UV and optical light transmission properties in deep ice at the South Pole

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Abstract. Both absorption and scattering of light at wavelengths 410 to 610 nanometers were measured in the South Pole ice at depths 0.8 to 1 kilometer with the laser calibration system of the Antarctic Muon And Neutrino Detector Array (AMANDA). At the shortest wavelengths the absorption lengths exceeded 200 meters—an order of magnitude longer than has been reported for laboratory ice. The absorption shows a strong wavelength dependence while the scattering length is found to be independent of the wavelength, consistent with the hypothesis of a residual density of air bubbles in the ice. The observed linear decrease of the inverse scattering length with depth is compatible with an earlier measurement by the AMANDA collaboration (at ~515 nanometers).

Introduction

The light transmission properties of the deep ice of the Antarctic ice cap are crucial to the AMANDA experiment which uses the deep ice at the South Pole as detector medium to observe neutrinos from astrophysical sources. Relativistic muons are produced in charged-current interactions between neutrinos and the ice inside and around the detector volume. Muons traversing the detector can be registered through detection of Čerenkov light emitted along their tracks. The effective size and angular resolution of the AMANDA telescope depend critically on the clarity of the ice in the optical and ultraviolet part of the electromagnetic spectrum.

The first in situ measurements of the optical properties of the glacier ice at the South Pole were performed by the AMANDA collaboration during the austral summer 1993–94 [Askebjer, et al., 1995]. The absorption length for light at a wavelength of 515 ± 15 nm was found to be significantly larger than expected from laboratory measurements on ice freshly grown from purified water [Grenfell and Perovich, 1981]. This unexpected result shows both that the absorption in ice itself is smaller than previously thought and that the concentration of absorbing impurities has to be very low in glacier ice. In the present paper we report on new measurements in the wavelength range from 410 nm to 610 nm obtained in the 1994–95 season.

Experimental Setup

A laser calibration system within the AMANDA detector was used to study the transmission properties of the ice. The detector configuration used in this and the previous calibration consists of four strings each equipped with 20 photo-multipliers (PMs) spaced vertically at 10 m intervals and separated horizontally by ~30 m at depths between 810 m and 1000 m. Every PM in the detector is accompanied by an optical fiber that connects a pulsed laser at the surface to a nylon sphere close to the PM. Light at wavelengths that could be varied between 410 nm and 610 nm from a dye laser driven by a Nd:YAG laser operating at 355 nm was coupled into one optical fiber at a time. The laser was pulsed with a frequency of 10 Hz. Each pulse had a time spread of 4 ns full width at half maximum. A monochromator was used to determine the absolute wavelength to a precision better than 2 nm. The total time dispersion was 12 ns (full width at half maximum) mainly due to the optical dispersion of the multimode fiber.

The Model

As the light was emitted isotropically into the ice by the diffusing nylon spheres it was detected by neighboring PMs in the array. The transmission properties of the ice were determined by measuring the arrival times of
photons at surrounding PMs. The first measurements, made in the 1993-94 season [Askebjer, et al., 1995], showed much longer propagation times of the light than what would be expected for direct light. A model was developed [Askebjer, et al., 1995] assuming that light scatters in a random fashion on residual air bubbles trapped in the ice. During the accumulation of snow and ice, air is trapped in the ice, giving rise to air bubbles. As the pressure from the accumulating snow and ice increases, the number and size of the air bubbles decrease. The bubbles convert into solid inclusions of air hydrates [Pricc, 1995] as a function of depth, time and temperature. Their contribution to scattering is very small due to their refractive index being almost identical to that of ice. The existence of air hydrates in glacier ice was first suggested by Miller [Miller, 1969] and later studied in ice cores by Shoji and Langway and by Lipenkov et al. [Shoji, Langway, 1982 and Uchida, et al., 1989].

