A COMPARISON OF NEW CALCULATIONS OF THE YEARLY $^{10}$Be PRODUCTION IN THE EARTHS POLAR ATMOSPHERE BY COSMIC RAYS WITH YEARLY $^{10}$Be MEASUREMENTS IN MULTIPLE GREENLAND ICE CORES BETWEEN 1939 AND 1994 – A TROUBLING LACK OF CONCORDANCE

PAPER #2

W.R. Webber$^1$, P.R. Higbie$^2$ and C.W. Webber$^3$

1. New Mexico State University, Department of Astronomy, Las Cruces, NM  88003, USA
2. New Mexico State University, Physics Department, Las Cruces, NM  88003, USA
3. Microsoft Corp., Building 88, Redmond, WA 98052, USA
ABSTRACT

We have compared the yearly production rates of $^{10}\text{Be}$ by cosmic rays in the Earths polar atmosphere over the last 50-70 years with $^{10}\text{Be}$ measurements from two separate ice cores in Greenland. These ice cores provide measurements of the annual $^{10}\text{Be}$ concentration and $^{10}\text{Be}$ flux levels during this time. The scatter in the ice core yearly data vs. the production data is larger than the average solar 11 year production variations that are being measured. The cross correlation coefficients between the yearly $^{10}\text{Be}$ production and the ice core $^{10}\text{Be}$ measurements for this time period are <0.4 in all comparisons between ice core data and $^{10}\text{Be}$ production, including $^{10}\text{Be}$ concentrations, $^{10}\text{Be}$ fluxes and in comparing the two separate ice core measurements. In fact, the cross correlation between the two ice core measurements, which should be measuring the same source, is the lowest of all, only ~0.2. These values for the correlation coefficient are all indicative of a “poor” correlation. The regression line slopes for the best fit lines between the $^{10}\text{Be}$ production and the $^{10}\text{Be}$ measurements used in the cross correlation analysis are all in the range 0.4-0.6. This is a particular problem for historical projections of solar activity based on ice core measurements which assume a 1:1 correspondence. We have made other tests of the correspondence between the $^{10}\text{Be}$ predictions and the ice core measurements which lead to the same conclusion, namely that other influences on the ice core measurements, as large as or larger than the production changes themselves, are occurring. These influences could be climatic or instrumentally based. We suggest new ice core measurements that might help in defining more clearly what these influences are and-if possible-to correct for them.
Introduction

The use of $^{10}$Be concentration measurements in polar ice cores has become an important new tool for probing the recent history of solar activity and its interaction with the Earth's environment through the solar modulation of cosmic rays. The initial papers on this subject (e.g., Beer, et al., 1990, 1998) suggested that the $^{10}$Be concentration in polar ice cores, in some cases dating back a few 1,000 years, might provide a "monitor" of solar modulation activity in the same way that neutron monitors presently monitor this solar modulation level (Beer, 2000). This possibility arises because the $^{10}$Be produced in the atmosphere by cosmic rays is believed to precipitate out of the atmosphere in a uniform way in the form of rain or snow after a time period ~ 1 year. This is in contrast to $^{14}$C which is also produced by cosmic rays and is used as an indicator of solar activity in the past, but which has a much longer and more involved sequestering process.

Most of these historical studies dating back several hundred years using $^{10}$Be have considered atmospheric effects to be relatively unimportant and have therefore assumed a simple 1:1 correspondence between changes in $^{10}$Be production in the Earth's atmosphere and $^{10}$Be concentration measurements in ice cores (e.g., Steinhilber, et al., 2010, and references therein). This approach is used in spite of several cautionary arguments concerning the importance of atmospheric effects (e.g., Lal, 1988; Nikitin, et al., 2005). Newer calculations using more specific atmospheric models have continued to emphasize the importance of the atmospheric contribution to the $^{10}$Be concentration measurements (e.g., Field, Schmidt and Shindell, 2009, and references therein).

In a recent paper (Webber and Higbie, 2010a) we have approached this question from a different perspective, examining the cross-correlation between yearly average $^{10}$Be concentration values in ice cores and evaluations of yearly average $^{10}$Be production by incident cosmic rays over the most recent 60-70 years. The cross-correlation coefficients we determined (~ 0.3) and the slopes of the regression lines between $^{10}$Be concentration and $^{10}$Be production (~ 0.5) both strongly suggest that other factors are modifying a simple 1:1 relationship between the $^{10}$Be production and the concentration measurements and that these other factors may be of comparable importance to the production changes themselves.

Recently, new $^{10}$Be concentration measurements have been reported from an ice core in Northern Greenland (NGRIP) (Berggren, et al., 2009). These measurements are valuable for
several reasons. First, they provide the opportunity to compare in detail the yearly $^{10}\text{Be}$ measurements made in two cores, the original Dye-3 core and the new NGRIP core, with the atmospheric $^{10}\text{Be}$ production which is known to be the same at both locations. Both ice cores are in the same general region but ~1000 km apart and are on the polar plateau of latitude independent cosmic ray intensities above ~60° geomagnetic latitude. Second, the new ice core studies include $^{10}\text{Be}$ flux calculations as well as concentration measurements for both the NGRIP core as well as the older Dye-3 core. The $^{10}\text{Be}$ flux is defined as $F=CR$ where $C$ is the concentration and $R$ is the snow accumulation rate determined from measurements and calculations. It has been argued that the $^{10}\text{Be}$ “flux” values may provide a better representation of the actual $^{10}\text{Be}$ atmospheric production since they account for the yearly snowfall differences (Beer, et al., 2000). In this new paper we expand on the Webber and Higbie, 2010a paper, examining the cross correlation and other features of the most recent $^{10}\text{Be}$ ice core data of Berggren, et al., 2009.

