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Key Points:
- Excursion in 774-776 A.D. due to a rapid change in 14C production
- Event must be global and uniform in scale
- Phenomenon is reproduced in two new locations, making a total of five

Supporting Information:
- Readme
- Table S1

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Excursions in the ^{14}C record at A.D. 774–775 in tree rings from Russia and America

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Abstract The calibration of radiocarbon dates by means of a master calibration curve has been invaluable to Earth, environmental and archeological sciences, but the fundamental reason for calibration is that atmospheric radiocarbon content varies because of changes in upper atmosphere production and global carbon cycling. Improved instrumentation has contributed to high-resolution (interannual) radiocarbon activity measurements, which have revealed sudden and anomalous activity shifts previously not observed at the common resolution of 5–10 years of most of the calibration scale. One such spike has been recently reported from tree rings from Japan and then again in Europe at A.D. 774–775, for which we report here our efforts to both replicate its existence and determine its spatial extent using tree rings from larch at high latitude (northern Siberia) and bristlecone pine from lower latitude (the White Mountains of California). Our results confirm an abrupt ~ 15‰ ^{14}C activity increase from A.D. 774 to 776, the size and now the hemispheric extent of which suggest that an extraterrestrial influence on radiocarbon production is most likely responsible.

1. Introduction

Cosmic rays interact with the Earth's atmosphere to produce secondary particles and also products. One of the most well known of these products is carbon-14, which is produced in the atmosphere by the action of secondary galactic cosmic ray (GCR) neutrons on nitrogen in the atmosphere due to the reaction $^{14}N(n,p)^{14}C$ [*van der Plicht*, 2007; *Burr*, 2007]. The mean production rate has been the subject of much discussions in the past, but the current consensus values are 1.6–2.0 atoms/cm^2/s [*Masarik and Reedy*, 1995; *Mak et al.*, 1999; *Kovaltsov et al.*, 2012].

In general, ^{14}C levels are measured as fraction of modern carbon, F [*Donahue et al.*, 1990]. Either $^{14}C/^{13}C$ or $^{14}C/^{12}C$ ratios may be used to calculate F. Here we consider only $^{14}C/^{13}C$ ratios. In this case F is defined as

$$F = \frac{(^{14}C/^{13}C)_{S[-25]}}{(^{14}C/^{13}C)_{1950[-25]}} \quad (1)$$

where $(^{14}C/^{13}C)_{S[-25]}$ is the measured ratio for the sample, blank corrected and adjusted to a $\delta^{13}C = -25‰$; and $(^{14}C/^{13}C)_{1950[-25]}$ is the measured ratio of the standard, blank corrected, adjusted to $\delta^{13}C = -25‰$, and recalculated to 1950 A.D. [see *Burr and Jull*, 2009].

It is often of interest to understand past levels of ^{14}C. This can be done by converting the ^{14}C measured in a sample of known age in the past to a $\Delta^{14}C$ value according to equation (2)

$$\Delta^{14}C = 1000 \times \left(Fe^{\lambda t} - 1\right) \quad (2)$$

where F is defined above in equation (1), λ is the true decay constant of ^{14}C ($1.209 \times 10^{-4}\,yr^{-1}$) and t is the known age of the material [*Stuiver and Polach*, 1977]. At the time the sample formed $\Delta^{14}C$ is a measure of the radiocarbon content of the atmosphere, relative to the A.D. 1950 atm, expressed in per mil (‰). This term allows time-dependent changes in atmospheric ^{14}C to be accurately identified.

