LETTER

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A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan

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Increases in ^{14}C concentrations in tree rings could be attributed to cosmic-ray events[1–7], as have increases in ^{10}Be and nitrate in ice cores[8,9]. The record of the past 3,000 years in the IntCal09 data set[10], which is a time series at 5-year intervals describing the ^{14}C content of trees over a period of approximately 10,000 years, shows three periods during which ^{14}C increased at a rate greater than 3‰ over 10 years. Two of these periods have been measured at high time resolution, but neither showed increases on a timescale of about 1 year (refs 11 and 12). Here we report ^{14}C measurements in annual rings of Japanese cedar trees from AD 750 to AD 820 (the remaining period), with 1- and 2-year resolution. We find a rapid increase of about 12‰ in the ^{14}C content from AD 774 to 775, which is about 20 times larger than the change attributed to ordinary solar modulation. When averaged over 10 years, the data are consistent with the decadal IntCal ^{14}C data from North American and European trees[13]. We argue that neither a solar flare nor a local supernova is likely to have been responsible.

We used two individual Japanese cedar trees (tree A and tree B). We collected two series of measurements of the ^{14}C content (Δ^{14}C, see Fig. 1 legend) of tree A. The first consists of biennial measurements from AD 750 to 820. The second consists of yearly measurements from AD 774 to 780. The data for overlapping years match within measurement errors, confirming that the two series of measurements are reproducible. The measurements of ^{14}C content in tree B were collected at 1-year resolution, from AD 770 to 779. The data from tree A and tree B are consistent (reduced $\chi^2 = 1.3$, degrees of freedom d.f. = 10). These data are presented in Supplementary Information.

Figure 1a shows the variation of ^{14}C content of Tree-A (after the two series of data were combined) and Tree-B for the period AD 750–820. In our data, we observe an increase of ^{14}C content of 12‰ within 1 year (AD 774–775), followed by a decrease over several years. The significance of this increase (AD 774–775) with respect to the measurement errors is 7.2σ.

In order to compare our results with IntCal98 (ref. 13), we averaged the yearly data to obtain a series with decadal time resolution. The result is shown in Fig. 1b. In the IntCal98 data, the ^{14}C content increased by about 7.2‰ over 10 years (AD 775–785). The two series are consistent with each other within measurement errors. The event causing the increased ^{14}C content in AD 775 could not have been local, because the IntCal data were obtained from North American and European trees, whereas we used Japanese trees.

To have produced a large number of ^{14}C nuclei in the atmosphere in AD 775, the cosmic-ray intensity must have increased considerably. The decadal record of another cosmogenic nuclide, ^{10}Be, can be obtained from the layers of ice or snow from Dome Fuji in Antarctica. These data include the relevant period, and exhibit a sharp peak in the ^{10}Be flux around AD 775 (ref. 14). However, the dating of ice core layers is more ambiguous than that of tree rings. The age of a layer is determined by locating several well-known volcanic events, and matching the production rate pattern of ^{10}Be with the ^{14}C production