Since the number of scatterings each photon undergoes between emission and detection was found to be large, a random walk (diffusion) model was found adequate to describe the data. The absorption of the ice itself was added as an extra parameter in the model. The random walk model [Askebjer, et al., 1995] that describes the observed time distributions can be written as

\[ u(d, t) = \frac{1}{(4\pi D t)^{3/2}} e^{-\frac{d}{4D t}} \frac{e^{-\frac{d}{\lambda_a}}}{\lambda_a} , \]

where \( u(d, t) \) is the density of photons at a distance \( d \) from the source at time \( t \) (normalized to unity at \( t=0 \)) and \( \lambda_a \) is the absorption length. The diffusion constant \( D \) is given by

\[ D = \frac{c_i \lambda_{eff}}{3} , \]

where \( c_i \) is the speed of light in ice and the effective scattering length \( \lambda_{eff} \) is related to the scattering length \( \lambda_{sub} \) through the formula

\[ \lambda_{eff} = \frac{\lambda_{sub}}{1 - \langle \cos \theta \rangle} \]

where \( \theta \) is the scattering angle and \( \langle \cos \theta \rangle \) is the average value for spherical and smooth bubbles (for discussion see [Askebjer, et al., 1995]). Intuitively the diffusion model can be justified by observing the arrival time distributions in Fig. 1 keeping in mind the expected arrival time of 44 ns corresponding to 10 m. The number of scatterings required for obtaining such arrival times must thus be large. The previous measurements [Askebjer, et al., 1995] showed excellent agreement with this random walk model including absorption. The absorption length was measured to be 59.1(stat) \pm 3(syst) m. The scattering length was found to increase from approximately 0.1 m to 0.2 m from the top to the bottom of the detector.

**Analysis**

The measurements from the 1994-95 season reported here were made at ten different wavelengths, viz., 410 nm, 415 nm, 420 nm, 435 nm, 450 nm, 475 nm, 500 nm, 530 nm, 590 nm and 610 nm.

For short wavelengths we measured flight times even greater than 10 \( \mu s \). Fig. 1 shows time distributions for 410 nm and 610 nm wavelengths for 10 m distance between the emitter and the receiving PM. The solid curves in Fig. 1 show the random walk model fitted to the data. The expected arrival time for direct light is only 44 ns. In each individual run the laser intensity was adjusted so that the data sample was dominated by single photo-electron (p.e.) events. The fraction of multi-p.e. events was less than a few percent. By selecting distributions where the number of multi-p.e. events is less than 1% the effect of enhanced short flight times on the estimates of the absorption and the scattering length is negligible, as determined by Monte Carlo simulations. Arrival times were measured relative to the PM closest to the emitter. Only time distributions where at least 2000 hits were registered by the receiving PM were selected. In total 461 time distributions with different wavelengths and distances were used. The average of the depth of the emitter and the receiving PM was used as the depth for each measurement.

In the previous analysis [Askebjer, et al., 1995] a straightforward chi-square method was found to be sufficient to fit the obtained time distributions. For the new data covering a large range of absorption lengths we found that a maximum likelihood fit was superior in giving unbiased estimates of the parameters.

In table 1 the observed absorption length is listed for different wavelengths. Fig. 2 shows the wavelength dependence at the top, middle and bottom of the detector. The absorption length at short wavelengths is found to be an order of magnitude longer than what was reported for the best laboratory ice measurements [Grenfell and Perovich, 1981]. We believe that the difference in absorption length between the top and bottom of the de-
tector (see Fig. 2) is due to different concentrations of impurities in the ice at different depths, as measured for instance in ice cores from the Antarctic station in Vostok [Petit, et al., 1990]. The absorption of light in ice itself increases rapidly with the wavelength at values above 410 nm. Absorption by dust particles will then have less influence on the total absorption at longer than at shorter wavelengths. Hence, the difference in absorption should be largest at short wavelengths, which is what we observe. The impurities have greater influence on absorption than on scattering, because the scattering is dominated by the high concentration of air bubbles, which do not absorb light.

Only statistical errors are given in table 1. The systematic errors were estimated by Monte Carlo simulations. The effects of multi-p.e. events, shift in time scale and uncertainty in the relative distances between the PMs were studied. A shift in the time scale can arise from a different transit time in the reference PM due to the fact that the supply voltage was reduced by 30–50% in order not to saturate this PM. Monte Carlo simulations were also used for determining cuts for sample selection. For the absorption length we found that 5% was a conservative number for the systematic error for all wavelengths.

The scattering length was found to increase with depth independently of the wavelength as also was found in the previous analysis [Askbejer, et al., 1995]. In addition, new measurements at depths between 1500 m and 1800 m show an increase in the scattering length of nearly two orders of magnitude. We ascribe this to a decrease with depth of the number density of bubbles and their projected area. In Fig. 3 the inverse scattering length, $1/\lambda_{\text{sub}}(\text{depth})$, and a fitted line are shown. In addition $1/\lambda_{\text{sub}}(\text{depth})$ for two selected wavelengths, 415 nm and 475 nm, is plotted to show that there is no significant wavelength dependence, which supports the air bubble hypothesis. The systematic error for the scattering length is $\sim17\%$. The slope of the fitted line in Fig. 3 is consistent within errors with the slope found in the previous analysis.

