Reconstructing the 11-year solar cycle length from cosmogenic radionuclides for the last 600 years

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The cyclic behavior of the solar magnetic field has been known for centuries and the 11-year sunspot cycle is one of the most important features directly visible on the solar disc. Using sunspot records it is evident that the length of this cycle is variable. A hypothesis of an inverse relationship between the average solar activity level and the solar cycle length has been put forward (e.g. Friis-Christensen & Lassen, 1991), indicating longer solar cycles during periods of low solar activity and vice versa. So far, studies of the behavior of the 11-year solar cycle have largely been limited for the last 4 centuries where observational sunspot data are available. However, cosmogenic radionuclides, such as 10Be and 14C from ice cores and tree rings allow an assessment of the strength of the open solar magnetic field due to its shielding influence on galactic cosmic rays in the heliosphere. Similarly, very strong solar storms can leave their imprint in cosmogenic radionuclide records via solar proton-induced direct production of cosmogenic radionuclides in the Earth atmosphere.
Here, we test the hypothesis of an inverse relationship between solar cycle length and the longer-term solar activity level by using cosmogenic radionuclide records as a proxy for solar activity. Our results for the last six centuries suggest significant solar cycle length variations that could exceed the range directly inferred from sunspot records. We discuss the occurrence of SPEs within the 11-year solar cycle from a radionuclide perspective, specifically the largest one known yet, at AD 774-5 (Mekhaldi et al., 2015).

1: Cosmogenic radionuclides

Cosmogenic radionuclides, such as ^{10}Be and ^{14}C are the most reliable proxies for past solar activity. The principle behind this is outlined here:

→ Cosmogenic radionuclides are produced in the interaction between galactic cosmic rays and the constituents of the Earth's atmosphere

→ Due to the shielding of the solar magnetic field, the production of cosmogenic radionuclides is inversely correlated to the solar modulation. The same principle holds true for the geomagnetic field

→ After production the radionuclides are deposited in natural archives such as ice cores and lake sediments for 10Be and tree rings for 14C

