Spectral neutron flux oscillations of cosmic radiation on the Earth's surface

W. Rühm,[1] U. Ackermann,[1] C. Pioch,[1] and V. Mares[1]

Received 12 January 2012; revised 13 June 2012; accepted 19 June 2012; published 9 August 2012.

[1] Two Bonner Sphere Spectrometers (BSS) were used – one at the Schneefernerhaus, Germany (altitude: 2650 m; geomagnetic cut-off: 4.1 GV), the other at the Koldewey station on Spitsbergen (sea level; geomagnetic: cut-off 0 GV) – to measure continuously the spectral flux distribution of secondary neutrons from cosmic radiation. At the Schneefernerhaus, the flux of thermal neutrons was about 75% higher in summer than in winter, that of epithermal neutrons about 80%, that of neutrons between 0.125 and 17.8 MeV about 32%, and that of neutrons above 17.8 MeV about 4%, respectively. The period of the observed oscillations was very close to one year. Similar oscillations were observed at the Koldewey station, with somewhat smaller amplitudes (40%, 45%, 22%, and 2%, respectively). At both stations, the flux of the neutrons above 17.8 MeV increased with time similar to the count rates measured by nearby neutron monitors. While this increase reflects changes in the Sun's activity, the observed oscillations are due to changes in ground albedo neutrons and their absorption due to snow. Consequently, the monthly averaged neutron ambient dose equivalent rates, H*(10), oscillated by about ±7% at the UFS and about ±4% at the Koldewey Station. The results demonstrate that BSS measurements could be used to monitor secondary neutrons from cosmic radiation above about 20 MeV. Below detailed neutron transport calculations are necessary to correct for changes in ground albedo neutrons and snow cover. The data presented here can be used as an experimental basis to perform such simulations.

Citation: Rühm, W., U. Ackermann, C. Pioch, and V. Mares (2012), Spectral neutron flux oscillations of cosmic radiation on the Earth's surface, *J. Geophys. Res.*, *117*, A08309, doi:10.1029/2012JA017524.

1. Introduction

[2] Secondary cosmic radiation is the complex field of particles being produced when primary cosmic radiation hits the atmosphere. These secondary particles including mainly neutrons, protons, photons, electrons, positrons, pions, and muons, are well understood and described [e.g., *Schraube et al.*, 1997, 1999; *Heinrich et al.*, 1999; *Roesler et al.*, 2002]. Of note is that secondary neutrons are of particular interest because they contribute up to 60% to dose from cosmic radiation at flight altitudes, and for example at the Zugspitze mountain, i.e., at an elevation of 2650 m [*Rühm et al.*, 2009b; *Chen and Mares*, 2010]. Thus, various efforts have been made in the past to detect secondary neutrons from cosmic radiation at ground level, either by the use of neutron monitors (NMs) (see, e.g., Neutron Monitor Data Base, http://www.nmdb.eu/, accessed in January 2012) or, more recently, by means of Bonner Sphere Spectrometers (BSSs) [*Schraube et al.*, 1997; *Leuthold et al.*, 2007; *Rühm et al.*, 2009a], which have been developed in the 1960s [*Bramblett et al.*, 1960].

[3] Measurements with NMs (which are mainly sensitive to high-energy neutrons above 20 MeV [*Clem and Dorman*, 2000; *Pioch et al.*, 2011]) have shown that snow affects the flux (which corresponds to the term "fluence rate" recommended by the *International Commission on Radiation Units and Measurements* [1998]) of secondary neutrons on the Earth's surface under certain circumstances [*Eroshenko et al.*, 2008]. For example, Tanskanen observed changes in the count rate of his NM depending on the amount of snow on the monitor's building [*Tanskanen*, 1968].

[4] Recently we observed that neutron flux distributions obtained on a snowy and on a dry day were significantly different from each other [*Rühm et al.*, 2009b]. From this we hypothesized that there might also be seasonal changes in the flux distributions of secondary neutrons from cosmic radiation. In order to test this hypothesis, we investigated any potential changes in neutron flux due to snow in the environment as a function of neutron energy, based on data from two BSS spectrometers that are being operated at ground level since several years. It is shown that the neutron flux varies with the amount of snow in the environment and, consequently, with season, being higher during the summer season and lower

[1]Institute of Radiation Protection, National Research Center for Environmental Health, Helmholtz Zentrum München, Neuherberg, Germany.

Corresponding author: W. Rühm, Institute of Radiation Protection, National Research Center for Environmental Health, Helmholtz Zentrum München, Ingolstädter Landstr. 1, DE-85764 Neuherberg, Germany. (werner.ruehm@helmholtz-muenchen.de)

0148-0227/12/2012JA017524

during the winter season. While the neutrons below an energy of 1 MeV are most affected, the neutrons above about 20 MeV are least affected. The observed effect is the result of the interaction of secondary neutrons with the surface of the Earth, and has its origin in so-called ground albedo neutrons shielded by the snow cover of the environment.

2. Materials and Methods

2.1. Measurement Locations

[5] In 2005, a BSS system was installed at the environmental research station "Schneefernerhaus" (UFS) close to the summit of the Zugspitze mountain, Germany (2,650 m above sea level; cut-off rigidity: 4.1 GV for the period of January and February 2008 [*Bütikofer et al.*, 2007]), to perform *continuous* measurements of the spectral flux distribution of secondary neutrons from cosmic radiation [*Leuthold et al.*, 2007]. Since October 2005, the system is running in a measurement shed on the terrace (6×15 m^2) of the station and is providing routine data since 2006. The shed has a steep roof, is covered by a plain aluminum skin, and heated inside. This design was chosen to avoid situations where snow would cover the roof and, as a consequence, shield cosmic radiation. Moreover, the station's staff regularly shovels the snow from the terrace during wintertime. As a result, most of the time of the year there was not much snow on the terrace (with a few exceptions after heavy blizzards for example during weekends).

[6] A similar system was installed in May 2007 at the Koldewey Station of the Alfred-Wegener-Institute (AWI), which is a part of the French - German Arctic Research Base AWIPEV. The AWIPEV base represents a cooperation of the German AWI and the French Polar-Institute Paul Emile Victor (IPEV). The station is located in Ny-Ålesund (Spitsbergen) at sea level. Its coordinates are N 78° 55′ 24″ and E 11° 55′ 15″ (town center), which corresponds to a cut-off rigidity of about 0 GV for the period of January and February 2008 [*Bütikofer et al.*, 2007]. The spectrometer was installed inside a one-floor extension of the station, which served as a storage room before [*Rühm et al.*, 2009a]. This system is providing routine data since 2008.

