*International Journal of Astrobiology*

**cambridge.org/ija**

# Climate change via $CO_2$ drawdown from astrophysically initiated atmospheric ionization?

Adrian L. Melott[1], Brian C. Thomas[2] and Brian D. Fields[3]

[1]Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA; [2]Department of Physics and Astronomy, Washburn University, Topeka, Kansas 66621, USA and [3]Department of Astronomy and Department of Physics, University of Illinois, Urbana, IL 61801, USA

**Research Article**

**Cite this article:** Melott AL, Thomas BC, Fields BD (2020). Climate change via $CO_2$ drawdown from astrophysically initiated atmospheric ionization? *International Journal of Astrobiology* **19**, 349–352. https://doi.org/10.1017/S1473550420000117

Received: 27 April 2020
Revised: 4 May 2020
Accepted: 6 May 2020
First published online: 28 May 2020

**Key words:**
Climate change; glaciation; supernovae

**Author for correspondence:**
Adrian L. Melott, E-mail: melott@ku.edu

## Abstract

Motivated by the occurrence of a moderately nearby supernova near the beginning of the Pleistocene, possibly as part of a long-term series beginning in the Miocene, we investigated whether nitrate rainout resulting from the atmospheric ionization of enhanced cosmic ray flux could have, through its fertilizer effect, initiated carbon dioxide drawdown. Such a drawdown could possibly reduce the greenhouse effect and induce the climate change that led to the Pleistocene glaciations. We estimate that the nitrogen flux enhancement onto the surface from an event at 50 pc would be of order 10%, probably too small for dramatic changes. We estimate deposition of iron (another potential fertilizer) and find it is also too small to be significant. There are also competing effects of opposite sign, including muon irradiation and reduction in photosynthetic yield caused by UV increase from stratospheric ozone layer depletion, leading to an ambiguous result. However, if the atmospheric ionization induces a large increase in the frequency of lightning, as argued elsewhere, the amount of nitrate synthesis should be much larger, dominate over the other effects and induce the climate change. More work needs to be done to clarify the effects on lightning frequency.

## Introduction

There are various effects from relatively nearby supernovae, beyond the traditional emphasis on ozone depletion due to the ionization of the Earth's atmosphere. These include muon irradiation on the ground, the fertilizer effect of nitrates generated in the atmosphere, the fertilizer effect of iron deposited from the supernova and indirect second-order effect of nitrate deposition from lightning, which is itself enhanced by atmospheric ionization. We have found that many of them are too small to be important and others in fact competitive in intensity to ozone depletion.

In this paper we explore the idea that deposition of nitrate on the biosphere from the effects of ionizing radiation from a moderately nearby (50 pc) supernova might provide enough fertilizer effect to cause a drawdown of $CO_2$ and thereby cool the climate, possibly setting off the glaciations typical of the Pleistocene (as well as possibly at the end of the Ordovician). This is interesting because the Plio-Pleistocene transition to an icehouse climate is close to the time indicated by cosmogenic nuclide deposits for one or more nearby supernovae. The production of $NO_2$ results from the ionization and dissociation of molecular nitrogen, the resulting species reacting with oxygen in the atmosphere. The $NO_2$ may react with water or hydroxyl in the atmosphere and is rained out as dilute nitric acid. The chemistry is explored in detail in Mancinelli and Mckay (1988) and Thomas *et al.* (2005).

In recent years there has been a surge of evidence for moderately nearby supernovae within the last few My (Binns *et al.*, 2016; Fimiani *et al.*, 2016; Ludwig *et al.*, 2016; Melott, 2016; Wallner *et al.*, 2016). Recent assessments (Fry *et al.*, 2016; Mamajek, 2016) have favoured distances close to the 40 pc proposed by Benítez *et al.* (1999). Recent studies of the effects upon the Earth of such an event have included enhanced solar ultraviolet-B (UVB 280–315 nm) due to ozone depletion, visible light effects on nocturnal organisms, increased radiation from cosmic ray secondaries (primarily muons and neutrons) and direct deposition of cosmogenic radioisotopes (Melott *et al.*, 2017; Melott and Thomas, 2018; Thomas, 2018; Melott *et al.*, 2019).