In a recent series of papers studying annual tree rings, *Miyake et al.* [2012] reported on the existence of excursions in the radiocarbon record at A.D. 774–775, followed by a less intense event at A.D. 993–994

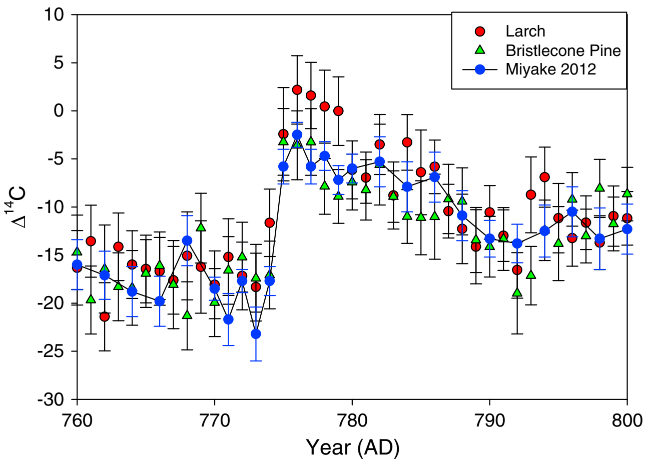

Figure 1. Record of $\Delta^{14}C$ (‰) between A.D. 760 and A.D. 800 in tree rings from bristlecone pine (White Mountains, California, USA) and larch (Yamal Peninsula, Siberia, Russian Federation), compared to the record of *Miyake et al.* [2012] from Japanese cedar.

[*Miyake et al.*, 2013]. The A.D. 774–775 "spike" is observed as a change in $\Delta^{14}C$ of ~ 12–15‰ in a 1–2 year period. Apart from the event at A.D. 993–994, there are no other reported excursions of this magnitude in the last several thousand years [*Usoskin and Kovaltsov*, 2012]. The initial work of *Miyake et al.* [2012] on the A.D. 774–775 event was based on annual rings from Japanese cedar trees. The first event has been independently confirmed by other investigators on European oak trees [*Usoskin et al.*, 2013], with a change in $\Delta^{14}C$ of ~ 15‰. In addition, *Güttler et al.* [2013a, 2013b] report on a record from the Southern Hemisphere using Kauri wood from New Zealand. This Kauri record shows the same amplitude in $\Delta^{14}C$ but with a small offset due to the Southern Hemisphere regional effect. *Liu et al.* [2014] have recently reported on a similar excursion in $\Delta^{14}C$ determined from dated corals in the South China Sea.

Our purpose in this study is to investigate whether this signal is truly global by selecting continental locations from the western United States and northwestern Siberia. These sites were chosen to be as diverse as possible from the previously published locations. A second goal was to elucidate any changes in regional effects that might be manifest in the results. These locations should also sample different regional ^{14}C offsets and would not show effects due to either the ocean (as in the case of Japan) or the Southern Hemisphere [*Stuiver et al.*, 1998; *Hogg et al.*, 2013]. Third, we then discuss the possible implications of these results for past extreme radiation events or other possible cosmic events.

2. Samples and Methods

In this study, we investigate the variations in ^{14}C in annual tree-ring records from different locations in the western United States (California White Mountains bristlecone pine [*Pinus longaeva*] 37°77′N, 118°44′W, 3539 mean annual sea level (MASL)) and Siberia (Yamal Peninsula larch [*Larix sibirica* Ldb] 67°31′N, 70°40′E, 350 MASL). All samples were crossdated and absolutely dated with large-sample size tree-ring records using standard dendrochronological methods [*Salzer et al.*, 2009; *Hantemirov and Shiyatov*, 2002]. Annual tree rings from each site were separated for the period 760 to 800 A.D.

Samples were pretreated to extract cellulose in the accelerator mass spectrometry (AMS) laboratory. These were then combusted to CO_2 and converted to graphite using standard procedures [*Jull et al.*, 2008]. The graphite powders produced are pressed into AMS targets and measured using the National Electrostatics Corporation AMS system at the University of Arizona, at a terminal voltage of 2.5 MV. The $^{14}C/^{13}C$ ratio of the sample is compared to known standards (Oxalic_I and II, National Institute of Standards and Technology standards SRM4990B and 4990C, respectively), and the result corrected to the measured value of $\delta^{13}C$ made offline on a stable isotope mass spectrometer, giving a value for fraction of modern carbon (F). Details of the AMS calculations at Arizona are given by *Donahue et al.* [1990] and *Burr et al.* [2007]. The ^{14}C results are also converted from F to $\Delta^{14}C$ as discussed in equation (1).

