Using a cube of 50,000 year-old South Pole ice to peer into Space

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What Physicists Do Sonoma State University, September 12, 2005
What some physicists do

• Using the smallest to study the largest
• Some astrophysics
• What’s so great about neutrinos?
• How to detect neutrinos
• What’s so great about the South Pole?
• How to go to the South Pole
• What is it like at the South Pole? (slide show)
Seeing: Cosmic Messengers

"You can see a lot by looking"

Yogi Berra

Visible light

Also: Cosmic Rays →

X-rays

Infrared

Neutrinos
Cosmic Rays and Cosmic Neutrinos

Cosmic rays are charged particles (protons etc) from space.

Cosmic rays of extremely high energy have been observed.

Origin of cosmic rays is not understood → existence of spectacular particle accelerators in the Universe.

Neutrinos and cosmic rays are associated → particle physics.

Fluxes of Cosmic Rays

- Flux (m\(^2\) s\(^{-1}\) GeV\(^{-1}\))
- (1 particle per m\(^2\)-second)
- Kne (1 particle per m\(^2\)-year)
- Ankle (1 particle per km\(^3\)-year)

Atmospheric neutrinos

Unexplained

Explained by SN?
What do we know about neutrinos?

- Most abundant particle (~100 trillion through body each second)
- (Almost) no mass
- No charge
- Three types (flavors)
- Almost never interact
- When they interact, they can create a charged particle (electron, muon, tau)
- Higher energy → more interesting → rarer
Neutrinos have helped us before:

In our solar system:
Neutrinos from the Sun prove internal fusion

Just outside our galaxy:
Neutrinos from Supernova 1987A explain last
gasp of dying stars

Well beyond our galaxy:
Neutrinos from massive Black Holes...some day
Need to look at higher energies → larger detectors!
Sources of neutrinos

More exciting possibilities to explore at higher energies

The Sun

$\Phi^e_{\nu} = 6 \times 10^{10} \nu / \text{cm}^2 \text{s}$
$E_\nu \sim 0.1-20 \text{ MeV}$

Nuclear Reactors

$E_\nu \sim \text{few MeV}$

Accelerators

$E_\nu \sim 0.3-30 \text{ GeV}$

Human Body

$\Phi_\nu = 340 \times 10^6 \nu / \text{day}$

Atmospheric $\nu$'s

$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$

$\Phi_\nu \sim 1 \nu / \text{cm}^2 \text{s}$
$E_\nu \sim 0.1-100 \text{ GeV}$

Earth's radioactivity

$\Phi_\nu \sim 6 \times 10^8 \nu / \text{cm}^2 \text{s}$

Some examples:
Possible sources of UHE Cosmic Rays (and neutrinos?)
Active Galactic Nucleus: generic cosmic accelerator
CasA Supernova Remnant in X-rays

Shock fronts

Fermi acceleration
Gamma Ray Bursts

Fireball: Rapidly expanding collimated ball of photons, electrons and positrons becoming optically thin during expansion

Shocks: external collisions with interstellar material (e.g. remnant—guaranteed TeV neutrinos!!) or internal collisions when slower material is overtaken by faster in the fireball.

Protons and photons coexist in the fireball
~35% of all matter in the Universe is **Dark Matter**

Dark Matter is matter that must be there (to hold everything together with gravity)

but:

- we cannot see it (yet)
- we don’t know what it is made of

Prime Candidate: the Neutralino (a WIMP)
Particle propagation in the Universe

**photons:**
can be absorbed on intervening matter or radiation

**protons:**
deflected by magnetic fields lose information about direction

And at high energies:
p and $\gamma$ react with CMB background

**neutrinos:**
- will reach us
- point back to their source

*But* are very difficult to detect!
“I have done a terrible thing, I have invented a particle that cannot be detected.”

Wolfgang Pauli

Only weak interactions → indirect detection
How to build a neutrino detector

“Project Poltergeist”
First detection of neutrinos (from nuclear reactors)

Cowan and Reines, 1956

anti-neutrino + proton → neutron + positron
[various reactions] → several photons

Seen by light sensors
How to build a neutrino detector

Look for the neutrino’s interaction product (e, µ, τ)

Use the Earth as a filter

Needle in haystack: 1 in 1,000,000 is ν

Detector
How to detect muons from neutrinos

Cherenkov radiation: sonic boom of light
• infrequently, a cosmic neutrino is captured in the ice, i.e. the neutrino interacts with an ice nucleus

• in the interaction a muon (or electron, or tau) is produced

• the muon radiates blue light in its wake

• optical sensors capture (and map) the light
Why at the South Pole?