Most biota (in the absence of humans) are nitrate-starved (Schlesinger and Bernhardt, 2013) and thus it is interesting to consider the possible effects of nitrate deposition as a side effect of astrophysical radiation enhancements. Previous assessments have suggested a small effect (Melott, 2005; Thomas and Honeyman, 2008; Neuenswander and Melott, 2015), but the longer duration of the effect of cosmic rays compared with the earlier burst situations provides an opportunity for a significant effect. Melott *et al.* (2017) and Thomas *et al.* (2016) showed that the effect of prompt ionizing photons from a supernova at 50 pc

© The Author(s), 2020. Published by Cambridge University Press

CAMBRIDGE UNIVERSITY PRESS

or more is quite small, three orders of magnitude lower than the threshold for major environmental effects. Therefore, the focus is on the extended cosmic ray flux.

## Nitrate as a possible initiator of $CO_2$ drawdown

Nitrate fertilization leading to $CO_2$ drawdown reduced greenhouse effect and subsequent climate cooling is not a new idea. First, terrestrial carbon uptake can easily alter atmospheric $CO_2$ levels (Le Quere *et al.*, 2015; Keenan *et al.*, 2016). Such carbon uptake is stimulated by the deposition of additional nitrate from the atmosphere on land (Thomas *et al.*, 2009) and in the oceans (Ganeshram *et al.*, 1995). Nitrogen isotope changes have been documented at the Plio-Pleistocene Transition (Oesch 2016) and a fertilizer-based $CO_2$ drawdown has been blamed for the late Ordovician glaciation (Shen *et al.*, 2018). The long duration of cosmic ray exposure from one or more supernovae at 50–100 pc motivates a re-examination of this effect, particularly since the Plio-Pleistocene cooling was accompanied by a $CO_2$ drawdown (Bartoli *et al.*, 2011). This has been presented as a cause for the transition from woodland to savannah in Africa (Cawthra, 2019) and this in turn for megaherbivore extinctions in the same area (Faith *et al.*, 2018).

## Production and deposition of nitrate from supernova enhanced cosmic ray flux

Atmospheric ionization caused by cosmic rays leads to the formation of nitrogen oxides, which catalytically deplete ozone and are removed from the atmosphere as $HNO_3$. This leads to the deposition of $NO_3^-$ (Thomas *et al.*, 2005). Any event that creates significant ionization of the atmosphere will cause both ozone depletion and deposition of $NO_3^-$. These production and removal processes will persist as long as the enhanced cosmic ray flux is incident on the atmosphere.

Modelling of the atmospheric chemistry effects following a nearby supernova (Melott *et al.*, 2017) includes deposition of $HNO_3$ via rain/snow. From these results, we computed a global deposition of about 7.5 Tg N $yr^{-1}$. This is less than 10% of the preindustrial deposition of order 85 Tg $yr^{-1}$ (Schlesinger and Bernhardt, 2013, p. 453). We conclude that the effect is likely to be small, although it might be greater if an increase in lightning were caused by the increased atmospheric ionization – a possibility discussed later in this paper.

## Iron deposition – a possible additional fertilizer effect?

Iron is also a fertilizer and increased iron deposition has been hypothesized as a forcing agent for terrestrial climate and also linked to the late-Ordovician cooling (Reiners and Turchyn, 2018). Iron can also act as a reducing agent for nitrates, converting them to ammonia, a more available source of nitrogen (Summers and Chang, 1993). In this context, we evaluate the deposition of iron, one of the major outputs of element synthesis in supernovae. Consider a supernova exploding at distance $r$ and isotropically ejecting a mass $M_{Fe}$ of iron. The resulting surface density of iron on Earth will be (Ellis *et al.*, 1996)

$$\Sigma = \frac{1}{4}\frac{f_{\rm dust} M_{\rm Fe}/m}{4\pi r^2} = 0.03 \ \ \mu{\rm mol\ m^{-2}} \ \ f_{\rm dust}\left(\frac{M_{\rm Fe}}{0.1\ M_\Theta}\right)\left(\frac{50\ pc}{r}\right)^2$$

which corresponds to $9 \times 10^8$ g globally. Here $m$ is the mass of an iron atom and the factor of ¼ is the ratio of the Earth's cross-section to the surface area. The factor $f_{\rm dust} \leq 1$ accounts for the fact that at the distances of interest, only the iron that is sequestered into dust particles will traverse deeply enough into the inner solar system to arrive at Earth (Athanassiadou and Fields 2011; Benitez *et al.*, 1999; Fry *et al.*, 2016). This signal is stretched over timescales of $\Delta t = 1$ *Myr* or more (Ludwig *et al.*, 2016; Wallner *et al.*, 2016), so the average flux from the supernova is $3 \times 10^{-14}$ mol $m^{-2}$ $yr^{-1}$, or about $1.7 \times 10^{-12}$ g $m^{-2}$ $yr^{-1}$. Clearly, this is a tiny amount. The terrestrial flux today is about $10^{-3}$ g $m^{-2}$ $yr^{-1}$, of which no more than half is due to modern anthropogenic sources (Duce and Tindale, 1991; Hamilton *et al.*, 2020). Indeed, the smallness of the supernova signal motivated a focus on live radioisotopes such as $^{60}$Fe in order to remove the terrestrial background (Ellis *et al.*, 1996).

