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Has the Earth been exposed to numerous supernovae within the last 300 kyr?

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Abstract: Firestone (2014) asserted evidence for numerous (23) nearby ($d < 300$ pc) supernovae (SNe) within the Middle and Late Pleistocene. If true, this would have strong implications for the irradiation of the Earth; at this rate, the mass extinction level events due to SNe would be more frequent than 100 Myr. However, there are numerous errors in the application of past research. The paper overestimates likely nitrate and ^{14}C production from moderately nearby SNe by about four orders of magnitude. Moreover, the results are based on wrongly selected (obsolete) nitrate and ^{14}C datasets. The use of correct and up-to-date datasets does not confirm the claimed results. The claims in the paper are invalid.

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Introduction: ionizing radiation from supernovae (SNe)

Firestone (2014; hereafter F14) bases arguments for abundant moderately nearby SNe (Wheeler 2012) on data of measured cosmogenic isotope deposition and nitrate accumulation in terrestrial archives. The claimed rate of 23 SNe within 300 pc of the Earth within the last 300 kyr would exceed the average galactic rate by a factor of 4; so the claim is suspicious if only on this basis. The average galactic rate has about 2 SNe per Myr within 100 pc (Fields 2004); due to the geometry of the galactic disc one would expect about 20 per Myr within 300 pc, or only six within the last 300 kyr. Of course, the Earth may lie in an unusually active region of the Galaxy, but such claims bear further examination. We examine the F14 claims here.

Mass extinctions

If the true galactic rate were four times higher, mass extinctions would occur more frequently than every 100 Myr, due only to SNe (Gehrels *et al.* 2003; Fields 2004; Melott & Thomas 2011). F14 estimates (his Section 5) events closer than 10 pc about every 12 Myr. Such events would cause major mass extinctions (e.g. Gehrels *et al.* 2003). There are some indications of astrophysical radiation-based mass extinctions (Melott *et al.* 2004; Melott & Thomas 2009) but not nearly so frequently; the 'Big Five' mass extinctions occur at about 100 Myr intervals, and some, such as the end-Permian and end-Cretaceous events, are clearly not radiation events (Bambach 2006).

Radiation from SNe

SNe remain visible as SNe remnants, typically an expanding shell of hot gas, for of order of a million years (Draine 2010). Only three observed ones, RX J08520-4622, Vela and Geminga (actually a neutron star) lie within 300 pc and are possibly less than 300 kyr old. This is quite at variance with the claim that there have been 23 such events.

In what follows, the computations depend upon the ionizing radiation (viz. hard X-rays, γ-rays and cosmic rays) fluence from the SNe. F14 deduces, for example, that there is as much energy as 2×10^{49} erg for the initial burst of ionizing radiation. This is more typical of the total electromagnetic radiation output (including visible light) of an SN, and considerably higher than the modern measurement of X-rays (Soderberg *et al.* 2008), which lies at about 2×10^{46} erg, with no γ-rays detected. Over a period of months, X-ray emissions continue at a lower flux, accumulating as much as 10^{47} erg (Melott & Thomas 2011). Although rare, extreme outliers may produce two orders of magnitude more (Levan *et al.* 2013). There is a kinetic energy component of order of 10^{51} erg; this may be taken as an upper limit to the possible energy in cosmic rays. Of course the photon transport to the Earth is at the speed of light, but the cosmic rays have diffusive transport, taking hundreds to thousands of years longer for the cases we will consider. The PeV cosmic rays would arrive in perhaps 300 yr for a 100 pc distant SN. However, most would arrive later (e.g. for an SN at 250 distance the maximum of cosmic rays would arrive with a 4–40 kyr delay, using the mean free path of cosmic rays in the interstellar medium as 2.5–25 pc; see, e.g. Lingenfelter & Ramaty, 1970), and spread out over a similar time, as their time profile would have a typical shape of a diffusive propagation wave. There is no observed evidence for such a wave.

Nitrates

Ionizing radiation breaks the triple bond of N_2, making possible the synthesis of oxides of nitrogen in the atmosphere, which are normally present at low abundance. Gehrels *et al.* (2003) contains some estimates from nearby SNe. Nitrate peaks in ice cores have been proposed as signatures of SNe, and F14 considers this question. Historical SNe are used as examples, including in F14. It is now possible, given detailed numerical simulations (e.g. Thomas *et al.* 2007; Melott & Thomas 2011) to compute the nitrate deposition from ionizing radiation onto the Earth. For X-rays and γ-rays, 10^{-4} ng erg^{-1} is a good estimate of the global average in the X-ray regime, with no strong dependence upon the time development of the radiation, beyond simple causality (Ejzak *et al.* 2007).

Nitrate deposition at these low fluxes will scale nearly linearly with ionizing fluence at the Earth. Let us examine the historical SNe, and parameterize the expected nitrate deposition based on their X-ray fluence and distance, using simply the inverse square law. The expected nitrate deposition from SN X-rays is of order of

$$d = 1\,\text{ng cm}^{-2}(R/100\,\text{pc})^{-2}(F/10^{46}\,\text{erg}),$$

where F is the total fluence of ionizing radiation for an SN at the distance R.