2.2. Spectrometers

[7] Both BSSs consist of 15 proportional counters filled with ^{3}He gas (172 kPa ^{3}He partial pressure) and covered by polyethylene (PE) spheres of various thicknesses. The PE contains much hydrogen which efficiently thermalizes incident secondary neutrons from cosmic radiation. The thermal neutrons are then detected by the proportional counters situated in the center of each PE sphere through the ^{3}He(n, p)^{3}H reaction. In addition, both BSSs include two PE spheres with lead shells, to increase the response to high-energy neutrons above 10 MeV. Finally, a 16th proportional counter is used without any surrounding material ("bare detector"), which measures thermal environmental neutrons. To obtain quantitative results in terms of neutron flux the response functions of each sphere and the bare detector as a function of neutron energy are required. These were calculated by means of the MCNP code below 20 MeV and a combination of HMCNP/LAHET for energies above 20 MeV [*Mares et al.*, 1991, 1998; *Mares and Schraube*, 1998]. The pulse height spectrum provided by each detector is stored, and the count rate is obtained by integrating over a region of interest that was defined for each detector before installation using an Am/Be neutron source. Count rates from the BSS at Spitsbergen were stored every five minutes and additionally every hour, while they were stored every hour at the UFS. Details are given in *Leuthold et al.* [2007] and *Rühm et al.* [2009a].

[8] Given the calculated response functions of the BSS, the count rates measured were unfolded by means of the MSANDB code (M. Matzke, Neutron metrology file NMF-90, NEA databank, 1987, available at http://www.nea.fr/abs/html/iaea1279.html), a modified version of the SAND code [*McElroy et al.*, 1967]. Some aspects of this unfolding procedure are given in *Simmer et al.* [2010]. The overall measurement procedure allows continuous determination of the spectral flux distribution of secondary neutrons from cosmic radiation every hour.

2.3. Spectral Neutron Flux Distributions

[9] The present study aimed at investigation of seasonal effects. Therefore, all detector counts were integrated over a period of one month. As a result, the number of counts in the bare detector was between 133,000 and 276,000 per month at the UFS for the period from January 2006 to May 2009, and about 22,000–38,000 per month at Spitsbergen for the period from January 2008 to December 2009. In contrast, the number of counts per month of the detector surrounded by the 9 inch PE sphere including the lead sphere with 1 inch thickness was 356,000–490,000 at the UFS, and about 56,000–75,000 at Spitsbergen. The number of counts obtained by the detectors in the other spheres was between these values. From this it can be concluded that, for both locations, the number of counts per months obtained by each detector used was high enough to allow a statistical uncertainty of less than one percent. In order to investigate any seasonal variation in the shape, the neutron energy distribution was divided into four regions: a) thermal region ($E < 0.4$ eV), b) epithermal region ($0.4 < E < 0.125$ MeV), c) MeV region ("evaporation peak"; $0.125 < E < 17.8$ MeV), and d) 100 MeV region ("cascade peak"; $E > 17.8$ MeV). The monthly averaged neutron flux integrated over these four energy regions was finally plotted as a function of time, and fitted using the function given in equation (1):

$$y = a \cdot \sin[(2 \cdot \pi \cdot t \cdot b/365) + d] + c \cdot t + e \qquad (1)$$

where y is the relative flux in the four investigated energy regions, t is the time in days, and a, b, c, d, and e are fit parameters. This function includes a sine function with amplitude a and period b to describe any seasonal oscillations, and a straight line with slope c to describe any linear trend with time.

[10] Among the fit parameters used in equation (1), a, b, and c have a relevant physical meaning: a represents the (relative) amplitude of any seasonal oscillation, b the period of the oscillation, and c is the slope of any linear long-term trend that may be present for example due to any long-term change of solar activity, during the period of observation.

2.4. Calculation of Dose

[11] In order to calculate ambient dose equivalent values from the measured spectral neutron flux distributions, the H*

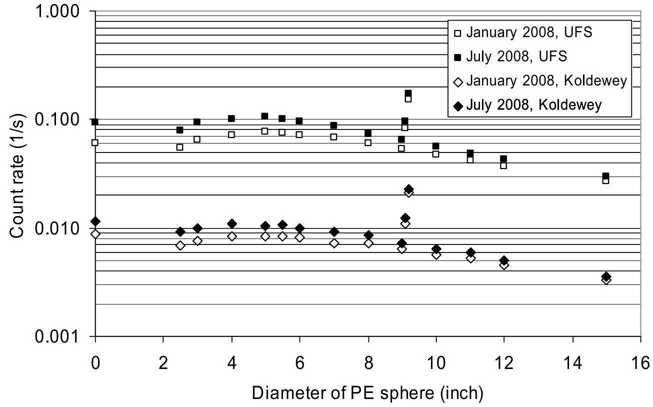

Figure 1. Mean count rates measured in January (open symbols) and July 2008 (black symbols), at the UFS (squares) and the Koldewey station (diamonds); *x* axis provides diameter of the polyethylene (PE) spheres; 0: bare detector without PE sphere; the two high data points at 9.1 and 9.2 inch represent the count rates from those 9 inch PE spheres that include lead shells; data are corrected for a reference pressure of 740 and 1013 hPa for the UFS and the Koldewey station, respectively; for details see text.

(10) fluence-to-dose conversion coefficients as proposed by the *International Commission on Radiological Protection* (*ICRP*) [1997] and calculated by *Pelliccioni* [2000] were used.