**The Data**

In Table 1 we show the following data. In columns B and C are the $^{10}\text{Be}$ concentration and flux data from NGRIP (Berggren, et al., 2009). Column D shows the $^{10}\text{Be}$ production data from Webber, Higbie and McCracken, 2007, updated to 2009. Columns E and F show revised Dye-3 concentration and flux data also from Berggren, et al., 2009. Column G is a weighted average of the NGRIP and Dye-3 concentration data. Column H is the yearly average sunspot data through 2009 (http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html#american), and column I is the yearly average high latitude neutron monitor rate through 2009 (with the 1954 rate = 100.0).

First we compare the yearly $^{10}\text{Be}$ production rate with the high latitude neutron monitor rate. These two rates are shown in Figure 1. The cross correlation coefficient between these rates is 0.995 and the slope of the normalized regression line between the two sets of data is 0.322 (Figure 2A). This high cross correlation is not surprising since the NM rate is used as one of the bases to determine the production rate. Differences in the correlation coefficient from 1.0 arise from slight differences in the rigidity dependence of the solar modulation from cycle to cycle.

The comparison of the $^{10}\text{Be}$ production rate and the sunspot number for this 70 year time period is shown in Figure 2B. Here the cross correlation coefficient = 0.841 and there is more
scatter in the individual data points. These differences are partly caused by the differences in solar modulation between the positive and negative polarity periods of the 22 year solar polarity cycle. Nevertheless, the sunspot number makes an acceptable proxy for the $^{10}$Be production for this restricted time period if one is interested in accuracies of 10-20%. Notice, however, that the value of the maximum $^{10}$Be production at zero sunspot number is $\sim 5.1$ atoms/cm$^2$/sec$^1$. For the modern epoch this is the maximum production rate of $^{10}$Be that should be expected. At the time of the “Grand Maximum” of $^{10}$Be concentration at $\sim 1700$ AD, the $^{10}$Be concentration was at least 1.6 times higher than this (e.g., Beer, 2000; McCracken, et al., 2004). This high level of concentration cannot be explained by the modern epoch sunspot data, and requires a “new” regression line for production that must be a factor $\sim 1.6$ times higher for a given sunspot number to describe this earlier data period.

Turning now to the ice core data we show in Figure 3A the scatter plot of the new NGRIP yearly $^{10}$Be flux data and $^{10}$Be production in the polar atmosphere. Here the scatter is very large with some extreme flux years. The cross correlation coefficient is 0.397 and the slope of the best fit normalized regression line is 0.503. For a lag of $\pm 1$ year the cross correlation coefficient drops to $\sim 0.30$. For the NGRIP concentration data the cross correlation coefficient is 0.341 and the slope of the normalized regression line is 0.469, slightly worse than those values for the flux, and still below a cross correlation coefficient of 0.50 which is considered to be a “weak” correlation and still with a slope that is much less than that for an expected 1:1 correspondence.

In Figure 3B the scatter plot of the Dye-3 concentration vs. $^{10}$Be production is shown. Here the scatter is again very large with a significant fraction of “high” concentration years. The cross correlation coefficient is now 0.306 and the slope of the best fit normalized regression line is 0.573. This slope is increased as a result of a number of anomalously “high” data points (see Webber and Higbie, 2010a). Again, lags of $\pm 1$ year do not significantly alter the correlation coefficient.

For the Dye-3 flux data in Figure 3C the correlation coefficient with $^{10}$Be production is only 0.224. This is evident from the extreme scatter of the data. The slope of the best fit normalized regression line is 0.437.

In Figure 4A we show the scatter plot of the average of the NGRIP plus 2 x Dye-3 yearly concentration measurements with the $^{10}$Be production. Here the cross correlation coefficient is
0.414, just slightly higher than the individual NGRIP and Dye-3 concentration measurements separately. The best fit normalized regression line slope is 0.544.

In Figure 4B we show a scatter plot between the NGRIP and Dye-3 flux measurements themselves. This comparison should be independent of the $^{10}\text{Be}$ production calculations since both NGRIP and Dye-3 would be expected to observe the same $^{10}\text{Be}$ production, whatever it is, since they are both on the polar plateau for $^{10}\text{Be}$ production as noted earlier. Here the scatter is very large and the correlation coefficient = 0.256. The regression line slope $\sim$ zero implies essentially no correlation!