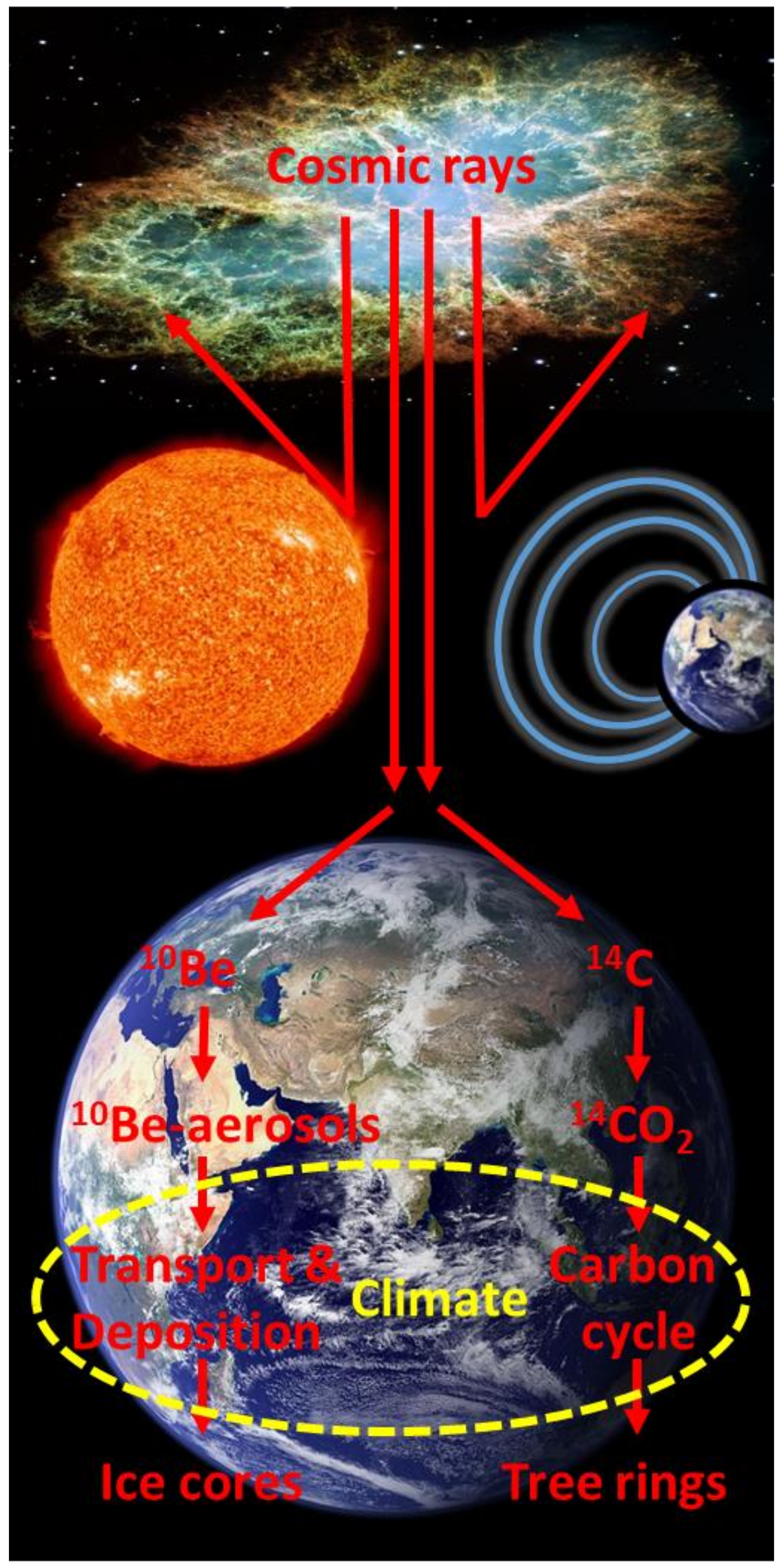

Figure 1. The principle behind using cosmogenic radionuclides as proxies for solar activity.

2: Data

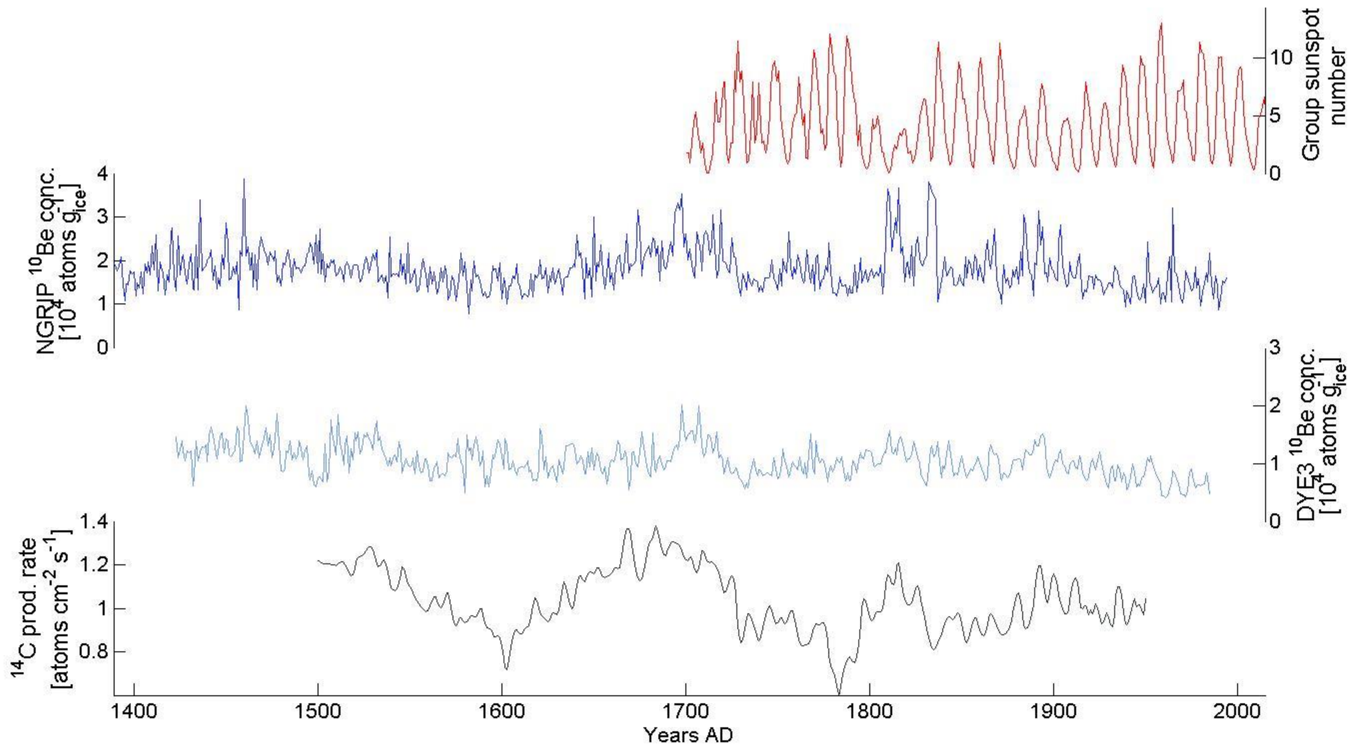

Figure 2. The five data sets used in this study: Group sunspot number (Svalgaard & Schatten, 2015), NGRIP ice core ^{10}Be (Berggren et al. 2009), DYE3 ice core ^{10}Be (Beer et al. 1990) and the modelled 14C production rate between 1500 and 1950 (Muscheler et al. 2016).