2.5. Meteorological Data

[12] Various meteorological parameters are being measured at the UFS and the Koldewey station. These parameters include air temperature, air pressure, relative humidity, wind velocity and wind direction, and precipitation rates. According to equation (2), data on air pressure are used to correct the raw count rates measured with the spectrometer [*Schraube et al.*, 1997; *Leuthold et al.*, 2007].

$$N_{cor} = N \cdot \exp[-\beta(p_0 - p)] \quad (2)$$

where N is the observed count rate at a particular pressure p, and N_{cor} is the corrected value at a reference pressure p_0. For the barometric coefficient β, a value of 0.721% per hPa was used (K. Röhrs, The neutron monitor at Kiel (Germany), Extraterrestrial Physics Department, Institute for Experimental and Applied Physics, Christian-Albrechts University of Kiel, Kiel, Germany, 1995) for the measurements at the UFS. This is the coefficient used to correct the reading of the neutron monitor (NM) in Kiel, Germany. In order to test whether this coefficient can be used for pressure correction at the UFS, we have measured the count rates of the 5 inch PE sphere and the 9 inch PE sphere with lead shell during periods of time when the pressure at the UFS changed significantly within a few hours. Assuming that the neutron flux depends exponentially on air pressure, and using a least squares fit through the regression curve of the logarithm of the hourly count rates against pressure, we obtained a barometric coefficient of 0.80% per hPa. Schraube and colleagues reported a barometric coefficient of 0.82% per hPa [see *Schraube et al.*, 1997]. Both these coefficients agreed within their statistical uncertainty with the coefficient of 0.721% per hPa used for the NM of the University in Kiel. Therefore, the latter value was used for all spheres at UFS. For the Koldewey station, a value of 0.741% per hPa was used which is also used to correct the reading of the neutron monitor in Apatity, Russia (E. Vashenyuk, Polar Geophysical Institute, Apatity, Russia, private communication, 2008). For both stations, after application of these barometric coefficients (0.721% per hPa for the UFS, and 0.741% per hPa for the Koldewey Station), no residual correlation of the BSS count rates with pressure could be observed within the uncertainties involved [see also *Rühm et al.*, 2009a, Figure 3].

[13] Data from the UFS were corrected to a reference pressure of 740 hPa, while those from the Koldewey station were corrected to a reference pressure of 1013 hPa.

3. Results

3.1. Measured Count Rates

[14] As an example, Figure 1 shows the mean count rates obtained by the 16 detectors of the UFS BSS and corrected for air pressure, for January and July 2008. The figure also includes similar data obtained from the Koldewey BSS. As already mentioned above, the number of counts included per data point is more than 20,000. As a result, the corresponding statistical uncertainties are smaller than the dimension of the symbols in the figure.

[15] The figure demonstrates at least two interesting features. First, the count rates obtained at mountain altitudes (UFS) are a factor of 8.3 greater than those from the Koldewey station, for January, while they are a factor 8.8 greater for July. Most of this difference can be explained the shielding of the atmosphere, i.e., by the different air pressures being about 740 hPa at the UFS, and 1013 hPa at Spitsbergen (using equation (1), the pressure difference of 273 hPa corresponds to a factor of 7.2). Note that geomagnetic shielding may also contribute to the difference in the count rates measured at the two sites. However, this contribution is small compared to that resulting from the different altitudes at both sites. For example, our calculations show that at sea level and a geomagnetic cut-off rigidity of 0 GV (which corresponds to the site of the Koldewey Station), this difference is less than 10% compared to sea level and 4 GV (the geomagnetic cut-off rigidity that corresponds to the location of the UFS on the Zugspitze mountain).

[16] Second, the figure shows the changes between January and July to be more pronounced for the bare detector and detectors surrounded by small spheres, whereas those detectors surrounded by larger PE spheres or by those including lead show smaller changes, for both BSS systems. Note that those spheres with smaller diameters are more sensitive to low-energy neutrons, while spheres with larger diameters are more sensitive to high-energy neutrons. Considering this fact Figure 1 already suggests a larger seasonal change of the low-energy part of the neutron spectrum than of the high-energy part.

3.2. Unfolded Spectral Neutron Flux Distributions at UFS

[17] Figure 2 shows, as an example, the unfolded spectral neutron flux distribution using the mean count rates obtained at the UFS in January and July 2008, respectively (Figure 1).

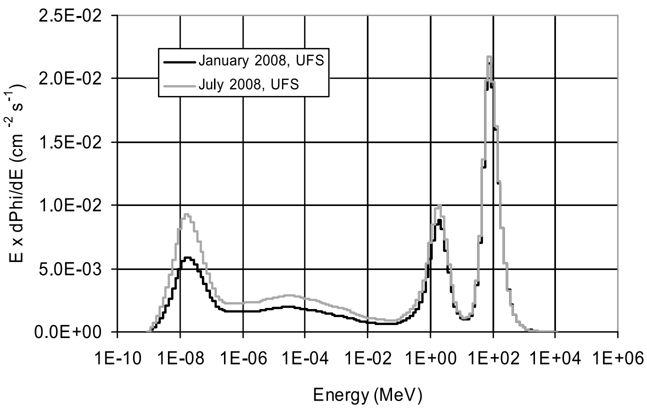

Figure 2. Spectral neutron flux distribution for January and July 2008, at the UFS.

The figure presents the data in the lethargy representation. In this representation, the *y* axis displays the neutron flux per lethargy unit $d\phi/dln(E/E_0)$ which mathematically corresponds to $d\phi/dE \cdot E$. When this quantity is plotted linearly versus a log-energy scale, then equal areas below the curve correspond to equal fluxes. The mean spectral neutron flux distributions exhibit four typical features: a) the Maxwell-Boltzmann peak that is due to thermalized neutrons, b) a flat intermediate region with epithermal neutrons, c) the MeV peak that is due to evaporation neutrons from highly excited residual nuclei, and d) the 100 MeV peak that is due to a broad minimum in the corresponding neutron-air reaction cross-sections at high energies. These components are typical for secondary neutrons from cosmic radiation [e.g., *Leuthold et al.*, 2007; *Rühm et al.*, 2009a; *Pioch et al.*, 2010], but also for example outside the shielding of high-energy particle accelerators [*Mares et al.*, 1998; *Mares and Schraube*, 1998; *Simmer et al.*, 2010; *Wiegel et al.*, 2009].

[18] Note that there are almost no differences between both neutron energy distributions, for neutron energies above about 10 MeV. However, there is some difference when looking at the evaporation peak (1–2 MeV), and this difference is even more pronounced for the epithermal and thermal region of the distribution. The same pattern can be observed when the mean count rates obtained at the Koldewey station in January and July 2008 (Figure 1) are unfolded, although the differences between the January and July distributions are somewhat smaller (see below).

[19] Similar distributions as those shown in Figure 2 have been obtained every month for the period January 2006–May 2009, for the UFS, and for the period January 2008–December 2009, for the Koldewey station. In order to quantify any seasonal changes in the monthly spectral neutron flux distributions obtained, we have calculated the mean number of neutrons per cm^2 and second, for each month, for the four major regions: thermal (<0.4 eV), epithermal (0.4 ev–0.125 MeV), evaporation region (0.125 MeV–17.8 MeV), and cascade region (>17.8 MeV). As noted earlier, this corresponds to the area below the curves in Figure 2, in the corresponding energy regions. The results, normalized to the corresponding mean numbers obtained for UFS (average over the measurement period), are shown in Figure 3.