In summary, regarding the ice core measurements, we observe: 1) The scatter in the individual yearly data points in the cross correlation with $^{10}\text{Be}$ production is very large in all comparisons whether one considers the measured $^{10}\text{Be}$ concentrations or the deduced $^{10}\text{Be}$ fluxes, 2) The corresponding cross correlation coefficients are very low. Even the highest value of 0.414 obtained for the weighted average NGRIP plus Dye-3 data is still well below the criterion of 0.5 which is generally considered a weak correlation. 3) Adding the two different ice core measurements or comparing the $^{10}\text{Be}$ flux determinations vs. concentration measurements of $^{10}\text{Be}$ in one ice core improves the correlations only slightly. 4) The best fit normalized regression line slopes between the ice core data and the $^{10}\text{Be}$ production are between $\sim$0.4-0.6 or only about $\frac{1}{2}$ of the expected value of 1.0 for a direct correspondence. 5) A cross-correlation of both of the yearly $^{10}\text{Be}$ concentration and flux measurements from the two sites (which should be observing the same $^{10}\text{Be}$ production) give correlation coefficients less than 0.25 in both cases and slopes of regression lines (which should be $\sim$1.0) of between 0.0 and 0.3. The level of non-correlation described above requires some explanation.

**Discussion – The Large Scatter in the Data and the Regression Line Slopes of 0.4-0.6 Instead of 1.0**

The large scatter between the $^{10}\text{Be}$ ice core measurements and $^{10}\text{Be}$ production calculations and the resulting lack of correlation on a year to year basis, described above, could arise in several ways. Two possibilities are; 1) Severe climatic effects on a time scale $\sim$1-2 years or less (e.g., Pedro, et al., 2006). These effects could be very local or more general effects covering large geographic scales. 2) “Instrumentally” based effects that somehow introduce a large variability in what are more uniform variations.
It has been shown by Berggren, et al., 2009, and other earlier work (e.g., Beer, et al., 1998) that the historical $^{10}\text{Be}$ data do show the persistence of a “11 year” variation comparable to that of sunspots (Schwabe cycle) when the $^{10}\text{Be}$ data is “filtered” with a band pass of 8-16 years. This would seem to imply some level of correlation between the ice core data and the $^{10}\text{Be}$ production data unless the 11 year variation in the ice core data were mainly a climatic effect. Berggren, et al., 2009, find that this 11 year $^{10}\text{Be}$ variation is large during the recent time period we have studied in this paper. Because of the extensive use of $^{10}\text{Be}$ as a significant source on past solar activity, in some cases of a detailed quantitative nature (e.g., McCracken, et al., 2004), it is important to understand how the observed lack of concordance between ice-core and production data on $^{10}\text{Be}$ on a yearly basis in the modern era will affect the accuracy of these quantitative historical studies. For example; Can the presently available $^{10}\text{Be}$ ice-core data really prove anything about solar activity in the past; a question that has been also asked (and answered) in recent papers by Nikitin, et al., 2005, and Stozhkov, 2007.

In evaluating this ice core data it is important, not only to try to understand the source of the large scatter in the data that is observed, but also to understand why the regression line slopes between $^{10}\text{Be}$ ice core data and $^{10}\text{Be}$ production data are only ~½ of those expected for a simple 1:1 correspondence between $^{10}\text{Be}$ ice core measurements and $^{10}\text{Be}$ production. The value of this slope is particularly important for extrapolating the $^{10}\text{Be}$ ice-core records to earlier times in a quantitative sense and it is quite different from a simple 1:1 correspondence that is now used (see Steinhilber, et al., 2010; Webber and Higbie, 2010b, and references therein).

Perhaps most significant is the result of extrapolating the observed regression lines to zero production. In all cases, this extrapolation leads to a non-zero ice core $^{10}\text{Be}$ flux or concentration when the production equals zero. These non-zero $^{10}\text{Be}$ values are large, ~0.5 times or greater than the values measured at the recent times of maximum modulation. These significant non-zero values are not expected, given the present “one track” $^{10}\text{Be}$ models for production with subsequent distribution through the atmosphere and ultimate “precipitation” which is recorded in ice cores. If, however, the disposition of $^{10}\text{Be}$ is more like that of $^{14}\text{C}$ where several reservoirs are involved (e.g., atmosphere, ocean and soil) each on different time scales, then the non-zero intercept could be explained as well as the large scatter of the data between the “direct” production and ice core observations. In this case the “indirect” contribution of $^{10}\text{Be}$ to
the ice core measurements from the other reservoirs or “channels” may be of comparable importance to the “direct” production contribution. In fact, the regression line slopes may be the first indication of the importance of these “indirect” channels in the $^{10}\text{Be}$ sequestering process and may alter the current viewpoint of ice core $^{10}\text{Be}$ data as providing a measure of coincident $^{10}\text{Be}$ production.

**Discussion – Overall view of $^{10}\text{Be}$ Ice Core Data and the Solar Modulation Level**

In Figure 5 we show the $^{10}\text{Be}$ flux measured at NGRIP from 1600 A.D. to 1994. The data is presented as 5 year running averages. The average maximum flux ($x 10^3$) for the 5 most recent periods of minimum solar (sunspot) activity is 8.55 atoms/cm$^2$s$^{-1}$ and for the 5 most recent periods of maximum activity is 6.75 atoms/cm$^2$s$^{-1}$. The upper bound of the shaded region corresponds to a $^{10}\text{Be}$ flux which is ~1.5 times the recent average maximum $^{10}\text{Be}$ flux. There are several time periods from about 1640 to ~1892 when the $^{10}\text{Be}$ flux measured in the NGRIP ice core is above this level. At about 1695 A.D. and again about 1812 this flux level is ~2.0 times the average measured at the time of the 5 most recent sunspot minima. These are sustained time intervals of high fluxes because of the 5 year running averages used. In order for these high earlier fluxes of $^{10}\text{Be}$ to be solely caused by increases in $^{10}\text{Be}$ production, assuming a 1:1 correspondence between ice core $^{10}\text{Be}$ and $^{10}\text{Be}$ production, requires that the $^{10}\text{Be}$ production at the top of the atmosphere be at least 1.5-2.0 times the average production at the time of the 5 most recent sunspot minima.

