one instrument

\[
5 \times 10^5 \text{ pixels} \times 10^6 \mu\text{s/s} \times \pi \times 10^7 \text{s/year} \times 0.1 \times 2.3 \times 10^{-14} = 36,000 \text{ accidentals (PE \geq 10)}
\]

\[
\ldots \times 3.6 \times 10^{-33} = \sim 10^{-14} \text{ accidentals (PE \geq 20)}
\]

Using 2 satellites separated by ~ 10 km viewing same area: \sim 10^{-9} accidentals (PE \geq 10)

\sim 10^{-47} accidentals (PE \geq 20)

However, 0.1 Hz/cm² cosmic ray rate:

\sim 10^{10} \text{ pixel hits/year observation time (single instrument)}

\sim 25 \text{ ground-position corresponding pixel hits/year observation time (two instruments)}

Requires further rejection power (signal characteristics?)
Other Possibilities:
Black-Hole-Producing, Strongly-Interacting Neutrinos

Event rates based upon OWL electron neutrino aperture
(older Maksutov baseline)

New baseline has ~ 20% reduction in $\nu_e$ aperture

Summary: Catching Neutrinos from Orbit

General Feature: Large aperture and target masses

- $\approx 10^{20}$ eV Measurements, fluorescence:
  - Ability to measure neutrinos from `top-down' processes, statistically distinguish from `bottom-up' photomeson neutrinos
  - Taus in atmosphere: non-viable
  - Strongly-interacting neutrinos: get’em if their there
  - Potential for other neutrino measurement
    - ‘Upward’ tau neutrino via Cherenkov
      - “Edgy” to non-viable
  - EUSO 400 km / OWL 550 km orbits will allow for reduction of energy threshold ($\sim 3 \times 10^{19}$ eV) for air fluorescence events
    - Trade-off energy threshold and aperture