F14 quotes Dreschhoff & Laird (2006) regarding evidence from historical SNe. The following table shows the measured and expected nitrate deposition in the GISP2-H ice core from Summit, Greenland, assuming 10^{46} erg fluence. Distances are from Green (2004; see also Green 2014). These peaks include 1–2 months of deposition. By including the months of extended X-ray emissions the expected numbers may be increased, but still are four orders of magnitude too small to account for nitrate peaks speculatively associated with the historical SNe.

Table 1: *Nitrate Deposition from Historical Supernovae*

Date	Event	Distance (kpc)	Nitrate measured (ng cm^{-2})	Nitrate expected (ng cm^{-2})
1573/74	Tycho	2.3	177	0.0019
1605	Kepler	2.9	266	0.0012
1667	Cas A?	3.4	150	0.0009
1700	Cas A?	3.4	218	0.0009

Other historical SN nitrate spikes cited by F14 were from Rood *et al.* (1979). The 1974 South Pole ice core cited by F14 was the first core from this site analysed for nitrate and the conclusions of Rood *et al.* (1979) have been generally discredited. This assertion is based on Dreschhoff *et al.* (1983), who retracted the results after a second South Pole ice core was drilled in 1978 and found that most of the nitrate spikes in question could be attributed to 'artefacts of contamination.' They concluded, 'While we cannot reject totally the idea that SNe may be detectable in the nitrate signal, it is clear that the extreme spikes did not result from this source.' This second South Pole core, along with an ice core from Vostok Station were cited in Dreschhoff & Laird (2006), however, the nitrate fluences above background (roughly 600 ng cm^{-2} for South Pole and Vostok samples) hypothesized as due to SNe are too large by more than five orders of magnitude to match predictions.

Photons from the 19 additional SNe 'observed' by F14 at distances of 100–300 pc could be expected to produce nitrate deposition in amounts similar to those 'expected' in our Table, far below the noise level in these measurements. Even if the X-ray fluence were closer to the 10^{49} erg suggested by F14, which exceeds most SNe, they would still be far too small to account for the measured nitrate.

The cosmic-ray flux will arrive over hundreds to thousands of years, and may take a substantial fraction of the kinetic energy of the SN; using the recent consensus value for the efficiency of conversion of bulk kinetic energy to cosmic rays of order of 10%, we adopt 10^{50} erg as a typical value for the injection of cosmic rays into the interstellar medium. The arrival will be energy-dependent (e.g. Erlykin & Wolfendale 2010) with the highest energy cosmic rays arriving first and an extended tail of lower energy ones. The aggregate energy incident upon the Earth in cosmic rays will be of order of 10^8 erg cm^{-2} for a 100 pc event. This would give a small, very extended, excess nitrate deposition, which would be challenging to measure.

Carbon-14

An additional argument of F14 is based on ^{14}C variation. However, several crucial errors have been made here.

First, F14 analysed the data shown in his Fig. 2 to claim a saw-tooth structure with several peaks and decays. That figure is a composite of two datasets: INTCAL04 (Reimer *et al.* 2004) for the age range 0–26 kyr age, and Hughen *et al.* (2004) for the age older than 26 kyr, the latter being arbitrarily lifted up by 22.5% to match INTCAL04 at 26 kyr ago. One can see that the two pieces do not match each other in the most recent well-dated part, implying that the 22.5% offset is wrong. Moreover, these datasets are outdated. Hughen *et al.* have later strongly revised their dataset (Hughen *et al.* 2006, see Fig. 5 there), so that Fig. 2(b) of F14 is dramatically modified, no longer showing the saw-tooth structure. The use of INTCAL04 is also not valid. The INTCAL series has been greatly updated recently with INTCAL09 and INTCAL13 (Reimer *et al.* 2013) officially released. It is important that the dataset of Hughen *et al.* (2006) is explicitly included in INTCAL13. The time series of Δ^{14}C for INTCAL13 shown in Fig. 1 has little in common with the dataset used by F14. In particular, there are no spikes ca. 18 and 22 kyr ago. There are also no saw-tooth structures with exponential 'decays' before 26 kyr ago (Fig. 2(b) in F14, 2014). The variability beyond 26 kyr is much smaller than claimed by F14 and can be explained by the climate and geomagnetic field variability. This invalidates F14's claims.