There are substantial uncertainties in the supernova distance, ejecta isotropy, iron yield and dust fraction, at least factors of two and potentially an order of magnitude each. Even allowing for enormous favourable variations in these parameters, it is clear that the infall flux on Earth is minutely small. For comparison, the total influx of iron from extraterrestrial (and mostly interplanetary) dust onto the Earth today amounts to 0.35 $\mu$mol $m^{-2}$ $yr^{-1}$. We see that a supernova contributes a negligible fraction even of the extraterrestrial iron flux on Earth, let alone the other bioavailable iron sources. Thus, the supernova ejecta deposition will have no significant fertilizer effect.

## Ozone depletion and UVB increase – a competing effect

Cosmic ray flux from a nearby supernova leads to depletion of stratospheric ozone, which results in increased penetration of solar UVB radiation to Earth's surface and into the upper part of the ocean. UVB is known to have harmful effects on most organisms and primary producers are especially vulnerable (Llabres *et al.*, 2013; Peng *et al.*, 2017; Benca *et al.*, 2018).

Atmospheric chemistry modelling of the supernova case considered here (Melott *et al.*, 2017; Thomas, 2018) show a globally averaged reduction of ozone of about 25%. Calculations of the increase in surface-level UVB and subsequent biological impacts (Thomas, 2018) show a reduction in photosynthesis by marine phytoplankton ranging from a few per cent to around 40%. The larger values are seen for only one biological weighting function quantifying the effects on an Antarctic phytoplankton community; two other phytoplankton inhibition weighting functions show a reduction of a few per cent to around 10%. For a case with ozone depletion significantly higher than that considered here, Neale and Thomas (2016) found only a few per cent reductions in photosynthesis for two of the most abundant, globally distributed, marine phytoplankton species.

Therefore, while the reduction in primary productivity is a likely result of a nearby supernova and would reduce the $CO_2$ drawdown effect, the impact is likely to be small.

## Muon irradiation – an additional competing effect

Cosmic ray primaries generate a shower of muons, which normally constitute a substantial fraction of irradiation at the surface. In Melott *et al.* (2017) we showed that the muon dose at the surface will reach a level of about fifteen times the total irradiation from all sources within 100 years and remain above this normal

https://doi.org/10.1017/S1473550420000117 Published online by Cambridge University Press

background for thousands of years. If we add in the cosmic ray trapping effect of the magnetic field in the walls of the Local Bubble and/or multiple supernovae (Breitschwerdt *et al.*, 2016) the duration of the effect may be greater. Muon irradiation has the additional effect of affecting life up to a kilometre below the surface of the ocean (Melott and Thomas, 2018; Melott *et al.*, 2019). Nevertheless, only a small increase in mutation and carcinogenesis is expected for phytoplankton, although the effect may be large for megafauna (Melott *et al.*, 2019). We conclude that muon irradiation is a small competing effect with regard to atmospheric chemistry.

## Lightning and nitrate – a possible dominant contributor

We have previously argued (Melott and Thomas, 2019) that the large increase in atmospheric ionization (estimated as a factor of 50 in the lower troposphere) is likely to cause a major increase in the frequency of lightning. In Melott and Thomas (2019) we suggested a possible linkage to fires and tree cover changes, especially relevant for hominins in northeast Africa. In pre-industrial times, lightning is the main contributor to the fixing of atmospheric nitrogen, mostly in the form of oxides of nitrogen, which are mostly rained out as nitrate ion (Schlesinger and Bernhardt, 2013). Therefore, if there is a large increase in lightning, there should be a large increase in nitrate flux as well. Our results, which so far suggest a small effect, of the order of 10%, could change completely. If the lightning enhancement is as large as suggested in Melott and Thomas (2019), this would be overwhelming. We cannot, however, estimate the magnitude of this effect, since there are large uncertainties in the mechanism of lighting and its connection to high energy cosmic rays.