In a recent paper, Webber and Higbie, 2010b, have shown that for the new LIS H and He spectra they have derived, which are consistent with the H and He spectra measured by Voyager 1 beyond 110 AU, the maximum possible increase of $^{10}\text{Be}$ production above the value at the Earth at the time of the five most recent maxima is, in fact, 1.5 times, or the upper limit of the shaded region in Figure 5.

If we consider the additional fact that the slope of the observed normalized regression lines between $^{10}\text{Be}$ in ice cores and $^{10}\text{Be}$ production is actually ~0.5 and not 1.0, as described earlier in this paper, then we have an upper limit to the absolute maximum $^{10}\text{Be}$ flux which is only ~1.25 times the recent average maximum intensity of $^{10}\text{Be}$ measured. This value corresponds to the lowest bound of the shaded region in Figure 5. This lower bound includes many other earlier time periods with $^{10}\text{Be}$ flux values that exceed those possible from $^{10}\text{Be}$ production alone from the full LIS spectrum. Indeed this implies that more than 50% the $^{10}\text{Be}$
flux increase around, e.g., 1700 A.D., 1810 A.D. and 1895 A.D. is due to non-production related increases!

Examining in more detail the most recent time period from ~1940 to 1990 when $^{10}$Be production calculations, $^{10}$Be ice core measurements and sunspot observations are all available, we show in Figure 6 the yearly values of these three quantities. Here the sunspot number is inverted and taken one year earlier than production to allow for the propagation of the solar wind to the heliospheric termination shock. The $^{10}$Be ice core data is taken as a 5 year running average to reduce scatter in the data.

First we note the quite good agreement between the 11 year profiles for $^{10}$Be production (blue) and sunspot number (red). This is consistent with the relatively high cross correlation coefficient $\sim$0.85 as described earlier. On the other hand the $^{10}$Be ice core 11 year profiles are very jittery, even though 5 year running averages are used. The amplitude of each 11 year profile is quite different in the $^{10}$Be ice core data and does not correspond well to the amplitude (or the more regular shape) of the corresponding 11 year profile in production or in sunspots. In particular the maximum level of $^{10}$Be flux varies from ~0.7 to 1.0 for the 5 most recent 11 year cycles whereas the production itself varies by $\pm$ 5%. And finally, SS #18 starting in ~1943 shows a well defined maximum (minimum) in both production and sunspot number, but essentially this cycle does not exist in the NGRIP $^{10}$Be flux data (it is weakly present in the NGRIP concentration data and the Dye 3 flux and concentration data).

All of the features described above suggest that the simple sunspot number is a much more robust indicator of solar activity and solar modulation during the modern time period than the current $^{10}$Be ice core measurements.

Turning again to the longer term studies of solar modulation, in particular the 11 year (Schwabe) cycle and its persistence over time, we refer again to Figure 5. Using the sunspot number as a reference, each cycle is well defined (data before 1700 A.D. is not used because there are contradictory estimates of the sunspot numbers). There are periods of lower amplitude e.g., 1790-1830 A.D. and again before ~1720 A.D. which are referred to as the Dalton and Maunder minima respectively. Note that the sunspot number does not go zero throughout these entire time periods, but the amplitude of the 11 year cycle is smaller with the peak sunspot numbers being ~50 instead of the normal values, 100-150. The distribution of the lengths of each sunspot cycle is sharply peaked with 9 cycles having a length of 10 years and 8 having a
length of 11 years (out of a total of 28 cycles). The shortest cycle is 9 years and the longest is 14 years. The cycles longer than 12 years appear to be associated with the various “Grand Minimum” periods.

Regarding the variability of the amplitude and length of the 11 year cycle obtained from the $^{10}$Be ice core flux values, it is difficult to determine a pattern. This is because some cycles are either missing or absent in the $^{10}$Be ice core data as compared with the sunspot 11 year variations. Some examples of these unusual cycles are noted by the vertical arrows shown in Figure 5. At about 1860 A.D. there was a peak in $^{10}$Be flux associated with a peak in sunspot number, the opposite to what would be expected for normal modulation conditions. These same is true at about 1829, and again at about 1884 and 1894. In effect the $^{10}$Be flux cycle is almost exactly out of phase with the sunspot cycle in these 4 cycles.

In 1922 the opposite was observed, a sunspot minimum, but with the absence of a corresponding peak in the $^{10}$Be flux. This is also the case in 1943 as has been noted earlier. Of the 28 sunspot minima observed since 1700 A.D., only 11 had $^{10}$Be flux maxima at the same time as the sunspot minima ($\pm$ 1 year).

What Can Be Extracted from the $^{10}$Be Ice Core Data?