[20] The data shown in Figure 3 demonstrate that there are seasonal oscillations of the neutron flux, being most pronounced for the thermal and epithermal energy region, while less pronounced in the MeV region. Interestingly, there is only a very small oscillation if any, for the 100 MeV region. Two anomalies in the data in Figure 3 are observed: the monthly averaged neutron flux obtained for August 2006 and September 2007 appear much lower than those from neighboring months. Interestingly, during these two months, heavy blizzards with a lot of snow were reported at the Zugspitze mountain, which modified the measured spectral neutron flux distributions considerably, during and after these events [*Rühm et al.*, 2009b]. These events were atypical for the seasons in which they occurred.

[21] To quantify the oscillation, we have fitted the data shown in Figure 3 (but without the two outliers in August 2006 and September 2007) using the function given in equation (1). Table 1 shows the results obtained for the amplitude and period of the oscillations, and for the slope of the straight line.

[22] The results shown in Table 1 confirm that the amplitudes of the oscillations are highest for thermal and epithermal neutrons (about ±28%), while they are about half for MeV neutrons (about ±14%), and very small if any for 100 MeV neutrons (about ±2%). As for the period of the oscillations, all results are in agreement with each other and with a period of one year. It is also quite interesting that significant slopes were obtained from both the MeV and 100 MeV data which are in agreement with each other (0.000031 versus 0.000030 per day). This suggests an increase in intensity with time that is independent of season (see discussion section).

3.3. Unfolded Neutron Energy Distributions at the Koldewey Station

[23] Figure 4 shows the mean spectral neutron flux distribution unfolded from the mean count rates obtained at the Koldewey station in January and July 2008, respectively (see Figure 1). As was the case for the neutron energy distributions from the UFS (Figure 2), there are almost no differences between both neutron energy distributions for

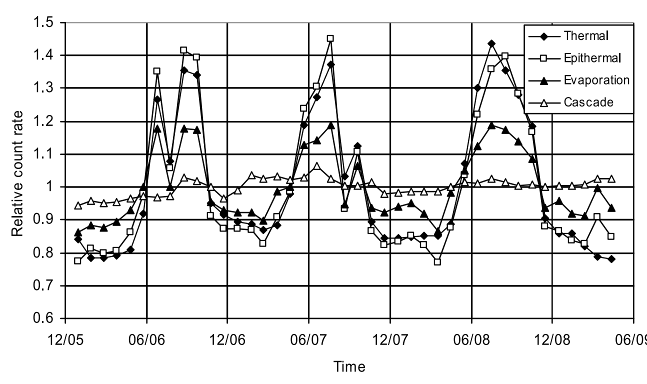

Figure 3. Monthly variation of neutrons at the UFS; data are given relative to the mean over the whole period: mean of thermal flux - 0.0216 n cm^{-2} s^{-1}; mean of epithermal flux - 0.0208 n cm^{-2} s^{-1}; mean of MeV flux - 0.0190 n cm^{-2} s^{-1}; mean of 100 MeV flux - 0.0321 n cm^{-2} s^{-1}; note that the data from two months (August 2006, and September 2007), are not considered typical because of heavy blizzards during these particular months.

Table 1. Result of a Fit of the UFS Data Shown in Figure 3 Using a Sine Function Plus a Straight Line (Equation (1))[a]

	Amplitude *a*	Period *b*	Slope *c* (d^{-1})
Thermal	0.273 ± 0.023	0.997 ± 0.013	0.000021 ± 0.000043
Epithermal	0.285 ± 0.024	0.993 ± 0.014	0.000009 ± 0.000046
0.125 < E < 17.8 MeV	0.138 ± 0.011	0.992 ± 0.013	0.000031 ± 0.000021
>17.8 MeV	0.0169 ± 0.0053	1.050 ± 0.049	0.000030 ± 0.000010

[a]Outliers from August 2006 and September 2007 were omitted.

neutron energies above about 10 MeV, while there is some difference for MeV neutrons, and the difference appears even more pronounced for epithermal and thermal neutrons.

[24] As was described above for the UFS data, the neutron flux obtained at the four defined energy regions (thermal, epithermal, MeV, and 100 MeV) were also calculated from the monthly averaged spectral neutron flux distributions measured at the Koldewey station. In terms of absolute values, they are considerably smaller than those obtained for the UFS due to the shielding effect of the atmosphere which is much less important at mountain altitudes than at sea level [*Rühm et al.*, 2009a]. In terms of relative values, the results are given in Figure 5 normalized to the mean values over the measurement period (note that the scaling of the *y* axis is the same as in Figure 3). It is evident from the figures that the seasonal pattern observed at the Koldewey station for Jan 2008–Dec 2009 is very similar to that observed at the UFS, although the magnitude of the effect appears to be somewhat smaller.

[25] This is quantified in Table 2, where the results of the fit parameters are summarized.

[26] Table 2 demonstrates that neutron flux oscillations were also present at the Koldewey station. As was the case for the UFS data, the period of these oscillations is roughly one year, with that obtained from the 100 MeV neutrons being slightly longer (1.232 ± 0.116 years). In contrast to the UFS data, however, the amplitudes of the fitted sine functions obtained from the Koldewey station data are significantly smaller – ±16.7% instead of ±27.3% for thermal, ±18.3% instead of ±28.5% for epithermal, ±10% instead of ±13.8% for MeV, and ±0.9% instead of ±1.7% for 100 MeV neutrons, respectively. Again, the seasonal changes observed for the 100 MeV neutrons are small, and a long-lasting trend of increasing neutron flux with increasing time (slope of about 6×10^{-5} per day) could be observed, which is consistent with that observed for MeV neutrons if the uncertainties are taken into account.