A major increase in lightning would cause a drawdown of CO2 and thereby cool the climate, helping to provide an explanation for the ongoing cooling over the Pliocene and Pleistocene. The additional flux of nitrate combined with lightning-initiated fires would enhance the transition to grasslands, as argued in Melott and Thomas (2019). More research is needed to make clear the connection between lightning and cosmic ray initiated atmospheric ionization.

## Conclusions

We conclude that the fertilizer effect of nitrate deposition is likely to be small, of order 10%, for the Plio-Peistocene supernovae at a distance of 50–100 pc. The additional effect of fertilization by iron-bearing dust is of orders of magnitude smaller. The inhibiting effects of damaging muon irradiation and UVB from ozone depletion are likely to go in the opposite direction, inhibiting photosynthesis. Therefore, for moderately nearby supernovae such as those indicated near the Plio-Pleistocene transition, it appears that no large effect is likely.

Lightning is the dominant pre-industrial source of nitrate deposition. These conclusions change completely if the high level of atmospheric ionization induces a large increase in lightning, which would cause a large increase in nitrate flux, overwhelming the other competing effects. This would enhance $CO_2$ drawdown, cooling the climate. More research is needed to clarify the cosmic ray-lightning connection. The greatest uncertainty in this assessment is the only partially understood mechanism of the initiation and propagation of lightning and the extent of the increase in lightning, which would be caused by increased atmospheric ionization.

**Acknowledgements.** We thank the referee, Dr Rocco Mancinelli, for comments which greatly improved the presentation of this manuscript.

## References

**Athanassiadou T and Fields BD** (2011) Penetration of nearby supernova dust in the inner solar system. *New Astronomy* **16**, 229.

**Bartoli G, Honisch B and Zeebe RE** (2011) Atmospheric $CO_2$ decline during the Pliocene intensification of Northern Hemisphere glaciations. *Paleoceanography and Paleoclimatology* **26**, PA4213.

**Benca JP, Duijnstee IAP and Looy CV** (2018) UV-B-induced forest sterility: implications of ozone shield failure in Earth's largest extinction. *Science Advances* **4**, e1700618.

**Benítez N, Maíz-Apellániz J and Canelles M** (1999) Evidence for nearby supernova explosions. *Physical Review Letters* **88**, 08110101.

**Binns WR, Israel MH and Christian ER** (2016) Observation of the $^{60}$Fe nucleosynthesis-clock isotope in galactic cosmic rays. *Science* **352**, 677.

**Breitschwerdt D, Feige J, Schulreich MM, de Avillez MA, Dettbarn C and Fuchs B** (2016) Unveiling recent supernovae near Earth by modeling $^{60}$Fe transport onto the deep sea crust. *Nature* **532**, 73–76.

**Cawthra H** (2019) Emergence of the African savannah. *Nature Geoscience* **12**, 588.

**Duce RA, Tindale and Neil W** (1991) Atmospheric transport of iron and its deposition in the ocean. *Limnology and Oceanography* **36**, 1715.

**Ellis J, Fields BD and Schramm DN** (1996) Geological isotope anomalies as signatures of nearby supernovae. *Astrophysical Journal* **470**, 1227.

**Faith JT, Rowan J, Du A and Koch PL** (2018) Plio-Pleistocene decline of African megaherbivores: no evidence for ancient hominin impacts. *Science* **362**, 938.

**Fimiani L, Cook DL, Faestermann T, Gómez-Guzmán JM, Hain K, Herzog G, Knie K, Korschinek G, Ludwig P, Park J, Reedy RC and Rugel G** (2016) Interstellar $^{60}$Fe on the surface of the moon. *Physical Review Letters* **116**, 151104.

**Fry BJ, Fields BD and Ellis JR** (2016) Radioactive iron rain: transporting $^{60}$Fe in supernova dust to the ocean floor. *Astrophysical Journal* **828**, 48.

**Ganeshram RS, Pedersen TF, Calvert SE and Murray JW** (1995) Large changes in ocean nutrient inventories from glacial to interglacial periods. *Nature* **376**, 755.

**Hamilton DS, Moore JK, Arneth A, Bond TC, Carslaw KS, Hantson S, Ito A, Kaplan JO, Lindsay K, Nieradzik L, Rathod SD, Scanza RA and Mahowald NM** (2020) Impact of changes to the atmospheric soluble iron deposition flux on ocean biogeochemical cycles in the Anthropocene. *Global Biogeochemical Cycles* **34**, e2019GB006448.