3. Results

3.1. Time Variance of the Measurements

Our results are shown in Figure 1 and also summarized in the supporting information (Table S1). Here we plot our results for both *bristlecone pine* and *Siberian larch* from known-age tree rings. We observe a marked offset in the $\Delta^{14}C$ value between A.D. 774 and 776. There is remarkable agreement between our

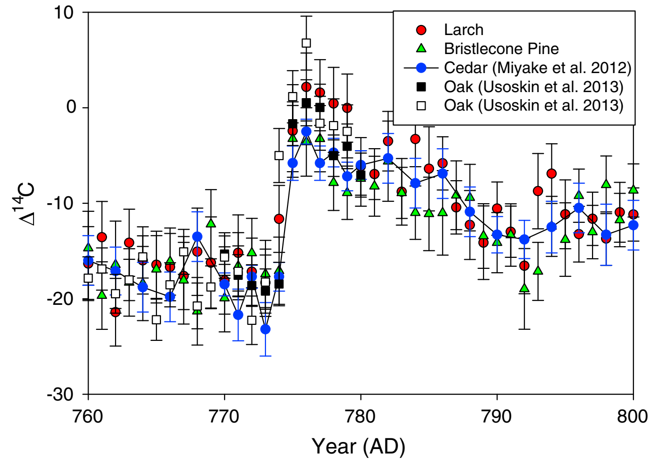

Figure 2. Record of $\Delta^{14}C$ (‰) between A.D. 760 and A.D. 800 in tree rings from White Mountains bristlecone pine and Yamal Peninsula larch, compared to the record in German oak [*Usoskin et al.*, 2013].

record and that of the two previous published results obtained by *Miyake et al.* [2012] and *Usoskin et al.* [2013]. The data of *Güttler et al.* [2013a, 2013b] show a similar effect. In Figure 2, we compare our results to these previous records. The amplitude of the effect appears to be almost identical between the different data sets, and the differences between the data are small regional offsets of the order of 3–5‰ [*Stuiver et al.*, 1998].

Upon closer inspection, some additional details are apparent. First, the rise in $\Delta^{14}C$ is uniform between the different records but with some small differences. In the *Miyake et al.* [2012] record, the increase appears to begin in 774 and continue to A.D. 776. A similar effect is seen in the *bristlecone pine* data. However, the European oak data [*Usoskin et al.*, 2013] and the *Siberian larch* results indicate that by A.D. 774, the tree rings were already elevated above the previous year. A similar effect appears to be present in the record of *Güttler et al.* [2013a]. This suggests that the incorporation of the ^{14}C signal from the event is not completely uniform. An analysis of our *bristlecone pine* and *Siberian larch* indicates that they are statistically indistinguishable based on the student's t test, $t = 1.489$ with 40 degrees of freedom. In all cases, the peak of the event in the ^{14}C record is in A.D. 776.