3: Method

→ The cross wavelet (XWT, Grinsted et al. 2004) is applied to a data set and a set number of sine waves with wavelengths varying between 7 and 16 years with an interval of 0.1 years

→ The resulting power matrices are corrected for the slope of the background spectrum

→ The two sine wave periods representing the two highest powers for each year are selected. If the highest power represents a period within 8-15 years, this is chosen to be the most likely cycle length estimate. If that's not the case, the period representing the second highest power is chosen. If the two highest powers are outside of 8-15 years no cycle length is estimated for that year.

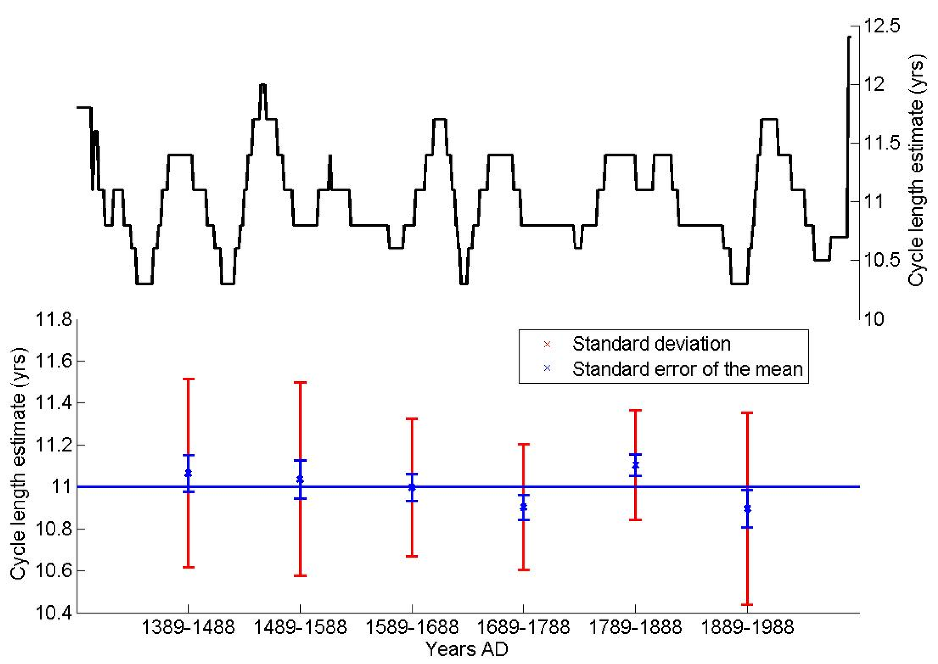

Figure 3. A) Results after applying the method to an artificial data set of a sine wave with wavelength of 11 years with noise similar to the noise in the NGRIP ^{10}Be data set. B) The average for every 100 years with standard deviation and standard error of the mean.

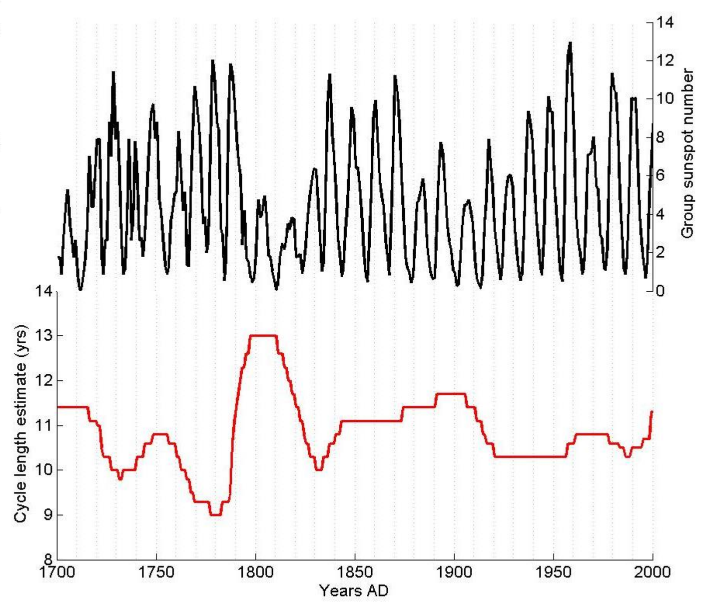

Figure 4. A) The Group sunspot data for the last three centuries. B) The cycle length estimate based on the Group sunspot data.