This question must inevitably arise because of the extreme scatter and low correlation coefficients between the $^{10}$Be production predictions and the $^{10}$Be ice core yearly data for the modern era. This $^{10}$Be uncertainty extends to earlier times as well as evidenced by the $^{10}$Be cyclic data in Figure 5 as described above which appears to be jittery (noisy?) in both time and amplitude, particularly with respect to the many cyclic peaks that should relate to a 11 year variation but correspond poorly with the much more regular 11 year sunspot cycle variation.

One does notice a certain “regularity” in the $^{10}$Be ice core variations, however. In Figure 5 we show as blue lines, the envelope of the “minima” in the $^{10}$Be cyclic intensity variations. This “envelope” has long term periodic maxima occurring at ~1685, 1815 and 1895 A.D. This type of variation could possibly be related to long term $^{10}$Be production changes. Indeed 22 year averages (filters) of the $^{10}$Be concentration, which smooth out the shorter term cyclic variations, show broad maxima at approximately these times (McCracken, et al., 2004). These times also, more or less, coincide with the times of maxima of $^{14}$C concentration in tree rings (Bard, et al., 1997).
The $^{14}$C concentration appears to have a much longer and more complex time history between production in the atmosphere (which is almost identical to that of $^{10}$Be) and its appearance as $^{14}$C in tree rings. Nikitin, et al., 2005, have determined a cross correlation coefficient of 0.49, with a lag ~6 years between the 22 year average $^{10}$Be data in Antarctica, and the $^{14}$C tree ring data.

The $^{10}$Be data as shown in Figure 5 needs a considerably better level of understanding, particularly with regard to the short term (~11 year) variability, before it should be used to ascertain the absolute magnitude of possible longer and shorter term changes in $^{10}$Be production, however.

Summary and Conclusions

In summary we observe that the scatter in the individual yearly ice core data points in the cross correlation with $^{10}$Be production for the last 50-70 years is very large in all comparisons; larger, in fact, than the 11 year solar modulation effect that is being determined. The corresponding correlation coefficients ~0.3-0.4 are very low. These correlation coefficients are well below the value ~0.5 which is generally considered a weak correlation.

The best fit regression line slopes between the ice core data and the $^{10}$Be production for this same time period are between 0.4-0.6 or only ~½ of the expected value of 1.0 for a direct correspondence.

Perhaps most troubling of all is the cross correlation of the yearly $^{10}$Be concentration and flux measurements themselves from two sites on the polar plateau which should be observing the same $^{10}$Be production. These cross correlation coefficients are the lowest of all, less than 0.25 for both concentration and flux measurements and the slopes of the regression lines are less than 0.3.

These low cross correlation coefficients and the regression line slopes ~0.5 or less, as well as the fact that for zero production there is a “large” non-zero intercept for the $^{10}$Be flux or concentration levels in ice cores may be indicative of the fact that current models relating $^{10}$Be production and $^{10}$Be in ice cores may be too simplistic. Other reservoirs for $^{10}$Be in addition to the current direct atmospheric sequestering process may be involved, similar to $^{14}$C.

From the point of view of the cyclic variations of the $^{10}$Be data, we find that in the 5 most recent 11 year cycles where production data is available for $^{10}$Be, sunspot number data is available, and yearly $^{10}$Be concentration and flux data are also available from two sites in
Greenland, the sunspot number provides the best determination of the \(^{10}\text{Be}\) production and the related solar activity. The \(^{10}\text{Be}\) ice core data provides a “poor” basis for determining the cyclic solar activity/\(^{10}\text{Be}\) production level and, in fact, the NGRIP data completely misses solar cycle #18.

Extending the above comparison in the modern age to earlier times after ~1700 A.D. when sunspot records were available, it is clear that the \(^{10}\text{Be}\) cyclic variations provide a very poor representation of the 11 year sunspot cycle. This is true regarding the magnitude of the individual cycles as well as their length or repetition rate. Only 11 of the 28 sunspot cycles since 1700 A.D. have \(^{10}\text{Be}\) flux maxima at times when the sunspot number is a minimum as would be expected from modulation theory.

When the first detailed \(^{10}\text{Be}\) measurements from polar ice cores were reported (e.g., Beer, et al., 1990) there was the hope that this ice core data could provide a “monitor” of past solar activity as it effects cosmic ray intensities incident on the Earth, in much the same way as neutron monitors are used to monitor this solar activity in the modern era (Beer, 2000). This “concept” with its 1:1 correspondence between \(^{10}\text{Be}\) production and \(^{10}\text{Be}\) in ice cores, has since been used extensively to interpret historical \(^{10}\text{Be}\) ice core data in terms of changes in heliospheric conditions and their effect on cosmic ray intensities incident on the Earth. Our results show that, given our current understanding (or lack of it) of the correspondence between \(^{10}\text{Be}\) production, sunspot numbers and the \(^{10}\text{Be}\) observed in ice cores, this is really not a reliable “concept” to use for historical extrapolation. The sunspot number itself remains the best indicator of cyclic (11 year) solar activity after ~1700 A.D.

The level of \(^{10}\text{Be}\) production in the Earth’s atmosphere at the minimum of the 5 most recent solar activity cycles is the same to within \(\pm 5\%\). If this production level has changed in the past, then the present uncertainties in the \(^{10}\text{Be}\) ice core data are such that the magnitude of these changes cannot be robustly determined. Calculations also show that if the LIS remains the same as it is now, the \(^{10}\text{Be}\) production should never increase by a factor of more than 1.3-1.5 over the average modern values at sunspot minimum at any time in the recent past, whereas increases by a factor ~2.0 have been observed in the \(^{10}\text{Be}\) ice core data.