4. Discussion

4.1. Size of the ^{14}C Effects

The atmosphere today contains ~ 750 Gt of carbon [*Schimel et al.*, 1996], equivalent to ~ 4.4×10^{28} ^{14}C atoms at a prebomb $^{14}C/^{12}C$ value of 1.177×10^{-12}. In A.D. 774, we expect that due to the lower concentration of CO_2, this value was closer to 600 Gt or ~ 3.5×10^{28} ^{14}C atoms (~ 814 kg ^{14}C). With an annual average production rate of ~ 1.8 ± 0.2 $^{14}C/cm^2/s$ [*Kovaltsov et al.*, 2012], this would produce ~ 3×10^{26} ^{14}C/yr (6.7 kg/yr). Because the amount of ^{14}C in the atmosphere is clearly much higher than the annual average production rate, a large amount of change in production is needed to explain the increase in the A.D. 774–776 sequence studied here. This value becomes even larger when exchange of atmospheric carbon with the surface ocean and biosphere is considered. Hence, it is clear from these values that a twofold increase in production rate would only increase the ^{14}C in the atmosphere a few percent. Since the atmosphere is in equilibrium with the oceans and the biosphere, exchanging ~ 90 Gt carbon per year with the ocean, and experiencing a net loss of ~ 60 Gt/yr to the biosphere [*Schimel et al.*, 1996], researchers have resorted to box model calculations to explain these effects [e.g., *Damon et al.*, 1995; *Usoskin and Kovaltsov*, 2012]. Because these models are all based on the same values for the carbon cycle (e.g., for reference levels), it is not necessary to repeat these calculations again. Previous authors have estimated the production rate of ^{14}C (atoms/cm^2/yr) required to explain these observations at between 1.3×10^8 and 1.7×10^8 atoms/cm^2/yr [*Usoskin et al.*, 2013; *Pavlov et al.*, 2013; *Miyake*, 2014]. An earlier higher estimate from the original *Miyake et al.* [2012] paper has been reduced by a factor of 4 [*Miyake*, 2014].

4.2. Constraints on the Intensity of a Possible Solar Flare Event

The initial work on this event by *Miyake et al.* [2012] and *Usoskin et al.* [2013] has generated a large amount of modeling as well as speculation as to the cause of this ^{14}C excursion. Almost all studies propose that there is a rapid change to the production rate of ^{14}C, which must be several times the normal galactic cosmic ray (GCR) production rate. Most authors speculate on a solar cause due to enhanced solar proton fluxes from solar cosmic ray or coronal mass ejection events. *Lingenfelter and Ramaty* [1970] were the first to note that a large solar proton event could produce more ^{14}C than the average annual GCR rate. Hambaryan and Neuhäuser (2013) and *Pavlov et al*. [2013] favor a gamma ray burst (GRB) as a source. Other authors have proposed solar proton events [*Usoskin and Kovaltsov*, 2012; *Thomas et al*., 2013; *Usoskin et al*., 2013], a cometary impact into the Sun generating intense solar flares [*Eichler and Mordecai*, 2013] and a comet impact into the Earth's atmosphere [*Liu et al*., 2014].

These discussions focus primarily on possible explanations for an external source of cosmic radiation which could be sufficient to produce this change in the ^{14}C production rate. According to *Miyake et al*. [2012], the production rate in this year must have been enhanced from the mean value by between 3.6 and 10 depending on the period of the event and the assumptions about storage in the stratosphere, however, this has since been reduced by a factor of 4 [*Miyake*, 2014]. Others have estimated the production rate of ^{14}C (atoms/cm^2/yr) required to explain these observations at between 1.3×10^8 and 1.7×10^8 atoms/cm^2/yr [*Usoskin et al*., 2013; *Pavlov et al*., 2013; *Miyake*, 2014]. Of course, all these estimates depend on the assumptions and models used.

Several authors have proposed different solar particle fluxes necessary to produce the effects discussed. Since the flux of solar particles is dependent on the energy spectrum of the event, there can be some variability in these estimates. We therefore standardize these reports for a flux $E > 30$ MeV [*Reedy*, 1996]. *Miyake* [2014] has revised their original estimate for the proposed solar proton event total fluence ($E > 30$ MeV) necessary to produce the A.D. 774–775 ^{14}C effect to 5×10^{10} p/cm^2. *Usoskin et al*. [2013] estimated a fluence of 4.5×10^{10} p/cm^2 and *Cliver et al*. [2014] have estimated 8×10^{10} p/cm^2.

Shea and Smart [1990] summarized all major solar proton events between 1955 and 1986. Subsequently, *Reedy* [1996] summarized solar flare events over the period A.D. 1954–1996 and found a few events of 1×10^{10} p/cm^2 (for $E > 30$ MeV) but no larger events.

