ICE PROPERTIES AT
SOUTH POLE

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Abstract

We have measured **wavelength dependence** and **depth dependence** of **scattering** and **absorption** in the ice with **in-situ light sources**.

- 300-600 nm
- 1200-2300 m
- $b_e = 1/\lambda_e$
- $a = 1/\lambda_a$
Embedded light sources

- **Isotropic source**
  - (YAG laser)

- **Cosθ source**
  - (N₂ lasers, blue LEDs)

- **Tilted cosθ source**
  - (UV flashers)

![Graph showing in-situ light sources used to measure optical properties](chart.png)
Light scattering in AMANDA

- Mie scattering
  - General case for scattering off particles

- Dust in AMANDA: $O(r) \sim O(\lambda)$

The Henyey-Greenstein approximation:

$$\frac{d\sigma}{d(\cos \theta)}(\lambda) = \frac{1-g(\lambda)^2}{(1+g(\lambda)^2-2g(\lambda)\cos \theta)^{3/2}}$$

$$g(\lambda) = \langle \cos \theta \rangle$$

Effective scattering length $\lambda_e = \frac{\lambda_s}{1-g}$

New best estimate of average for AMANDA ice:

$$g(400) = 0.94$$

(updated concentrations, corrected summing)
Photon propagation Monte Carlo

Hit probability at shell/band crossing:

\[
P_{\text{hit}} = \frac{\varepsilon_{\text{PMT}} \pi R_{\text{OM}}^2 \left( \frac{1 - \hat{n}_\gamma \cdot \hat{n}_{\text{OM}}}{2} \right)}{A_{\text{band}} |\hat{n}_\gamma \cdot \hat{n}_{\text{band}}|} \cdot e^{-\frac{t_{\text{ince}}}{\Lambda_a}}
\]

Timing distributions \( t(d, \theta) \):

\[
N(t) = \sum_{\text{hits}[t, t+\delta t]} P_{\text{hit}}
\]
Timing fits to pulsed data

Make MC timing distributions at grid points in $\lambda_e-\lambda_a$ space

At each grid point, calculate $\chi^2$ of comparison between data and MC timing distribution (allow for arbitrary $t_{shift}$)

Fit paraboloid to $\chi^2$ grid

- Scattering: $\lambda_e \pm \sigma_e$
- Absorption: $\lambda_a \pm \sigma_a$
- Correlation: $\rho$
- Fit quality: $\chi^2_{min}$
Flasher “afterglow”

Delayed “bump”, not seen in other data

Empirical correction:
fit sum of two random walk functions and subtract the second (works perfectly for all flasher data)

No explanation so far!
Example of flasher afterglow correction

before

after
Averaging fit results in 10 m bins

Averaging done in coefficients \((a, b_e)\) not lengths \((\lambda_a, \lambda_e)\)

Change since Zeuthen 2002
Reduces a, \(b_e\) by 5-10%
Scattering from pulsed data

- $\lambda = 337 \text{ nm}$
- $\lambda = 470 \text{ nm}$
- $\lambda = 370 \text{ nm}$
- $\lambda = 532 \text{ nm}$

scattering coefficient $[\text{m}^{-1}]$

depth $[\text{m}]$

bubbles dominate
Wavelength dependence of scattering
Wavelength dependence of scattering

Power-law fit:

\[ b_e \propto \lambda^{-(0.90 \pm 0.03)} \]

- nitrogen lasers
- UV LEDs (DOM flashers)
- blue LEDs
- YAG laser

wavelength averages
Absorption from pulsed data

532 nm refitted with better binning in $\lambda_a$

$\lambda = 337$ nm

$\lambda = 370$ nm

$\lambda = 470$ nm

$\lambda = 532$ nm
Temperature dependence of (ice) absorption

\[ \Delta a = (0.012 \pm 0.0018)a \Delta T \]

Published: (0.010 \pm 0.0012)
3-component model of absorption

Empirical model
(L. Bergström, P.B. Price)

Ice extremely transparent between 200 nm and 500 nm

Absorption determined by dust concentration in this range

Wavelength dependence of dust absorption follows power law
Raw data from DC sources

**Extreme UltraViolet (EUV) Module:**
Xenon arc lamp + filter (313±6 nm)

? Variable intensity

**Rainbow Module (RM):**
Halogen lamp + monochromator

? Variable wavelength
Fluence fits to DC data

In diffusive regime:

\[ N(d) \propto \frac{1}{d} \exp\left(-\frac{d}{\lambda_{\text{prop}}}\right) \]

\[ \lambda_{\text{prop}} = \sqrt{\frac{\lambda_d \lambda_c}{3}} \]

\[ c = \frac{1}{\lambda_{\text{prop}}} \]

No Monte Carlo!
Propagation coefficient from DC data
Absorption from DC data

Fluence fits give depth dependence of propagation coefficient \((c)\) at wavelength \(\lambda\).