In order that ice core data may in the future be utilized to provide an accurate historical record of cosmic ray intensity incident on the Earth’s polar atmosphere, new measurements or analyses need to be made. The measurements would need to include comprehensive yearly
measurements of $^{10}$Be covering the last 60 years (several 11 year cycles) up to and including 2009, in several nearby (within a few km) ice cores in order to isolate and understand the origin of the large fluctuations observed in the individual yearly ice core data. This would be an extension of the earlier measurements of Moraal, et al., 2005.
References

Bard, E., G. Raisbeck, F. Yiou and J. Jouzel, (1997), Solar modulation of cosmogenic nuclide production over the last millennium: Comparison between $^{14}$C and $^{10}$Be records, Earth Planet, Sci. Lett., 150, 453-462

Beer, J., et al., (1990), Use of $^{10}$Be in polar ice to trace the 11-year cycle of solar activity, Nature, 347, 164-166

Beer, J., S. Tobias and N. Weiss, (1998), An active sun through the Maunder minimum, Solar Phys., 181, 237-249

Beer, J., (2000), Neutron monitor records in broader historical context, Space Science Reviews, 93, 89-100

Berggren, A.M., et al., (2009), A 600-year annual $^{10}$Be record from the NGRIP ice core, Greenland, Geophys. Res. Lett., 36, L11801, doi:10.1029/2009GL038004

Field, C.V., G.A. Schmidt and D.T. Shindell, (2009), Interpreting $^{10}$Be changes during the Maunder Minimum, J. Geophys Res., 114, D02113, doi:10.1029/2008JD010578

Lal, D., (1988), Theoretically expected variations in the terrestrial cosmic-ray production rates of isotopes, Proceedings of the International School of Physics "Enrico Fermi", Course XCV, Edited by G. Cini Castagnoli, p.216, North Holland Publishing

McCracken, K.G., F.B. McDonald, J. Beer, G. Raisbeck and F. Yiou, (2004), A phenomenological study of the long term cosmic ray modulation, 850-1958 AD, J. Geophys. Res., 109, A12103, doi:10.1029/2004JA010685

Moraal, H., et al., (2005), $^{10}$Be concentration in the Ice Shelf of Queen Maude Land, Antarctica, South African Journal of Science, 101, 299-301

Nikitin, J., J. Stozkov, V. Okhlopkov and N. Svinzhevsky, (2005), Do Be-10 and C-14 give us information about cosmic rays in the past?, Proc., 20th ICRC, Pune, 2, 243-246

Pedro, J., et al., (2006), Evidence for climatic modulation of the $^{10}$Be solar activity proxy, J. Geophys. Res., 111, D21103, doi:10.1029/2005JF006764

Steinhilber, F., J.A. Abreu, J. Beer and K.G. McCracken, (2010) Interplanetary magnetic field during the past 9300 years inferred from cosmogenic radionuclides, J. Geophys. Res., 115, A01104, doi:10.1029/2009JA014193
Stozhkov, Yu, I., (2007), What can be extracted from data on the concentrations of Be-10 and C-14 natural radionuclides?, Bulletin of the Lebedev Physics Institute, 34, #5, 135-141 at Allerton Press Inc.

Usoskin, I.G., K. Horiuchi, S. Solanki, G.A. Kovaltsov and E. Bard, (2009), On the common solar signal in different cosmogenic isotope data sets, J. Geophys. Res., 114, A0.112, doi: 10.1029/2008JA013888

Webber, W.R., P.R. Higbie and K.G. McCracken, (2007), The production of the cosmogenic isotopes $^3$H, $^7$Be, $^{10}$Be and $^{36}$Cl in the Earths atmosphere by solar and galactic cosmic rays, J. Geophys. Res., 112, A10106, doi:10.1029/2007JA012499

Webber, W.R. and P.R. Higbie, (2010b) What Voyager cosmic ray data in the outer heliosphere tells us about $^{10}$Be production in the Earths polar atmosphere in the recent past, J. Geophys Res., in press

Webber, W.R. and P.R. Higbie, (2010a) A comparison of new calculations of $^{10}$Be production in the Earths polar atmosphere by cosmic rays with $^{10}$Be concentration measurements in polar ice cores between 1939–2005 – A troubling lack of concordance: Paper #1, http://arxiv.org/abs/1003.4989
### TABLE 1