The lunar record provides a good baseline of the long-term fluence of solar cosmic rays, since it provides an integral record. *Jull et al*. [1998] derived a long-term flux of 1.3×10^9 p/cm^2/yr, based on spallogenic ^{14}C in lunar rock surfaces. A recent reinvestigation by *Kovaltsov and Usoskin* [2014] confirms this estimate. Hence, any very large events in the past must be small in number, since they would also create radioactivity in lunar samples. *Reedy* [1996] constrains very large SPEs to a probability of $<10^{-4}$/year based on the tree-ring record. *Lingenfelter and Hudson* [1980] similarly constrain the number of SPEs over the last 7000 years to not more than one with flux $> 3 \times 10^{11}$ p/cm^2.

As noted by *Miyake et al*. [2012], their original calculated fluence of $>10^{11}$ p/cm^2 could produce biologically damaging levels of radiation, however, this has since been revised [*Miyake*, 2014]. This suggests that their original fluence calculation was too high [*Thomas et al*., 2013], and also one of the reasons that other possible origins of the ^{14}C event were considered. *Hamabaryan and Neuhäuser* [2013] proposed a gamma ray burst as an alternative source to produce the ^{14}C excess. *Pavlov et al*. [2013] also proposed a GRB, with more detailed considerations. Although *Miyake et al*. [2012] noted a possible correlation with ^{10}Be in ice cores, *Pavlov et al*. [2013] noted that such a correlation would not be required with a GRB, since most production of neutrons from a γ-ray burst would be at energy below the threshold for spallation production of ^{10}Be from oxygen.

4.3. A Cometary Event?

In a recent paper, *Liu et al*. [2014] proposed that the ^{14}C increase at A.D. 774–775 was caused by a cometary impact into the Earth's atmosphere. In their work, they observed a similar 15‰ excursion in corals about the same time. With biweekly sampling resolution in the coral, *Liu et al*. [2014] noted a brief 45‰ increase a few months after the initial rise in ^{14}C, followed by a subsequent increase of 15‰. They also cited Chinese historical records from A.D. 773 that described a major atmospheric disturbance at the time, including a significant dust event [e.g., *Napier*, 2001]. *Liu et al*. [2014] estimate that a comet of ~ 1.50×10^{11} kg could produce enough ^{14}C to account for the observed changes in atmospheric radiocarbon. This would be an object of over 1 km diameter, if we assume a density of 0.6 g/cm^3. *Overholt and Melott* [2013] calculated that a much more massive comet ($>10^{14}$ kg) would be needed to produce approximately this amount (see Figure 1a of their paper). However, their model assumes that comets receive a high cosmic ray dose during their transit of the outer solar system. If one assumes an impacting asteroid or other inner solar system object, then the amount of ^{14}C would be much lower. *Usoskin and Kovaltsov* [2014] also come to similar conclusions as to the size of a cometary impact needed to produce such effects. Recent studies on the Chelyabinsk

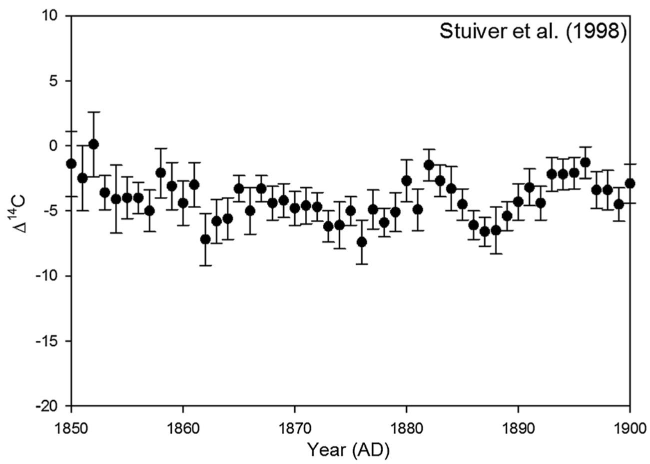

Figure 3. Record of $\Delta^{14}C$ (‰) between A.D. 1850 and A.D. 1900 from *Stuiver et al.* [1998].

meteoroid airburst indicate that it was an object of ~ 20 m diameter, with an energy release of ~ 590 kt trinitrotoluene (TNT) equivalent and a mass of ~ 1.3×10^7 kg [*Popova et al.*, 2013]. We note that the Tunguska airburst event is calculated to be about 20 times larger than Chelyabinsk with an energy release of 5–15 Mt TNT [*Borovička et al.*, 2013]. An object 10^4 times larger mass than Chelyabinsk would probably have close to 10^4 times the kinetic energy resulting in a postulated energy release of some 5900 Mt TNT (2.5×10^{16} J). This would be a truly massive event, if proven correct.