4: Solar cycle length reconstructions for the last 600 years

- Cycle length reconstructions differ when using different records (Figure 5). This is probably related to the data sets being affected by different climate and deposition processes.
- The cycle length reconstruction based on DYE3 (not shown) does not agree with the other reconstructions, probably due to the level of noise in this record. Higher correlation (0.49) between NGRIP and ^{14}C indicates an agreement between two records based on different processes.
- Sunspots are related to the closed solar magnetic flux while cosmogenic radionuclides are proxies of the open solar magnetic flux → perfect agreement not expected.
- Longer solar cycles are observed during the Maunder minimum.
- A negative correlation between cycle length estimate and solar modulation can be observed in Group sunspot number, NGRIP ^{10}Be and ^{14}C production rate (Figure 6).

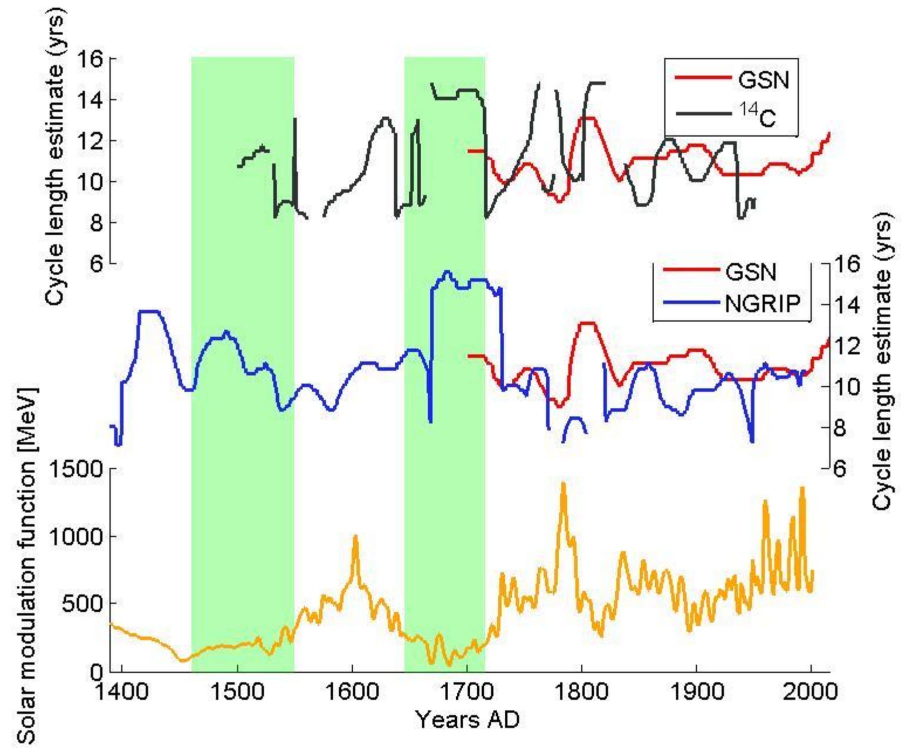

Figure 5: Cycle length reconstructions based on Group sunspot number, NGRIP ^{10}Be and ^{14}C production rate. The green shaded areas mark the Maunder and Spörer Grand solar minima. The lower plot is solar modulation (Muscheler et al. 2016).