In Fig. 4 the inverse absorption length is plotted as a function of wavelength together with previous data on laboratory ice [Grenfell and Perovich, 1981; Minton, 1971; Perovich and Govoni, 1991]. Our results merge with the data of Grenfell and Perovich at a wavelength of about 600 nm. We believe that a higher concentration of solid and dissolved impurities in the ice prepared in the laboratory [Grenfell and Perovich, 1981; Perovich and Govoni, 1991] probably accounts for the discrepancy between our new data and the previous data. We also believe that all of the data of Perovich and Govoni at 250 to 400 nm give too short apparent ab-

Table 1. Absorption length in different depth intervals of the South Pole glacier at different wavelengths.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>810m</th>
<th>875m</th>
<th>940m - 1000m</th>
</tr>
</thead>
<tbody>
<tr>
<td>410 nm</td>
<td>234.0±11.8 m</td>
<td>215.6±7.0 m</td>
<td>167.1±8.0 m</td>
</tr>
<tr>
<td>415 nm</td>
<td>240.0±6.2 m</td>
<td>215.6±7.0 m</td>
<td>167.1±8.0 m</td>
</tr>
<tr>
<td>420 nm</td>
<td>219.9±5.5 m</td>
<td>182.2±10.5 m</td>
<td></td>
</tr>
<tr>
<td>435 nm</td>
<td>208.1±1.9 m</td>
<td>182.2±10.5 m</td>
<td></td>
</tr>
<tr>
<td>450 nm</td>
<td>176.0±2.0 m</td>
<td>145.8±2.1 m</td>
<td></td>
</tr>
<tr>
<td>475 nm</td>
<td>115.0±0.8 m</td>
<td>101.8±1.3 m</td>
<td></td>
</tr>
<tr>
<td>500 nm</td>
<td>67.0±2.6 mu</td>
<td>65.4±0.9 mu</td>
<td></td>
</tr>
<tr>
<td>530 nm</td>
<td>38.2±1.1 m</td>
<td>37.9±0.6 m</td>
<td></td>
</tr>
<tr>
<td>590 nm</td>
<td>11.6±0.2 m</td>
<td>12.8±0.2 m</td>
<td></td>
</tr>
<tr>
<td>610 nm</td>
<td>9.8±0.2 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4. Inverse absorption length as a function of wavelength from measurements by Minton [Minton, 1971] (open squares), Perovich and Govoni [Perovich and Govoni, 1991] (filled squares), Grenfell and Perovich [Grenfell and Perovich, 1981] (open circles) and the AMANDA data at depths between 810 m and 875 m in the Antarctic ice (filled circles).

Absorption lengths due to scattering losses in their experiment. The observed long absorption lengths have been confirmed in an analysis using the Čerenkov light from atmospheric muons in AMANDA. That analysis suggests an absorption length of approximately 310 m at around 380 nm [Tilav et al., 1995].

Summary and Discussion

To summarize, we have measured in situ the absorption and scattering of light for wavelengths between 410 nm and 610 nm at depths between 810 m and 1000 m in the glacier ice at the South Pole. We observe surprisingly long absorption lengths, especially at short wavelengths. The absorption length is found to depend strongly on the wavelength, whereas no wavelength dependence is found for the scattering length. This supports the hypothesis that scattering on bubbles dominates the time dispersion. A possible alternative explanation is that the observed time distributions are caused by fluorescence in the ice. However, our measurement shows that this is very unlikely since the observed distance dependence [Askebjörn, et al., 1995] found in the time distributions can neither be duplicated by fluorescence nor by localized bubble concentrations (e.g., near the holes in which the strings were deployed). The actual time spent by the photons in the drill holes is only a small fraction of the measured travel time, and the method is therefore mainly sensitive to the properties of the glacier ice. Because of the large concentration of air bubbles at these depths the contribution of a low albedo component (e.g., dust) to scattering is undetectably small. If the dust concentration proves to be low enough deeper in the glacier where the bubbles are predicted to disappear [Price, 1995], then the long absorption lengths suggest that the deep ice at the South Pole will be a very good medium for a neutrino detector.

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References

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