| YEAR | NGRIP Conc x 10^4 | NGRIP Flux x10^3 | WH Polar Produc | DYE-3 Conc x 10^4 | DYE-3 Flux x 10^3 | (B+2E)/2 | SUNSPOT# NOAA | NM WRW 1954=100 |
|------|-------------------|------------------|----------------|------------------|------------------|-----------|---------------|-----------------|
| 1939.5 | 0.93 | 5.62 | 4.18 | 0.51 | 11.7 | 0.98 | 89 |
| 1940.5 | 1.31 | 9.10 | 4.45 | 0.56 | 11.6 | 1.215 | 68 |
| 1941.5 | 1.19 | 6.00 | 4.40 | 0.64 | 14.1 | 1.285 | 47 |
| 1942.5 | 1.01 | 5.60 | 4.62 | 0.89 | 15.6 | 1.43 | 31 |
| 1943.5 | 1.61 | 7.60 | 4.70 | 1.11 | 21.0 | 1.915 | 16 |
| 1944.5 | 1.63 | 7.70 | 5.22 | 0.57 | 7.8 | 1.385 | 9 |
| 1945.5 | 1.33 | 7.35 | 5.04 | 0.61 | 12.0 | 1.34 | 33 |
| 1946.5 | 1.12 | 7.75 | 3.32 | 0.65 | 17.3 | 1.245 | 91 |
| 1947.5 | 1.10 | 5.45 | 2.75 | 0.57 | 13.8 | 1.14 | 14 |
| 1948.5 | 1.16 | 7.90 | 3.18 | 0.905 | 12.6 | 1.485 | 137 |
| 1949.5 | 1.48 | 7.90 | 4.25 | 0.61 | 8.8 | 1.35 | 136 |
| 1950.5 | 1.02 | 4.52 | 4.60 | 1.18 | 17.8 | 1.705 | 84 |
| 1951.5 | 2.44 | 14.00 | 4.30 | 1.02 | 15.6 | 2.24 | 69.5 | 0.949 |
| 1952.5 | 1.50 | 8.00 | 4.56 | 1.02 | 14.2 | 1.77 | 31.5 | 0.963 |
| 1953.5 | 1.46 | 7.10 | 4.63 | 1.24 | 19.6 | 1.985 | 14 | 0.978 |
| 1954.5 | 1.26 | 6.80 | 5.05 | 0.77 | 14.7 | 1.445 | 4.4 | 1.00 |
| 1955.5 | 1.36 | 12.30 | 4.90 | 1.01 | 15.8 | 1.71 | 38 | 0.996 |
| 1956.5 | 1.42 | 6.80 | 4.23 | 0.57 | 10.5 | 1.28 | 142 | 0.951 |
| 1957.5 | 1.60 | 7.40 | 2.83 | 0.895 | 12.6 | 1.685 | 190 | 0.837 |
| 1958.5 | 1.00 | 5.10 | 2.70 | 0.41 | 6.0 | 0.925 | 185 | 0.826 |
| 1959.5 | 1.23 | 5.85 | 2.83 | 0.49 | 10.2 | 1.125 | 159 | 0.832 |
| 1960.5 | 1.25 | 5.90 | 2.92 | 0.41 | 9.5 | 1.05 | 112 | 0.845 |
| 1961.5 | 1.05 | 4.55 | 3.52 | 0.40 | 7.5 | 0.94 | 54 | 0.892 |
| 1962.5 | 1.66 | 9.10 | 3.90 | 0.50 | 7.8 | 1.28 | 37.5 | 0.914 |
| 1963.5 | 2.08 | 10.20 | 4.26 | 0.62 | 7.6 | 1.66 | 28 | 0.945 |
| 1964.5 | 1.45 | 7.90 | 4.74 | 0.69 | 15.5 | 1.235 | 10.2 | 0.978 |
| 1965.5 | 3.20 | 14.20 | 5.02 | 1.03 | 11.8 | 2.63 | 15 | 0.998 |
| 1966.5 | 1.74 | 8.40 | 4.54 | 0.593 | 8.2 | 1.478 | 47 | 0.962 |
| 1967.5 | 1.69 | 7.40 | 4.02 | 0.83 | 12.6 | 1.695 | 94 | 0.926 |
| 1968.5 | 1.44 | 8.60 | 3.62 | 0.47 | 5.8 | 1.175 | 106 | 0.896 |
| 1969.5 | 1.14 | 5.60 | 3.40 | 0.50 | 7.2 | 1.115 | 105 | 0.883 |
| 1970.5 | 1.04 | 5.20 | 3.48 | 0.40 | 9.8 | 0.92 | 104 | 0.889 |
| 1971.5 | 1.35 | 8.35 | 4.40 | 0.50 | 7.2 | 1.19 | 67 | 0.950 |
| 1972.5 | 1.76 | 8.10 | 4.65 | 0.35 | 9.6 | 1.23 | 69 | 0.971 |
| 1973.5 | 1.61 | 9.85 | 4.68 | 0.695 | 11.8 | 1.485 | 38 | 0.971 |
| 1974.5 | 1.47 | 6.05 | 4.50 | 1.00 | 14.6 | 1.755 | 34.5 | 0.961 |
| 1975.5 | 1.31 | 8.90 | 4.90 | 0.77 | 11.7 | 1.465 | 15.5 | 0.983 |
| 1976.5 | 1.38 | 9.60 | 4.95 | 0.59 | 9.1 | 1.31 | 12.5 | 9.86 |
| 1977.5 | 1.84 | 8.10 | 4.83 | 0.57 | 10.3 | 1.49 | 27.5 | 0.985 |
| 1978.5 | 1.39 | 7.10 | 4.40 | 0.62 | 11.8 | 1.345 | 92.5 | 0.955 |
| 1979.5 | 1.56 | 9.10 | 3.72 | 0.61 | 8.1 | 1.39 | 155 | 0.902 |
| 1980.5 | 0.96 | 4.70 | 3.39 | 0.60 | 8.3 | 1.095 | 154 | 0.879 |
| 1981.5 | 1.28 | 6.80 | 3.04 | 0.65 | 11.8 | 1.345 | 141 | 0.854 |
| 1982.5 | 1.47 | 7.20 | 2.93 | 0.66 | 13.4 | 1.395 | 116 | 0.848 |
| 1983.5 | 1.71 | 5.35 | 3.35 | 1.01 | 14.4 | 1.845 | 68.5 | 0.879 |
| 1984.5 | 1.52 | 10.10 | 3.59 | 0.50 | 6.0 | 1.26 | 46 | 0.889 |
| 1985.5 | 2.18 | 8.10 | 4.22 | 0.48 | 4.6 | 1.55 | 17 | 0.935 |
| 1986.5 | 1.46 | 8.75 | 4.92 | 0.67 | 11.8 | 1.345 | 13.5 | 0.980 |
| Year  | Conc. | Flux | Polar prod | Units |
|-------|-------|------|------------|-------|
| 1987.5 | 1.11  | 7.00 | 4.96       |       |
| 1988.5 | 1.65  | 6.10 | 3.93       | 100   | 0.913 |
| 1989.5 | 1.41  | 6.05 | 2.69       | 158   | 0.816 |
| 1990.5 | 0.86  | 6.80 | 2.63       | 142   | 0.806 |
| 1991.5 | 1.11  | 6.60 | 2.61       | 146   | 0.809 |
| 1992.5 | 1.52  | 7.90 | 3.62       | 94.5  | 0.890 |
| 1993.5 | 1.49  | 7.70 | 4.18       | 54.5  | 0.939 |
| 1994.5 | 1.59  | 9.10 | 4.34       | 30    | 0.953 |
| 1995.5 |       | 4.66 |           | 17.5  | 0.980 |
| 1996.5 |       | 4.90 |           | 8.6   | 0.989 |
| 1997.5 |       | 4.94 |           | 21.4  | 0.993 |
| 1998.5 |       | 4.63 |           | 64    | 0.971 |
| 1999.5 |       | 4.08 |           | 93    | 0.934 |
| 2000.5 |       | 3.08 |           | 120   | 0.866 |
| 2001.5 |       | 3.23 |           | 111   | 0.873 |
| 2002.5 |       | 3.20 |           | 104   | 0.871 |
| 2003.5 |       | 3.03 |           | 63    | 0.861 |
| 2004.5 |       | 4.00 |           | 40.5  | 0.922 |
| 2005.5 |       | 4.12 |           | 30    | 0.928 |
| 2006.5 |       | 4.70 |           | 15.5  | 0.975 |
| 2007.5 |       | 4.92 |           | 6.5   | 0.991 |
| 2008.5 |       | 5.03 |           | 2     | 0.998 |
| 2009.5 |       | 5.30 |           | 0.5   | 1.016 |