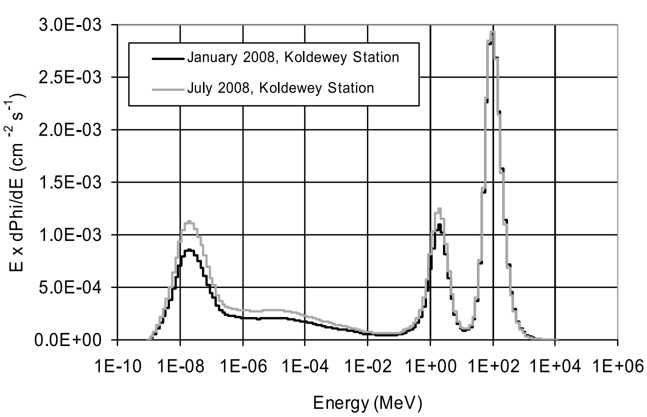

Figure 4. Spectral neutron flux distribution for January and July 2008, at the Koldewey station, Spitsbergen.

4. Discussion

[27] The data presented demonstrate that the flux of secondary neutrons from cosmic radiation measured at ground level oscillated with a period of about one year, for both locations investigated. It was observed that during the winter seasons, the flux of neutrons below about 20 MeV was significantly smaller compared to that in summer, while the flux of 100 MeV was not much affected and showed only a very small seasonal change if any. This already suggests that some climatic changes may be at least in part involved: It is very likely that the snow in the environment present during winter time shields the so-called ground albedo neutrons, i. e., high-energy neutrons that enter the ground, are moderated there and leave it as low-energy neutrons. The flux of albedo neutrons depends on the elemental composition of the ground and is strongly affected by its water content, because hydrogen is a very effective neutron moderator and absorber. A recent observation confirms this fact: It was reported that the energy distribution of secondary neutrons from cosmic radiation measured at the UFS during a warm and dry period was significantly different from that measured at the same location but three weeks later when a heavy blizzard had deposited about one meter of snow around the BSS measurement shed [*Rühm et al.*, 2009b]. Under these conditions, the flux of thermal, epithermal and MeV neutrons was significantly smaller than that obtained at dry conditions, while the flux of 100 MeV neutrons remained essentially unchanged. Interestingly, this ground

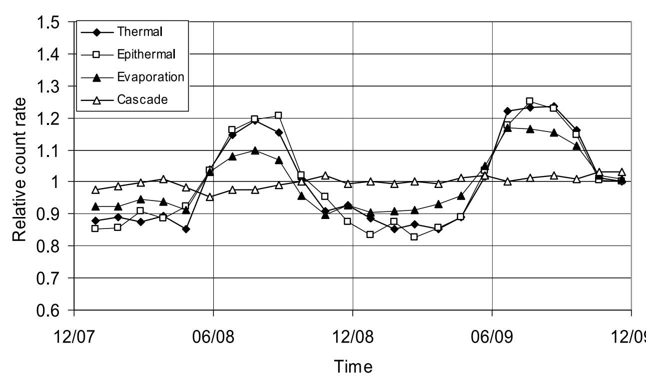

Figure 5. Monthly variation of neutrons at the Koldewey station; data are given relative to the mean over the whole period: mean thermal flux - of 0.0036 n cm^{-2} s^{-1}; mean epithermal flux - 0.0024 n cm^{-2} s^{-1}; mean MeV flux - 0.0026 n cm^{-2} s^{-1}; mean 100 MeV flux - 0.0056 n cm^{-2} s^{-1}.

Table 2. Result of a Fit of the Data From the Koldewey Station Shown in Figure 5 Using a Sine Function Plus a Straight Line (Equation (1))

	Amplitude a	Period b	Slope c (d^{-1})
Thermal	0.167 ± 0.019	0.987 ± 0.031	0.000065 ± 0.000067
Epithermal	0.183 ± 0.016	0.969 ± 0.025	0.000025 ± 0.000057
0.125 < E < 17.8 MeV	0.100 ± 0.014	0.933 ± 0.041	0.000112 ± 0.000049
>17.8 MeV	0.009 ± 0.004	1.232 ± 0.116	0.000064 ± 0.000012

albedo effect appears to be more pronounced at the UFS and less pronounced at the Koldewey station. This may be explained by the fact that the annual precipitation rate typical for the mountain altitude of the UFS (the mean precipitation rate at the summit of the Zugspitze mountain at 2,963 m above sea level was about 2,000 mm/y, for the period 1961–1990 (German Weather Service, http://www.dwd.de, accessed on 17 December 2010)) is much higher than that at the Koldewey station on Spitsbergen, where a rather dry climate is typical (for example, at Ny-Ålesund the mean annual precipitation rate was about 460 mm in 2008, and about 400 mm in 2009 (Norwegian Meteorological Institute, http://retro.met.no/observasjoner/svalbard/Ny-Alesund/, accessed on 20 December 2010)). Thus, in the vicinity of the BSS at the Koldewey station, much less humidity/water/snow (i.e., hydrogen) is present and, as a consequence, the seasonal variations in hydrogen concentration are also lower and their influence on the spectral neutron flux distribution smaller. As a consequence, the observed spectral neutron flux oscillations are expected to depend on local climate, and are therefore different at different regions – in areas where snow is persisting all the year (e.g., North Pole) these oscillations are expected to be very small, as they are in areas where it is dry all the year (e.g., dessert).

4.1. Discussion in Terms of Solar Cycle 23

[28] In addition to the seasonal changes described and discussed above, there was also a trend of increasing flux with increasing time. This could be quantified in particular for the 100 MeV neutrons that were not affected much by the seasonal changes discussed above (Tables 1 and 2). This increase may be explained by the fact that the Sun was – during the period of the reported measurements – in the declining phase of Cycle 23. A decrease in the Sun's activity leads to a decrease in shielding of galactic cosmic rays by the magnetic fields within the Heliopshere, which in turn leads to an increase in primary cosmic ray intensity. In order to quantify this effect, we have used data from the neutron monitor at Lomnicky Stit, Slovakia (Lomnicky Stit Neutron Monitor, http://neutronmonitor.ta3.sk/archive.php, accessed in April 2010), which is located at an altitude of 2,634 m above sea level and has a geomagnetic cut-off of 3.84 GV, similar to the location of the BSS operated at the UFS. Figure 6 shows the monthly data from this neutron monitor, for the period between January 2006 and May 2009, normalized to the average count rate during this period. A linear fit through the data results in a slope of (3.9 ± 0.4) × 10^{-5} d^{-1} that is very close to that obtained at UFS for neutrons with energies E > 0.125 MeV (Table 1).

[29] The data for neutrons with energies greater than 17.8 MeV measured at the Koldewey station also suggest a similar but somewhat steeper slope of (6.4 ± 1.2) × 10^{-5} d^{-1}. Interestingly, a slope of (5.9 ± 0.4) × 10^{-5} d^{-1} can be deduced from the data of the Apatity neutron monitor, Russia, located at about 181 m above sea level at a cut-off of 0.65 GV, which is very similar to that measured with the BSS operated at the Koldewey station, when the same period of time is investigated (Figure 7).