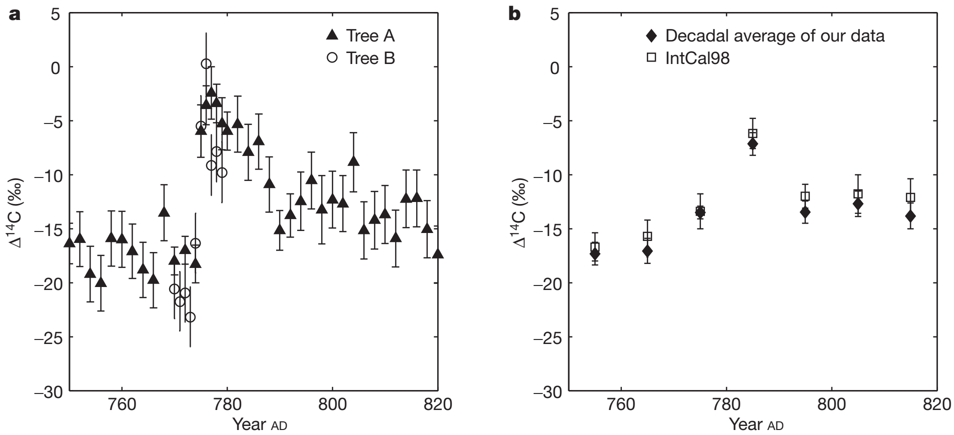

Figure 1 | Measured radiocarbon content and comparison with IntCal98. The concentration of ^{14}C is expressed as Δ^{14}C, which is the deviation (in ‰) of the ^{14}C/^{12}C ratio of a sample with respect to modern carbon (standard sample), after correcting for the age and isotopic fractionation[30]. **a**, Δ^{14}C data for tree A (filled triangles with error bars) and tree B (open circles with error bars) for the period AD 750–820 with 1- or 2-year resolution. The typical precision of a single measurement of Δ^{14}C is 2.6‰. Most data were obtained by multiple measurements, yielding smaller errors. Error bars, 1 s.d. **b**, The decadal average of our data (filled diamonds with error bars) compared with the IntCal98 data[13] (open squares with error bars), which is a standard decadal Δ^{14}C time series. Six standard samples (NIST SRM4990C oxalic acid, the new NBS standard) were measured in the same batch of samples. Because Δ^{14}C is calculated as the deviation of the ^{14}C/^{12}C ratio of a sample with respect to an average of ^{14}C/^{12}C of the six standard samples, the errors are the resultant of error propagation. An error for a sample is a statistical one from a Poisson distribution, and an error for the standard sample is the greater of either averaged statistical error from a Poisson distribution of Δ^{14}C for the six standard samples or the s.d. of values of ^{14}C/^{12}C for six standard samples.

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record reconstructed using the IntCal data. Although we cannot say with certainty that the ^{10}Be peak in the ice core occurred in AD 775, it is possible that the two peaks have the same cause. We take the agreements as further circumstantial evidence that the event was global.

To model the tree ring data, we simulated the temporal variations of ^{14}C content (using a four-box carbon cycle model) after a short-term increase in the ^{14}C production rate (based on a three-box model)[15]. Further details of this model are given in Supplementary Information. Using this model, we can calculate the hypothetical ^{14}C production rates needed to explain a rapid increase in the annual time series, for input durations of 0.1, 0.5, 1, 2 and 3 years. The best-fit values of the input ^{14}C production rate are provided in Supplementary Information. The model shows best agreement with tree ring data (Fig. 2) for a spike in ^{14}C production lasting less than 1 year. However, owing to the annual resolution of the ^{14}C data, we cannot assess the duration of this spike in more detail. Nevertheless, as the input period increases to $>$1 year, the agreement of the model with the measured data decreases. Therefore, the present data are consistent with a short-term, high-energy event producing ^{14}C, followed by a gradual decrease of ^{14}C content due to the global carbon cycle.

If the input period of ^{14}C production was 1 year, the production rate must have been 19 atoms $cm^{-2} s^{-1}$ (see Supplementary Information) to explain the effects of this event. This is about 10 times larger than the global average production rate by galactic cosmic rays (2.05 atoms $cm^{-2} s^{-1}$; ref. 16).

The increment of ^{14}C content in AD 775 was about 12‰. The source cannot be the solar cycle (that is, the Schwabe cycle), which on average has an 11-year period and an amplitude of 3‰ with respect to its effect on the atmospheric ^{14}C concentration[5]. An increase of 12‰ in 1 year is about 20 times larger than expected from the Schwabe cycle. Only two known phenomena can change the cosmic-ray intensity within 1 year: a supernova explosion or a large solar proton event (SPE).

First we consider the increase of ^{14}C content due to a supernova explosion. In this case, γ-rays can produce ^{14}C because γ-rays are unaffected by the Galactic magnetic field, unlike other charged particles from supernova explosions. The production mechanism is the reaction $^{14}N(n,p)^{14}C$ from secondary neutrons of energy 10–40 MeV produced in the cascade from hard γ-rays in the atmosphere. No detectable increase in ^{14}C corresponding to supernovae SN 1006 and SN 1054 was reported[4], and the energy of the event in AD 775 at the Earth must be larger than these. We assume that the differential energy spectrum of γ-ray emission from a supernova is described by a power law with an index of -2.5 (ref. 4). By integrating over γ-ray energies above 10 MeV, we obtain a ^{14}C production yield of 1.2×10^2 ^{14}C atoms erg^{-1}. We computed the production yield of ^{14}C due to γ-rays using the GEANT4 simulation code with QGSP-BERT-HP[17], which is valid for thermal neutron interactions. Based on this figure, the incident γ-ray energy necessary for this increase of ^{14}C content in the atmosphere is about 7×10^{24} erg. If the distance of the supernova were the same as that of SN 1006 (2 kpc; ref. 18), the total γ-ray energy would be 3×10^{51} erg. This energy release is 100 times larger than the γ-ray energy release from a normal supernova assuming that 1% of total supernova energy goes to γ-rays and that emission of energy is isotropic (typical total supernova energy is of the order of 10^{51} erg). Therefore, the supernova was closer than 2 kpc, so that the total γ-ray energy release is 3×10^{51} erg, which is a typical supernova energy. However, although there are no historical records of a supernova visible in the Northern Hemisphere around AD 775, there are historically unrecorded supernova remnants: for example, Cassiopeia A, which was found by radio observations, or Vela Jr (RX J0852.0$-$4622), which was found by the COMPTEL γ-ray observatory, based on the ^{44}Ti line; the distance to Vela Jr is hundreds of parsecs and its age is 10^3–10^4 years (refs 19–21). Therefore, we cannot rule out an undiscovered supernova remnant corresponding to the AD 775 event. But a supernova in AD 775 may be not probable, because a supernova that occurred relatively recently and relatively near Earth should still be tremendously bright (in radio, X-rays and ^{44}Ti), and such an object is not observed.