• Need something transparent to see the Cherenkov light
  Antarctic ice is the purest, most optically transparent *natural* material on earth

• Need large volume of it
  South Pole ice cap is two miles thick

• Can’t pay a lot for it
  South Pole ice is “free”

• Need electricity, food, transportation, other infrastructure
  US has “permanent” base at South Pole
The prototype: AMANDA

Antarctic Muon And Neutrino Detector Array

- Construction began in 1995
- Completed in 2000
- 19 strings
- 677 light detectors
- 200 m across
- ~500 m tall (most densely instrumented volume)

~10 neutrinos per day
A neutrino event seen in AMANDA

red = early
blue = late

A muon created by a neutrino
Scattering and Absorption of Light

- Scattering: Object is blurred
- Absorption: Object is dimmer

Makes it harder to “see” muons from neutrinos
Absorption

- Absorption by pure ice
- Absorption by impurities

Scattering

- Dust dominates
- Dust layers

In our detector, the light we see

Dust in ice core

Vostok
Holes are drilled into the ice with hot water

- 2000 m deep
- 60 cm wide
- 3-4 days
Optical Module deployment

String 16 - deployment

- OM deployment: 12 min/OM
- Average drop speed: 13 m/min

~10 hours
(30 hours before hole is too narrow)

The Millennium module
Got neutrinos? (What we have seen so far)

- ~10,000 neutrinos
- Could all be atmospheric
- No extraterrestrial ones (yet)
- No point sources (yet)

The technique works!
The IceCube Neutrino Observatory

IceTop air shower array
80 pairs of ice Cherenkov tanks

IceCube
4800 optical modules on 80 strings
1km³ instrumented volume

AMANDA
Proof that it works
~10 neutrinos/day
~10,000 neutrinos total since 2000
The IceCube Neutrino Observatory

IceTop air shower array
80 pairs of ice Cherenkov tanks

IceCube
4800 optical modules on 80 strings
1km³ instrumented volume

January 2005:
1 string + 4 IceTop tank pairs

Dec 2005-Jan 2006:
10-12 strings + 12 tank pairs

January 2010:
80-string array completed

~300 neutrinos/ day
January 2005:
First string deployed!
60 optical modules
Deepest module at 2450 m
In March 2005, AMANDA merged into the IceCube collaboration.
What are the odds?
(from New Scientist)

IceCube discovers cosmic neutrinos: 6/1

Finding Elvis alive: 100/1
Slide Show: A trip South for the “summer”
Antarctic geography

- South Pole
- Amundsen-Scott station (US)
- McMurdo station
- Lake Vostok
- Transantarctic Mountains
- Greenwich (UK)
- New Zealand & US
Christchurch, New Zealand
International Antarctic Center
C-130 (Hercules) with skis
First leg: 8 hours
McMurdo, Antarctica
Second leg: 3 hours
Crossing the Trans-Antarctic Mountains
Amundsen-Scott South Pole station

South Pole

Dome

Summer camp

IceCube

“North”

road to work

1500 m

2000 m

[not to scale]
Altitude: ~10,000 ft
Day: October-March
Night: April-September
South Pole glacial flow

“South Pole” is marked every Jan 1

The ice surface moves by one inch per day = 9 m/yr
Refrigeration of food
Cold weather protection
Summer Camp
Newer not always better
Cooked meal every 6 hours
(but very little fresh fruit/vegetables)
The AMANDA counting house:
MAPO (Martin A. Pomerantz Observatory)
Halos & sundogs
The Race Around the World
3 laps around South Pole marker = 2 miles
~1/3 of South Pole population are women
It’s a harsh continent...

ATTENTION
LIMIT WATER USE TO
TWO SHOWERS PER WEEK
ONE FULL LOAD LAUNDRY

2 showers x 2 minutes / week

...but there are other ways...
Leftover hot water from drilling put to good use.
Sometimes the world *does* revolve around you!
Last plane out: Feb 15