Another reasoning of F14 is that the trend in Δ^{14}C during the Holocene is caused by an SN 22 kyr ago. However, the observed Δ^{14}C variability during the Holocene is well explained by a combination of solar activity, geomagnetic variability and climate changes (e.g. Solanki *et al.* 2004; Vonmoos *et al.* 2006; Snowball & Muscheler 2007; Usoskin *et al.* 2007), assuming a constant flux of cosmic rays outside the heliosphere. In this paper, we mean, as 'Solar activity', magnetic activity on the Solar surface and corona (flares, coronal mass ejections,

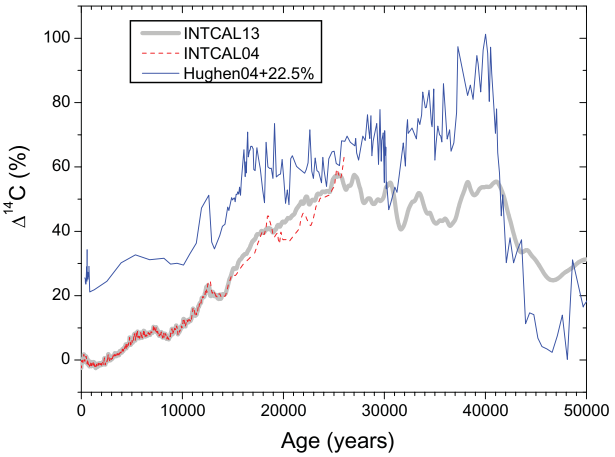

Fig. 1. Various series of $\Delta^{14}C$: thick – the most up-to-date series INTCAL13 (Reimer *et al.* 2013); Dashed – INTCAL04 series (Reimer *et al.* 2003); Thin – original series (uplifted by 22.5% following F14) of Cariaco Basin ocean core (Hughen *et al.* 2004). The series used by F14 is a combination of the red one extended by the blue one past 26 kyr. In addition, F14 has lifted the entire series by 5% to avoid negative values.

etc.) and consequently, disturbed heliospheric magnetic field and Solar wind, that leads to heliospheric modulation of cosmic rays (see, e.g. a review by Usoskin *et al.* 2013). Enhanced Solar activity leads to reduced (more modulated) flux of cosmic rays and thus to smaller ^{14}C production. All the observed variability of $\Delta^{14}C$ is perfectly explained by these factors without any need to invoke hypothetical SNe, contrary to F14 claims. This particularly refers to the last 3 kyr (Fig. 6 and Section 2.4 of F14) when the geomagnetic field is very well measured (see Usoskin *et al.* 2014). If F14 was correct with his reasoning, then this would unavoidably lead to reconstructed solar activity that is too low (even essentially negative) in the early Holocene, which is not observed. On the contrary, the solar activity reconstructed from ^{14}C shows a tendency to be too high (e.g. Fig. 6 in Vonmoos *et al.* 2006) suggesting that there was less (contrary to F14's suggestion) ^{14}C than expected, probably because of changing ocean circulation. Contrary to F14 claims, there is no evidence of historical SNe recorded in cosmogenic isotope data for the last millennium (see Supplement Information, Fig. S2 of Miyake *et al.* 2013).

Another problem is related to computations of the ^{14}C production from γ-rays. F14 uses the yield function (his Fig. 14) of Kovaltsov *et al.* (2012), but that yield function corresponds to ^{14}C production by cosmic ray *protons*. F14 explicitly assumes that it can be simply applied to cosmic γ-rays, but this assumption is wrong, as the physics of the processes induced by high-energy protons and γ-rays in the atmosphere are completely different. The yield function of atmospheric ^{14}C production by γ-rays was calculated by Pavlov *et al.* (2013, see Fig. 1) and it is much different from the yield function for protons used by F14. Pavlov *et al.* (2013) said that 'the mean yield of ^{14}C equals to 20–55 atoms erg^{-1} for the γ-ray flux entering the atmosphere…', whereas F14 uses about 20 000 neutrons erg^{-1} (since production of ^{14}C is the main sink for neutrons in the atmosphere, this implies roughly the same amount of radiocarbon production by γ-rays). Lingenfelter & Ramaty (1970) gave the number of ~1000 ^{14}C atoms erg^{-1} using a very rough estimate, which can serve as an upper limit. Thus, F14 overestimates the ^{14}C production by orders of magnitude. So, F14 arguments that γ-ray emission from the SN remnants can produce essential amounts of ^{14}C are not valid either, as anticipated by Lingenfelter & Ramaty (1970).

The arguments of F14 based on ^{14}C are invalid because:

1. They are based on outdated and improperly selected datasets;
2. They contradict other studies for the Holocene period that explained all the observed variability of $\Delta^{14}C$ by Solar activity, geomagnetic field and climate;
3. His computations are based on an improper model, which is not applicable to ^{14}C production by γ-rays, leading thus to an error of several orders of magnitude.

Conclusions

The high rate and high ionizing photon output claimed by F14 for SNe in this region of the Galaxy over the last 300 kyr are suspiciously high, and exceed available experimental data. This appears to be because he used obsolete and superseded datasets, and misapplied input parameters for computational models, so that predicted terrestrial ^{14}C and nitrate deposition exceed correct values by four or more orders of magnitude. The case for congruence with data is based on comparison of these incorrect predictions with out-of-date datasets.

We do not dispute indications of a relatively nearby SN perhaps 2.5 Myr ago (Fields 2004; Bishop *et al.* 2013; Fry *et al.* 2014) from ^{60}Fe deposition. However, the recent work of F14 shows major errors in both interpretation of data and computational modelling.

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