Extrapolate scattering coefficient \((b_e)\) from pulsed data to same wavelength.

Calculate absorption coefficient \((a)\) from diffusive formula: \(c = \sqrt{3ab_e}\)
Global 3-component fit

Include absorption from pulsed and DC sources

Same power law ($\lambda^{-\kappa}$) and ice exponential in each depth bin

$k = 1.08 \pm 0.01$

Fit separate $CM_{dust}$ for each depth bin
Correlating scattering with dust

From global 3-component fit to absorption

Empirical correlation

From scattering data
Scattering in the bubbly region above 1500 m

![Graph showing effective scattering coefficient vs. depth](image-url)

- **AMANDA-B data**
- **AMANDA-A data**
- **Fit: \( \exp(a + bz + cz^2) \)**
Absorption in the bubbly region above 1500 m

[Graphs showing dust concentration and absorptivity vs. depth and equivalent depth at Pole, with linear fit equations.]
A 6-parameter Plug-n-Play Ice Model

- $b_e(400,d)$
  - $A = 6954 \pm 973$
  - $B = 6618 \pm 71$
  - $D = 71.4 \pm 12.2$
  - $E = 2.57 \pm 0.58$
  - $\alpha = 0.90 \pm 0.03$
  - $\kappa = 1.08 \pm 0.01$

- $T(d)$

- Power law: $\lambda^{-\alpha}$

- Linear correlation with dust:
  - $CM_{dust} = D \cdot b_e(400) + E$

- 3-component model:
  - $CM_{dust} \lambda^{-\kappa} + Ae^{-B/\lambda}$

- Temperature correction:
  - $\Delta a = 0.01a \Delta T$

- $b_e(\lambda,d)$
- $a(\lambda,d)$
Building blocks of plug-n-play ice model

3 histograms (icemodel.hbk)

6 parameters (icemodel.par)

$A = 6954 \pm 973$

$B = 6618 \pm 71$

$D = 71.4 \pm 12.2$

$E = 2.57 \pm 0.58$

$\alpha = 0.90 \pm 0.03$

$\kappa = 1.08 \pm 0.01$

ascii table (icemodel.dat)

<table>
<thead>
<tr>
<th>Temperature offset (degrees) from center of detector (1730 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1105.000000 0.638462 0.062641 -10.032608</td>
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<tr>
<td>1115.000000 0.601788 0.068315 -9.907898</td>
</tr>
<tr>
<td>1125.000000 0.566827 0.082186 -9.782013</td>
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<tr>
<td>...</td>
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<tr>
<td>2395.000000 0.000000 0.000000 15.669115</td>
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</tbody>
</table>
How well does the model describe pulsed data?
How well does the model describe DC data?
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Method crosscheck using pulsed data

1. Translate pulsed data to DC data:
   - Hit counting
   - Throw away data for OM in run if $N_{hit} > 7$ in any event

2. Treat them like regular DC data:
   - Look in diffusive regime ($d > d_{min}$)
   - Perform fluence analysis
   - Extract propagation coefficient ($c$)

3. Compare resulting $c$ with $c = \sqrt{3ab_e}$ from timing fits
How well does the model describe absorption data?

- full p-n-p ice model
- DC absorption data
- pulsed absorption data
Systematics

Sources of uncertainty checked so far:

- $<\cos\theta>$: 2-3 %
- source shapes: 1-2 %
- angular acceptance: 1-2 %
- timing (+pulse timing): ~1%
- geometry: <1%

Rough (&conservative) estimate: 5-10% systematic error

To do:
- source wavelength distributions
- ...

Systematics: $<\cos\theta>$ dependence

- **scattering length**
- **absorption length**

$\Delta \lambda_c = -2.7 \%/0.1$

$\Delta \lambda_c = -2.5 \%/0.1$
<table>
<thead>
<tr>
<th>Ice Properties Summary Table</th>
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<tbody>
<tr>
<td></td>
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<td>scattering</td>
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