

## SOLAR MODULATION OF COSMIC RAY INTENSITY AND SOLAR FLARE EVENTS INFERRED FROM $^{14}\text{C}$ CONTENTS IN DATED TREE RINGS

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We have measured the  $\Delta^{14}\text{C}$  values in 42 rings (from 1824 to 1865 AD) of a white spruce grown in Mackenzie Delta ( $68^\circ\text{N}$ ,  $130^\circ\text{W}$ ) as our continuing effort of tracing the history of solar modulation of cosmic ray intensity. We also measured the  $\Delta^{14}\text{C}$  values in 6 rings (from 1940 to 1945 AD), searching for a  $^{14}\text{C}$  increase due to two large solar flares that occurred in 1942 and were detected by Forbush. The results will be presented and discussed.

1. Introduction. Carbon-14 nuclei in the atmosphere are produced by cosmic-ray-generated neutrons in  $^{14}\text{N}(n,p)^{14}\text{C}$  reaction. After the production, these nuclei react rapidly with ambient atmosphere to become  $^{14}\text{CO}_2$  molecules. The concentration of the  $^{14}\text{C}_2$  molecules is mainly determined by the rate of production and the rate of transfer, first to the troposphere from the stratosphere where most of them are produced, and then from the troposphere to the deep-sea sink reservoir. Since cosmic ray intensity is modulated by interplanetary magnetic fields whose strength depends on the solar activity, it is expected that the concentration is anti-correlated with sunspot numbers. While the long-term change in  $\Delta^{14}\text{C}$  in tree rings samples, which reflects the variation of the atmospheric  $^{14}\text{C}$  concentration, has been studied by many investigators and the correlation established beyond any doubt (e.g., Stuiver and Quay, 1980, and references therein), the question remains as to whether the amplitude of the expected 11-year variation is large enough to be measurable.

There was some indication that  $\Delta^{14}\text{C}$  values in grains and trees grown at high latitudes show 11-year periodicity (Baxter and Farmer, 1973). To study the possible latitudinal effect, we searched and, fortunately, obtained two sections of dated white spruce grown near Campbell River in Mackenzie Delta, Canada ( $68^\circ\text{N}$ ,  $130^\circ\text{W}$ ) from Dr. M. L. Parker of the University of British Columbia; one of the sections contains rings from 1510 to 1972 AD. Initial measurements of 27 samples, covering the period from 1866 to 1925 AD, indicated that the  $\Delta^{14}\text{C}$  values do exhibit a  $10\text{‰}$  fluctuation, anticorrelated with sunspot numbers. The results were reported at the 18th International Cosmic Ray Conference (Fan et al., 1983a, 1983b). In this paper we shall report  $\Delta^{14}\text{C}$  in the ring samples from 1824 to 1865 AD. We also measured the  $\Delta^{14}\text{C}$  in 1940 to 1945 rings, looking for the signature of  $^{14}\text{C}$  increase, due to two large solar flares that occurred in 1942 and were reported by Forbush (1946). The results will be discussed.

2. Experiment. The task of the measurements was divided between two institutions; the 1824 to 1865 rings were measured at the Department of History of Peking University, whereas the 1940 to 1945 rings were measured at the

Department of Physics of Nanjing University. The equipment used was similar; a liquid scintillator-photomultiplier tube device, which were carefully intercalibrated. Both systems used two photomultiplier tubes in coincidence to count  $^{14}\text{C}$  decay electrons and a pulse height discrimination to reduce cross-talks between the two tubes. There was, however, a slight difference between the two systems. At Peking University, 5-10 cm of lead was used to reduce cosmic-ray-induced background, whereas at Nanjing University, in addition to a lead shield, a plastic scintillator-photomultiplier tube system was used as an anti-coincidence shield. The result of the addition was a reduction of the background from 6 cpm to 2 cpm. An overall precision of both systems was about  $4\text{‰}$ , including a pure statistical uncertainty of  $\sim 3\text{‰}$ .

For each measurement, about 10 g of wood is needed. Because of the narrowness of the rings, except the 1928 ring, we had to combine two, and sometimes three, rings to obtain a sufficient specimen for one measurement. After being treated with the routine  $\text{HCl-NaOH-HCl}$  procedure to remove resin, the samples were converted to  $\text{CO}_2$  and then to benzene. For one measurement, 5 cc of synthesized benzene was used. The net count rate for a modern sample was 39 cpm. For each sample, we measured  $^{13}\text{C}/^{12}\text{C}$  for fractionation correction.

3. Results on Modulation of Cosmic Ray Intensity. The experimental results are expressed as  $\Delta^{14}\text{C}$  values which are the relative deviations of the measured  $^{14}\text{C}$  activities from the standard oxilic acid activity of the U.S. National Bureau of Standards, corrected for ages and isotope fractionations. For the sample prior to 1885, the correction for the Suess effect was not needed.

The data points, including 11 previously published values, are plotted in the bottom panel of Fig. 1, along with other published  $\Delta^{14}\text{C}$  values for comparison. To show the correlation with solar activity, we plotted in the upper panel the sunspot numbers with ordinates inverted. It is seen that, except for the 1922 cycle, with a delay of about five years, the  $\Delta^{14}\text{C}$  values are anti-correlated with sunspot numbers; the cross-correlation coefficient is  $\sim 0.6$ . At present, we are baffled by the reverse correlation in the 1822 cycle. Also, we feel uneasy about the five-year delay, which is longer than what we had expected. We do not rule out a possible error in the tree ring count.