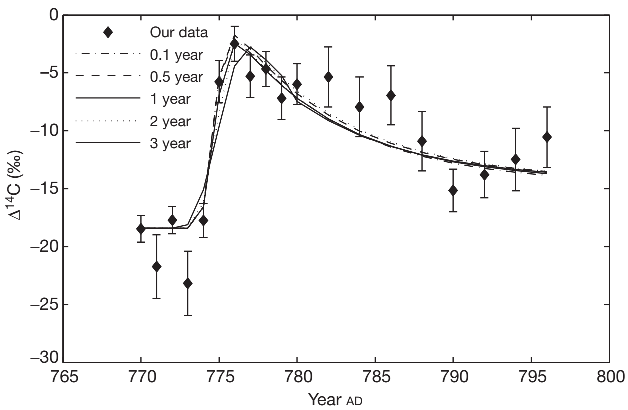

Figure 2 | Comparison of our data with a four-box carbon cycle simulation. Filled diamonds represent the Δ^{14}C values of our data, and lines represent an expected change by a four-box carbon cycle simulation. Various lines represent different cosmic-ray input durations of 0.1, 0.5, 1, 2 and 3 years. The Δ^{14}C value of the simulation in AD 773 is fixed at a value calculated by the weighted average of the three data from AD 770 to 772. Error bars, as in Fig. 1 legend.

Next we consider the case of an SPE. We assume that the flux of protons from an SPE as a function of rigidity (which is the momentum of the particle divided by the electric charge) is exponential: $\exp(-R/R_0)$, where R is the rigidity of protons and R_0 is the characteristic rigidity of the SPE. R_0 is set to 78 MV (ref. 5) in the following calculation. Unlike γ-rays, protons reaching the Earth are blocked by the geomagnetic field. We applied predicted (using EXPACS[22] software) vertical geomagnetic cut-off rigidities on the Earth for an assumed geomagnetic field the same as the present field, and calculated the flux at intervals of 10° in latitude, and obtained an average ^{14}C production yield of 10 ^{14}C atoms erg^{-1} using the GEANT4 code. The total proton energy necessary for this event was estimated to be 8×10^{25} erg at the Earth, which corresponds to 2×10^{35} erg at the Sun and may be compared to the total proton energy of 10^{29}–10^{32} erg in a normal SPE[23].

Because there is a 30% increase in the decadal ^{10}Be flux record in Dome Fuji from AD 755 to 785, we compared the production rate of ^{14}C with that of ^{10}Be (further discussions are presented in Supplementary Information.) It is possible that an SPE with an extremely hard energy spectrum could explain simultaneously the ^{14}C and ^{10}Be results, but it would have to be much harder than any flare observed so far. Furthermore, an annual time series of ^{10}Be flux would be necessary for a meticulous comparison. In fact, very large, energetic 'super flares' have been detected on normal solar-type stars. However, it is believed that a super flare has never occurred on our Sun, due to the absence of an historical record (such as a record of aurora and mass extinction caused by the expected destruction of the ozone layer[24]) and theoretical expectations[25–29].

With our present knowledge, we cannot specify the cause of this event. However, we can say that an extremely energetic event occurred around our space environment in AD 775. In the future, other high-resolution records (such as ^{10}Be and nitrate data), together with careful research of historical documentation around AD 775 and further surveys of undetected supernova remnants, may help us to clarify the cause.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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