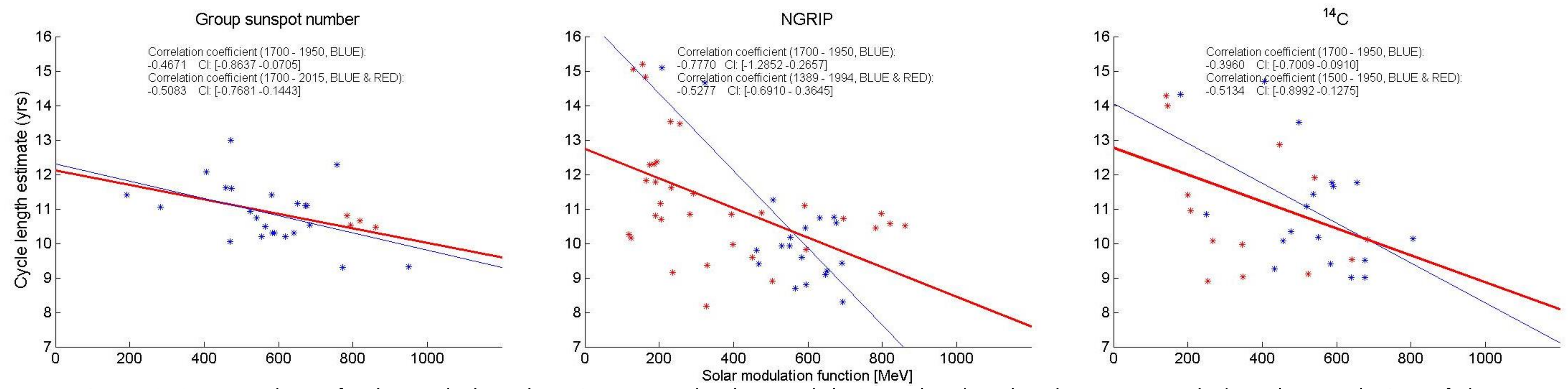

Figure 6. Scatter plots of solar cycle length estimates and solar modulation. The data has been resampled to the resolution of the resulting average cycle length for each data set. The blue data points and lines represent the period in time when all three records overlap (1700-1950 AD). The red lines take also the red points into consideration and represents the complete period of each data set.

5: The location within the 11-year solar cycle of the largest solar proton event observed so far

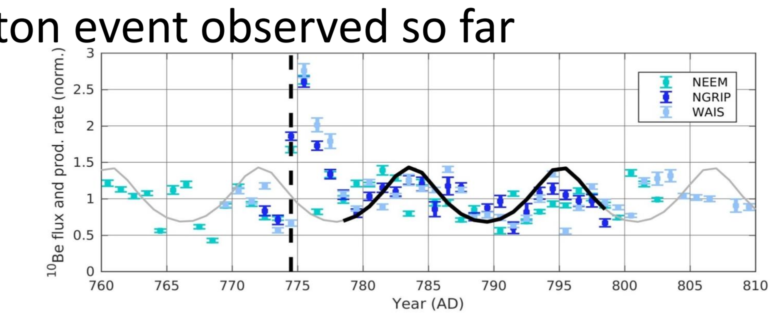

Figure 7. The 775-event (Mekhaldi et al. (2015) clearly stands out as a peak in the ^{10}Be records from three different ice cores. The black line represent the modelled ^{10}Be production based on a normal 11-year solar cycle and the grey line an extension of that model.

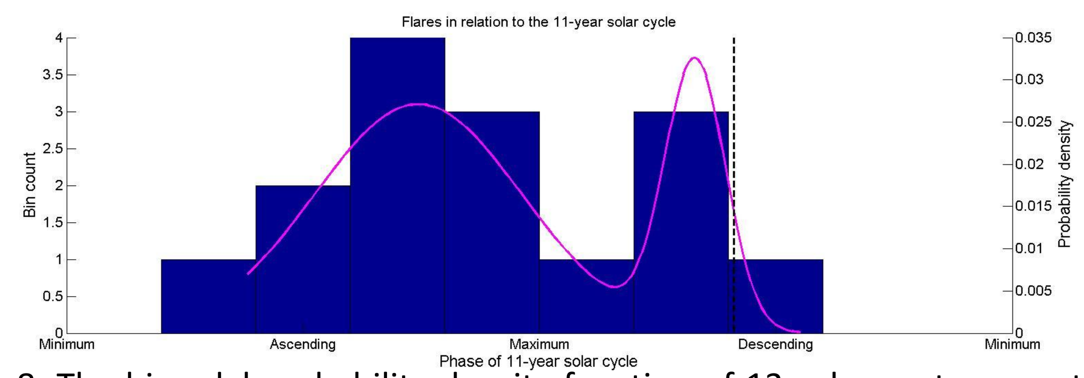

Figure 8. The bimodal probability density function of 13 solar proton events from Webber et al. (2007), the Carrington event in 1859 and the 775-event. The 775-event happened during the descending phase agreeing with most solar proton events happening during the ascending and descending phases.

Conclusions:

- The 11-year solar cycle can be reconstructed within reasonable estimates using cosmogenic radionuclides without too much noise
- A relationship between the solar cycle length and the solar activity level can be observed over the last 600 years
- Solar proton events appear to occur more often in the ascending and descending phases of the sunspot cycle than during the maximum and minimum of the cycle

Outlook:

- The Greenland ice core GRIP is being prepared for high-resolution measurements (approximately 2.5 years) of ^{10}Be to enable the reconstruction of the solar cycle length for more than 1500 years during the middle of Holocene (11 700 BP to today) making it possible to study this hypothesized relationship during a longer time period.

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