[30] Both figures demonstrate that the data obtained with our BSS instruments could be used to monitor the intensity of secondary neutrons from cosmic radiation over the whole period of investigation, if the analysis is restricted to neutron energies above 20 MeV. For neutron energies below 20 MeV, changes of ground albedo neutrons hide the smaller changes in primary cosmic ray intensity (although these may still be visible for MeV neutrons – see the slopes (parameters c) in Tables 1 and 2 which are significantly different from zero). Other factors that could not be quantified in the present study such as long-term climatic changes over several years may also contribute somewhat to the observed changes, but these contributions are expected to be small.

4.2. Implication on Radiation Dose Due to Secondary Neutrons From Cosmic Radiation

[31] It was shown here that the spectral shape of the neutron flux measured at ground level changes with season, particularly for neutron energies below 17 MeV. Because it was recently shown that these neutrons contribute about 40% to total neutron ambient dose equivalent [*Rühm et al.*,

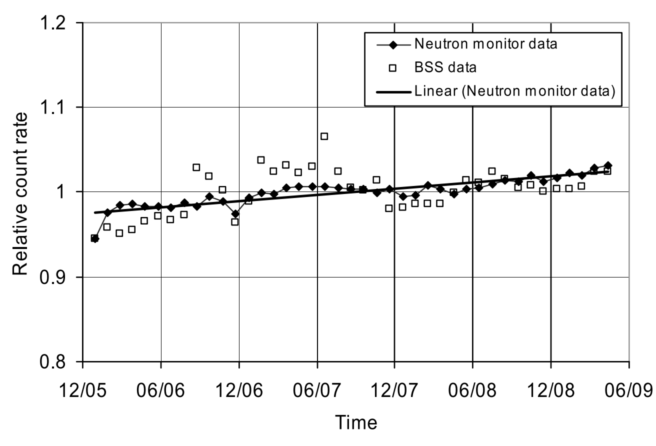

Figure 6. Count rate obtained by the neutron monitor at Lomnicky Stit, Slovakia, normalized to the average over the given time period (Jan 2006–May 2009; solid symbols) (Lomnicky Stit Neutron Monitor, http://neutronmonitor.ta3.sk/archive.php, accessed in April 2010); solid line represents a linear fit through the data with a slope of (3.9 ± 0.4) × 10^{-5} d^{-1}; open symbols represent measured BSS count rate at the UFS for the cascade region (see Figure 3).

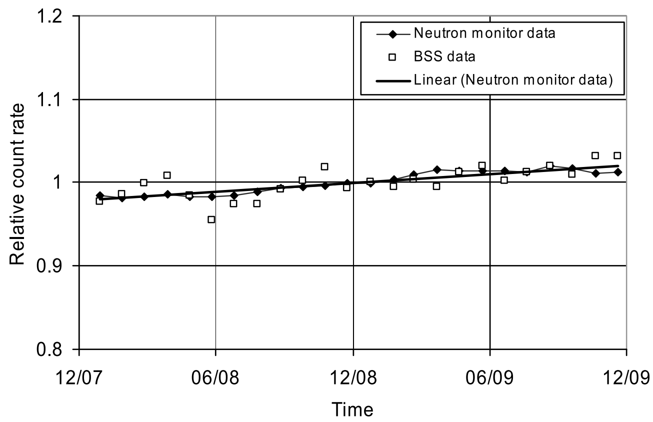

Figure 7. Count rate obtained from the neutron monitor at Apatity, Russia, normalized to the average over the given time period (Jan 2008–Dec 2009; solid symbols) (Apatity Neutron Monitor, http://cr0.izmiran.rssi.ru/apty/main.htm, accessed in April 2010); solid line represents a linear fit through the data with a slope of $(5.9 \pm 0.4) \times 10^{-5}$ d^{-1}; open symbols represent measured BSS count rate at the Koldewey station for the cascade region (see Figure 3).

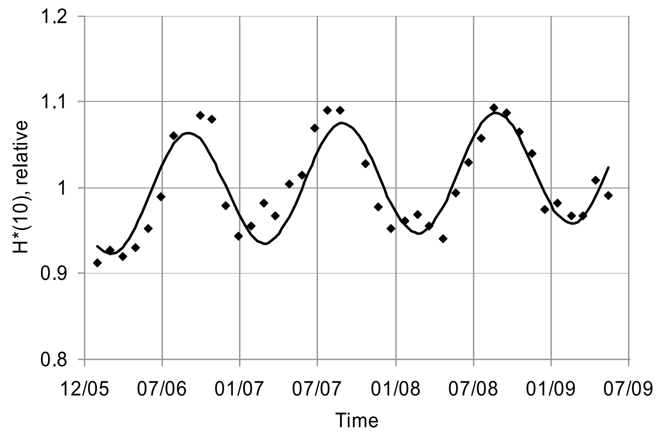

Figure 8. Symbols indicate monthly averaged values for the neutron ambient dose equivalent at the UFS as deduced by folding the BSS spectral neutron flux distributions with the H*(10) ICRP and Pelliccioni conversion function (outliers on August 2006 and September 2007 omitted). As in Figures 3 the data are normalized to the mean over the whole measurement period from January 2006 to April 2009; solid line indicates fit through the data using equation (1).

2009b], it is expected that these changes should also result in seasonal changes of the neutron dose rate. To quantify this expectation, we have folded the monthly neutron energy distributions obtained for the UFS, for January 2006 until June 2009, with the H*(10) fluence-to-dose conversion coefficients as proposed by the *ICRP* [1997] and calculated by *Pelliccioni* [2000], and obtained monthly values for the ambient dose equivalent rate from neutrons. The mean value over the whole measurement period (January 2006 to May 2009) was about 67.1 nSv/h. Indeed and as expected, the data do show a seasonal variation (Figure 8), and the fit parameters obtained applying equation (1) on the relative changes are: $a = 0.068 \pm 0.006$, $b = 0.999 \pm 0.014$, $c = (3.3 \pm 1.2) \times 10^{-5}$ d^{-1}. Thus, we observed an oscillation in dose rate with an amplitude of about 7% which means that the dose rate due to secondary neutrons from cosmic radiation is about 15% higher in summer than in winter times, at the UFS. The period of this oscillation is very close to one year. Finally, during the observation period there was a slight increase in dose rate (corresponding to an about 4% higher dose rate in May 2009 compared to January 2006), probably due to the decreasing solar activity during Solar Cycle 23.