A more important problem with any impact event is that it would have occurred in one hemisphere. The results shown here do not show any difference between the Northern and Southern Hemispheres at all [*Güttler et al.*, 2013a], in marked contrast to records of the injection of nuclear ^{14}C into the atmosphere during the period of aboveground atomic weapons testing [*Hua et al.*, 2013].

4.4. Does the Tree-Ring Record Show Other Potential Solar Cosmic Events?

Miyake et al. [2013] report on a second event at A.D. 993–994. However, they also assert that they found no evidence for other events over the last 3000 years. There has been much discussion in the literature, not only about solar events that might be observable in the ^{14}C record or ice cores but also other phenomena.

Usoskin et al. [2006] estimated that the A.D. 1956 solar proton event had a fluence of 10^9 p/cm^2, but it is not easy to observe any discernable effect in $\Delta^{14}C$ from 1956 due to the beginning of effects due to nuclear testing [*Hua et al.*, 2013]. Similarly, any effect of the A.D. 1946 event of 6×10^9 p/cm^2 [*Smart et al.*, 2006] is not clear based on the data of *Damon et al.* [1973a], which shows a difference of 7 ± 5‰ relative to A.D. 1946, but only 1.6 ± 4.2‰ relative to A.D. 1945. *Smart et al.* [2006] proposed that the Carrington event, an observed solar flare event that also had many documented effects on the Earth, including direct observations [*Carrington*, 1860], aurorae, and geomagnetic phenomena [*Desnains and Charault*, 1859]. Although this event is estimated to have an F_{30} of 1.9×10^{10} cm^{-2} [*Smart et al.*, 2006], there is no evidence for this event in the annual ^{14}C record of *Stuiver et al.*, 1998 nor of *Miyake et al.* [2013]. *Wolff et al.* [2012] reported that the F_{30} estimate from *Smart et al.* [2006] was based on ice core nitrate data, which does not show good evidence for solar flare events. Hence, this value may have been overestimated. In Figure 3, we plot the values of $\Delta^{14}C$ for the period A.D. 1850–1900, which shows no effect at A.D. 1859–1860. It is clear, therefore, that either this event was not as intense as proposed, or the ^{14}C system is affected only by certain solar events or perhaps other causes. Interestingly, *Fan et al.* [1985] and *Damon et al.* [1973b] appeared to identify anomalous $\Delta^{14}C$ excursions in A.D. 1943 wood from Arizona and the Mackenzie Delta, Canada, with excursions of ~ 15‰, presumably associated with A.D. 1942 solar proton events. However, this event was not confirmed in other records [*Stuiver et al.*, 1998], as is the case for the A.D. 774–775 event presented here.

5. Conclusions

We have confirmed the A.D. 774–775 event in the ^{14}C record at two additional locations, in the western United States and Russia. The amplitude of the event is very similar to previously reported results from Japan, Germany, and New Zealand. This emphasizes the global nature of this phenomenon and according to existing models, only a production-rate change could cause this type of event. The fact that the ^{14}C signal is observed in five very different locations with exactly the same amplitude is remarkable in itself. The exact cause of the event is unclear, although a number of mechanisms have been proposed, all of which require an extraterrestrial origin. It appears then that the A.D. 774–775 event is the first unambiguous case of extraterrestrial enhancement of atmospheric ^{14}C in the tree-ring record. More detailed work on annual samples from dendrochronologically dated wood may identify further examples of these excursions both spatially and temporally.

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