398 Conc. Units = atoms·g⁻¹
399 Flux units = atoms·cm⁻²·s⁻¹
400 Polar prod units = atoms·cm⁻²·s⁻¹

401
Figure Captions

**Figure 1:** Yearly average normalized high latitude NM rates (1954=100.0), yearly average $^{10}$Be production (on right hand axis).

**Figure 2A:** Scatter plot – normalized NM rate vs. $^{10}$Be production.

**Figure 2B:** Scatter plot – sunspot number vs. $^{10}$Be production.

**Figure 3A:** Scatter plot – NGRIP flux vs. $^{10}$Be production (normalized slope of regression line=0.503).

**Figure 3B:** Scatter plot – Dye-3 concentration vs. $^{10}$Be production (normalized slope of regression line=0.573).

**Figure 3C:** Scatter plot – Dye-3 flux vs. $^{10}$Be production (normalized slope of regression line=0.437).

**Figure 4A:** Scatter plot – Average NGRIP plus Dye-3 concentration vs. $^{10}$Be production (normalized slope of regression line=0.544).

**Figure 4B:** Scatter plot – Dye-3 flux vs. NGRIP flux (normalized slope of regression line=0.003).

**Figure 5:** Five year running average NGRIP flux data from Berggren, et al., 2009, from 1600 A.D. to the present. Also shown is the yearly average sunspot number (on an inverted scale) from http://www.ngdc.noaa.gov/stp/SOLAR/ftsunspotnumber.html#american. The shaded region shows the maximum limits for $^{10}$Be flux values for a full LIS spectrum incident on the Earth's atmosphere for different assumptions regarding the correspondence between $^{10}$Be production and $^{10}$Be ice core measurements. The dashed lines for the time period after 1940 represent the average maximum and minimum values of $^{10}$Be flux for the 5 most recent solar cycles. See text for a description of the blue lines.

**Figure 6:** Yearly average values for cosmic ray production of $^{10}$Be (from Webber, Higbie and McCracken, 2007) in blue; Sunspot number (from http://www.ngdc.noaa.gov/stp/SOLAR/ftsunspotnumber.html#american) on an inverted scale (in red) and five year running average $^{10}$Be flux from the NGRIP ice core (Berggren, et al, 2009) (in black). Data is shown from ~1930 to the present.
FIGURE 5

NGRIP FLUX (x 100)

TIME

0.4 0.8 1.2 1.6 2.0

1600 1700 1800 1900 2000

# SS

max min LIS LIS