[32] The dose rates obtained from the measurements at the Koldewey station are shown in Figure 9. The mean value over the whole measurement period (January 2008 to December 2009) was about 10.3 nSv/h. The fit through the data using equation (1) confirms the expected oscillations, which are somewhat less pronounced than those observed at the UFS (Figure 8). The corresponding fit parameters are $a = 0.038 \pm 0.005$ for the amplitude, b = 0.971 ± 0.034 for the period, and $c = (6.4 \pm 1.6) \times 10^{-5}$ d^{-1} for the slope. Thus, on Spitsbergen the dose rate from secondary neutrons from cosmic radiation is in summer times about 8% higher than in winter times.

[33] Note that during months without or with low snow cover (summer time), high-energy secondary neutrons from cosmic radiation that enter the soil are moderated and reflected by the soil as lower-energy neutrons. In contrast, during winter time these moderated and reflected neutrons are at least partly being absorbed by the overlying snow cover. It is thus expected that an increase in dose rate due to the decreasing solar activity should be particularly observable during these months. Indeed, when only UFS dose-rate data are taken for example from December – March, from Figure 8, a linear trend with a slope of $(4.1 \pm 0.9) \times 10^{-5}$ d^{-1} is found, similar to the slope deduced when data from the whole period were used ($(3.3 \pm 1.2) \times 10^{-5}$ d^{-1}, see above). Similarly, for the Spitsbergen data (Figure 9), a slope of $(5.7 \pm 2.4) \times 10^{-5}$ d^{-1} is obtained for December – March,

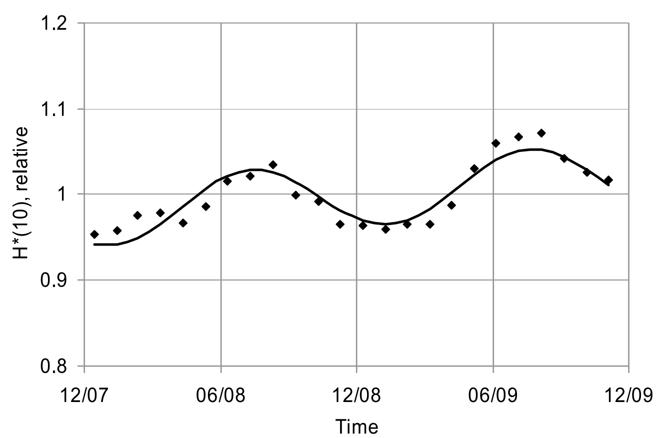

Figure 9. Symbols indicate monthly averaged values for the neutron ambient dose equivalent at the Koldewey station as deduced by folding the BSS spectral neutron flux distributions with the H*(10) ICRP and Pelliccioni conversion function. As in Figure 5 the data are normalized to the mean over the whole measurement period from January 2008 to Dec 2009; solid line indicates fit through the data using equation (1).

which compares to a slope of $(6.4 \pm 1.6) \times 10^{-5}$ d^{-1} when all data of Figure 9 are used (see above).

5. Conclusion

[34] In the present study, two Bonner sphere spectrometers were used to measure the spectral flux distributions of secondary neutrons from cosmic radiation at ground level continuously over several years. The results obtained suggest pronounced oscillations that depend on a) time – the period of these oscillations is very close to one year, b) neutron energy – the amplitude of the oscillations are most pronounced for thermal and epithermal neutrons, intermediate for MeV neutrons, and less pronounced for high-energy neutrons above 17.8 MeV, and c) location – the measured amplitude is larger at the UFS Schneefernerhaus, while it is smaller at the Koldewey Station. This effect could be explained by the seasonal changes of the flux of so-called ground albedo neutrons and the amount of snow in the environment surrounding the Bonner sphere spectrometers. Snow and water are, due to their high hydrogen content, the most important substances in the environment, in terms of neutron moderation and absorption. The ground albedo neutrons produced by secondary neutrons from cosmic radiation have energies from thermal to several MeV, with the main contribution in the thermal and epithermal regions. Considering that the mean free path of thermal neutrons in air is about 30 m, it can be assumed that an area of about hundred meters around the measurement position is important for this "snow effect" and should be taken into account. First and preliminary neutron transport calculations show that more water on the ground leads to less epithermal neutrons, which are either absorbed or moderated to thermal energies. Consequently, the number of thermal neutrons increases, but at the same time – depending on the amount of water assumed in the calculations - an increasing fraction of the moderated thermal neutrons is also absorbed. In contrast, the number of high-energy neutrons (above 20 MeV) remained essentially unchanged. However, the magnitude of these effects depends on various factors such as local geometry (e.g., shielding), height of water or snow above the ground, snow density, ground composition including humidity, surrounding structure material, etc., and more detailed calculations are required to draw any quantitative conclusion.

[35] The results presented here demonstrate that BSS measurements could be used to monitor the flux of secondary neutrons from cosmic radiation in absolute terms if the data are restricted to neutrons with energies greater than about 20 MeV. If the data below 20 MeV are to be analyzed quantitatively in terms of whether or not they are cosmic ray induced, however, detailed neutron transport calculations are necessary and a tool needs to be developed to correct BSS data for snow and ground albedo effects. The required simulations are presently under way. The data obtained in the present study are important because they can be used – when combined with meteorological data - as the experimental basis to develop and validate such tools.

[36] The annual dose from neutrons measured at the UFS Schneefernerhaus is about 600 μSv. The observed oscillations lead to changes in neutron dose of about $\pm$6.8%, with higher values during summer time and smaller values during winter time. The corresponding numbers for the Koldewey station are about 90 μSv for the annual neutron dose and $\pm$3.8% for the seasonal changes in neutron dose rate. Thus, despite of the observed seasonal oscillation of neutron flux the monthly averaged ambient dose equivalent from secondary cosmic neutrons could be estimated with about 7% systematic error at the UFS Schneefernerhaus, and about 4% at the Koldewey station.

[37] It is concluded that the observed neutron flux oscillations represent an important aspect which should be taken into account when any measurements of secondary neutrons from cosmic radiation at the surface of the Earth are performed.