4. Results on  $^{14}\text{C}$  Produced by Solar Protons. Damon et al (1973), in their study of the magnitude of the 11-year radiocarbon cycle, found that the  $^{14}\text{C}$  content in the 1943 ring of their Arizona tree sample ( $32^\circ\text{N}$ ,  $112^\circ\text{W}$ ) is exceptionally high. They attributed this high activity to the  $^{14}\text{C}$  production by two large solar flares, on February 28 and March 7 of 1942, detected by Forbush (1946). A similar increase was also observed by Burchuladze et al. (1980). Since our tree section was from Mackenzie Delta, only about  $10^\circ$  from the geomagnetic pole, we expect to observe a larger  $^{14}\text{C}$  activity in the tree rings than in the samples of Damon et al.

In Fig. 2 we plotted the six  $\Delta^{14}\text{C}$  values, together with the measurements by Damon et al. (1973) and that by Stuiver and Quay (1980), in the period from 1940 to 1954 AD. The high  $\Delta^{14}\text{C}$  values in the Mackenzie wood, as compared with that in the Washington wood of Stuiver and Quay and that in the Arizona wood of Damon et al., can be explained by the fact that in the near arctic circle, the air is less contaminated by fossil fuel burning. Disregarding the difference in the

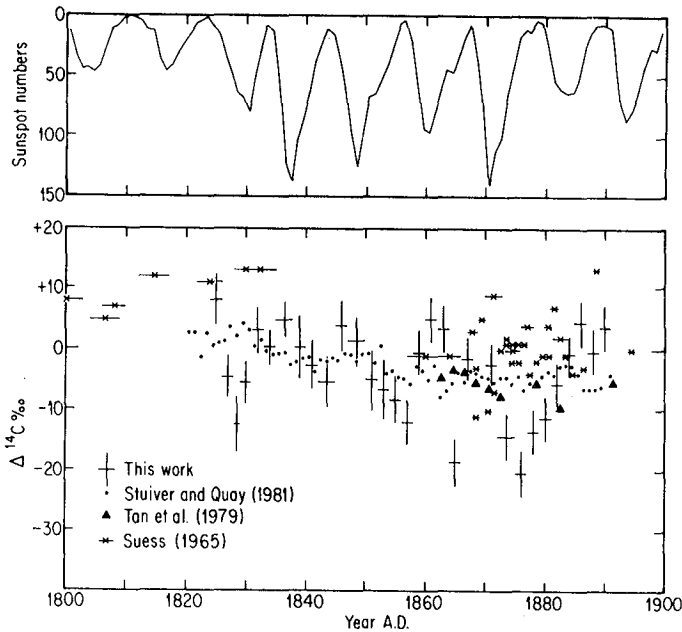


Fig. 1. Upper panel, sunspot numbers; lower panel,  $\Delta^{14}\text{C}$ .

general  $\Delta^{14}\text{C}$  level, the increase in  $\Delta^{14}\text{C}$  in the 1943 ring of the Mackenzie wood agrees remarkably well with that in the Arizona wood. The puzzling fact is that the Washington State sample does not show any sign of increase. If one assumes that the increase in  $\Delta^{14}\text{C}$  in the Mackenzie wood was indeed due to the two flares in 1942, then the magnitude of the flares can be estimated as follows:

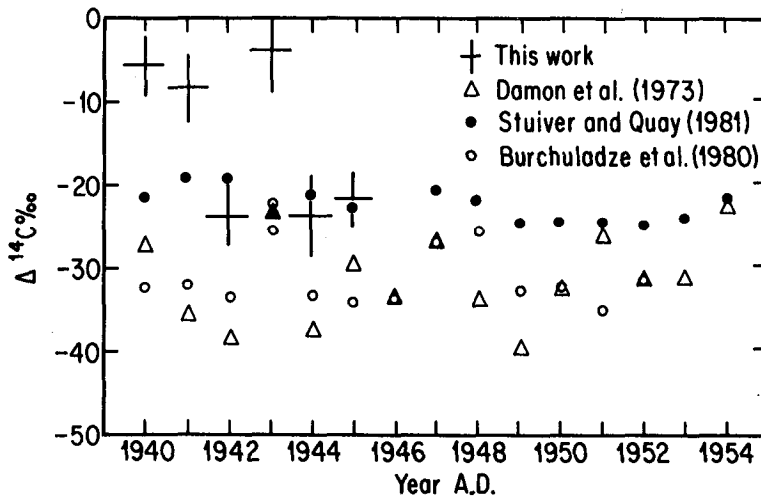


Fig. 2.  $\Delta^{14}\text{C}$

Lingenfelter and Ramaty (1970) calculated the  $^{14}\text{C}$  production rates during the 1953-1954 solar minimum and the 1957-1958 solar maximum period as 5.0 and 3.5  $^{14}\text{C}$  nuclei/cm<sup>2</sup> sec, respectively, in the 70°-90° geomagnetic latitude range. A 42% increase in the production rate from solar activity maximum to solar activity minimum period. The corresponding periods in the 19th century are 1866 to 1867 and 1870 to 1871. In these two periods, we found that there is a 20‰ increase in the  $\Delta^{14}\text{C}$  value. That is, a 40% increase in the production rate in the high latitude region results in a 20‰ increase in the  $\Delta^{14}\text{C}$  value. The  $\Delta^{14}\text{C}$  increase in the 1943 ring of the Mackenzie wood is about 20‰. Therefore, the  $^{14}\text{C}$  increase due to the two flares is equivalent to a 40% increase in the  $^{14}\text{C}$  production, or, 1.5  $^{14}\text{C}$  nuclei/cm<sup>2</sup> sec. According to Lingenfelter and Ramaty (1970), the number of  $^{14}\text{C}$  nuclei produced by the 1956 solar flare is equivalent to the one-year production by cosmic ray particles. Therefore, the combined effect of the two flares in 1942 is about one-half of that of the 1956 flare. We are continuing our search for larger events.

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