[38] **Acknowledgments.** S. Debatin from AWI is greatly acknowledged for providing the pressure data obtained at the Koldewey station. The current paper makes use of data obtained from the neutron monitors at Lomnicky Stit, Slovakia, and Apatity, Russia.

[39] Philippa Browning thanks the reviewers for their assistance in evaluating the paper.

References

Bramblett, R., R. Ewing, and T. Bonner (1960), A new type of neutron spectrometer, *Nucl. Instrum. Methods*, *9*, 1–12, doi:10.1016/0029-554X(60)90043-4.

Bütikofer, R., E. O. Flückiger, and L. Desorgher (2007), Characteristics for near real-time cutoff calculations on a local and global scale, paper presented at 30th International Cosmic Ray Conference, Int. Union of Pure and Appl. Phys., Merida, Mexico.

Chen, J., and V. Mares (2010), Significant impact on effective doses received during commercial flights calculated using the new ICRP radiation weighting factors, *Health Phys.*, *98*(1), 74–76, doi:10.1097/HP.0b013e3181bada5a.

Clem, J., and L. Dorman (2000), Neutron monitor response functions, *Space Sci. Rev.*, *93*, 335–359, doi:10.1023/A:1026508915269.

Eroshenko, E., P. Velinov, A. Belov, V. Yanke, E. Pletnikov, Y. Tassev, and A. Mishev (2008), Relationships between cosmic ray neutron flux and rain flows, paper presented at 21st European Cosmic Ray Symposium, Inst. of Exper. Phys., Slovak Acad. of Sci., Košice, Slovakia.

Heinrich, W., S. Roesler, and H. Schraube (1999), Physics of cosmic radiation fields, *Radiat. Prot. Dosim.*, *86*(4), 253–258, doi:10.1093/oxfordjournals.rpd.a032953.

International Commission on Radiation Units and Measurements (1998), Fundamental quantities and units for ionizing radiation, *Rep. 60*, Bethesda, Md.

International Commission on Radiological Protection (ICRP) (1997), *Conversion Coefficients for Use in Radiological Protection Against External Radiation*, *ICRP Publ.*, vol. 74, Pergamon, Oxford, U. K.

Leuthold, G., V. Mares, W. Rühm, E. Weitzenegger, and H. G. Paretzke (2007), Long-term measurement of cosmic ray neutrons by means of a Bonner spectrometer at mountain altitudes—First results, *Radiat. Prot. Dosim.*, *126*, 506–511, doi:10.1093/rpd/ncm102.

Mares, V., and H. Schraube (1998), High energy neutron spectrometry with Bonner spheres, paper presented at Regional Symposium on Radiation Protection, Int. Radiat. Prot. Assoc., Prague, 8–12 Sept.

Mares, V., G. Schraube, and H. Schraube (1991), Calculated neutron response of a Bonner sphere spectrometer with ^{3}He counter, *Nucl. Instrum. Methods Phys. Res., Sect. A*, *307*, 398–412.

Mares, V., A. Sannikov, and H. Schraube (1998), The response functions of a ^{3}He-Bonner spectrometer and their experimental verification in high energy neutron fields, in *Shielding Aspects of Accelerators, Targets and Irradiation Facilities*, pp. 237–248, Nucl. Energy Agency, Paris.

McElroy, W. N., S. Berg, T. Crockett, and R. G. Hawkins (1967), Spectra unfolding, *Rep. AFWL-TR-67-41*, vol. I–IV, Air Force Weapons Lab., Kirtland Air Force Base, N. M.

Pelliccioni, M. (2000), Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code, *Radiat. Prot. Dosim.*, *88*, 279–297, doi:10.1093/oxfordjournals.rpd.a033046.

Pioch, C., V. Mares, and W. Rühm (2010), Influence of Bonner sphere response functions above 20 MeV on unfolded neutron spectra and doses, *Radiat. Meas.*, *45*, 1263–1267, doi:10.1016/j.radmeas.2010.05.007.

Pioch, C., V. Mares, E. V. Vashenyuk, Y. V. Balabin, and W. Rühm (2011), Measurement of cosmic ray neutrons with Bonner sphere

spectrometer and neutron monitor at 79°N, *Nucl. Instrum. Methods Phys. Res., Sect. A*, *626–627*, 51–57.
Roesler, S., W. Heinrich, and H. Schraube (2002), Monte Carlo calculation of the radiation field at aircraft altitudes, *Radiat. Prot. Dosim.*, *98*(4), 367–388, doi:10.1093/oxfordjournals.rpd.a006728.
Rühm, W., V. Mares, C. Pioch, E. Weitzenegger, R. Vockenroth, and H. G. Paretzke (2009a), Measurements of secondary neutrons from cosmic radiation with a Bonner sphere spectrometer at 79°N, *Radiat. Environ. Biophys.*, *48*, 125–133, doi:10.1007/s00411-009-0219-y.
Rühm, W., V. Mares, C. Pioch, G. Simmer, and E. Weitzenegger (2009b), Continuous measurement of secondary neutrons from cosmic radiation at mountain altitudes and close to the North Pole—A discussion in terms of H*(10), *Radiat. Prot. Dosim.*, *136*(4), 256–261, doi:10.1093/rpd/ncp161.
Schraube, H., J. Jakes, A. Sannikov, E. Weitzenegger, S. Roesler, and W. Heinrich (1997), The cosmic ray induced neutron spectrum at the summit of the Zugspitze (2963 m), *Radiat. Prot. Dosim.*, *70*(1–4), 405–408, doi:10.1093/oxfordjournals.rpd.a031986.
Schraube, H., V. Mares, S. Roesler, and W. Heinrich (1999), Experimental verification and calculation of aviation route doses, *Radiat. Prot. Dosim.*, *86*(4), 309–315, doi:10.1093/oxfordjournals.rpd.a032963.
Simmer, G., V. Mares, E. Weitzenegger, and W. Rühm (2010), Iterative unfolding for Bonner sphere spectrometers using the MSANDB code—Sensitivity analysis and dose calculation, *Radiat. Meas.*, *45*, 1–9, doi:10.1016/j.radmeas.2009.03.023.
Tanskanen, P. J. (1968), Influence of snow on neutron monitor intensity, *Nature*, *219*, 926–927, doi:10.1038/219926a0.
Wiegel, B., et al. (2009), Intercomparison of radiation protection devices in a high-energy stray neutron field. Part II: Bonner sphere spectrometry, *Radiat. Meas.*, *44*, 660–672, doi:10.1016/j.radmeas.2009.03.026.