**Keenan TF, Prentice IC and Canadell JG** (2016) Recent pause in the growth rate of atmospheric $CO_2$ due to enhanced terrestrial carbon uptake. *Nature Communications* **7**, 13428.

**Le Quere C, Moriarty R, Andrew RM, Canadell JG, Sitch S, Korsbakken JI, Friedlingstein P, Peters GP, Andres RJ, Boden TA, Houghton RA, House JI, Keeling RF, Tans P, Arneth A, Bakker DCE, Barbero L, Bopp L, Chang J, Chevallier F, Chini LP, Ciais P, Fader M, Feely RA, Gkritzalis T, Harris I, Hauck J, Ilyina T, Jain AK, Kato E, Kitidis V, Klein Goldewijk K, Koven C, Landschutzer P, Lauvset SK, Lefevre N, Lenton A, Lima ID, Metzl N, Millero F, Munro DR, Murata A, Nabel JEMS, Nakaoka S, Nojiri Y, O'Brien K, Olsen A, Ono T, Perez FF, Pfeil B, Pierrot D, Poulter B, Rehder G, Rodenbeck C, Saito S, Schuster U, Schwinger J, Seferian R, Steinhoff T, Stocker BD, Sutton AJ, Takahashi T, Tilbrook B, van der Laan-Luijkx IT, van der Werf GR, van Heuven S, Vandemark D, Viovy N, Wiltshire A, Zaehle S and Zeng N** (2015) Global Carbon Budget. *Earth System Science Data* **7**, 349.

**Llabrés M, Agusti S and Fernandez M** (2013) Impact of elevated UVB radiation on marine biota: a meta-analysis. *Global Ecology and Biogeography* **22**, 131.

**Ludwig P, Bishop S, Egli R., Chernenko V, Deneva B, Faestermann T, Famulok N., Fimiani L, Gomez-Guzman JM, Hain K, Korschinek G, Hanzlik M, Merchel S and Rugel G** (2016) Time-resolved 2-million-year-old supernova activity discovered in Earth's microfossil record. *Proceedings of the National Academy of Sciences USA* **113**, 9232.

https://doi.org/10.1017/S1473550420000117 Published online by Cambridge University Press

**Mamajek EE** (2016) A Pre-Gaia Census of Nearby Stellar Groups. in Proceedings of IAU Symposium 314, Young Stars & Planets Near the Sun, ed. J. H. Kastner, B. Stelzer, & S. A. Metchev (Cambridge: Cambridge Univ. Press), p. 21. https://doi.org/10.1017/S1743921315006250

**Mancinelli RL and McKay CP** (1988) Evolution of Nitrogen Cycling. *Origins of Life* **18**, 311–325.

**Melott AL, Thomas BC, Hogan DP, Ejzak LM and Jackman CH** (2005) Climatic and biogeochemical effects of a galactic gamma-ray burst. *Geophysical Research Letters* **32**, L14808.

**Melott AL** (2016) Supernovae in the Neighbourhood. *Nature* **532**, 40.

**Melott AL and Thomas BC** (2018) Terrestrial effects of moderately nearby supernovae. *Lethaia* **51**, 325.

**Melott AL and Thomas BC** (2019) From cosmic explosions to terrestrial fires? *Journal of Geology* **127**, 475–481.

**Melott AL, Thomas BC, Kachelries M, Semikoz DV and Overholt AC** (2017) A supernova at 50 pc: effects on the earth's atmosphere and biota. *Astrophysical Journal* **840**, 105.

**Melott AL, Marinho F and Paulucci L** (2019) Muon radiation dose and marine megafaunal extinction at the end-pliocene supernova. *Astrobiology* **19**, 825–830.

**Neale JP and Thomas BC** (2016) Solar irradiance changes and phytoplankton productivity in earth's ocean following astrophysical ionizing radiation events. *Astrobiology* **16**, 245.

**Neuenswander B and Melott AL** (2015) Nitrate deposition following an astrophysical ionizing radiation event. *Advances in Space Research* **55**, 2946.

**Oesch LE** (2016) Nitrogen isotope changes in the equatorial Atlantic during the Plio-Pleistocene Transition. 14th *Swiss Geoscience Meeting*, Geneva.

**Peng S, Liao H, Zhou T and Peng S** (2017) Effects of UVB radiation on freshwater biota: a meta-analysis. *Global Ecology and Biogeography* **26**, 500.

**Reiners PW and Turchyn AV** (2018) Extraterrestrial dust, the marine lithologic record, and global biogeochemical cycles. *Geology* **46**, 863. https://doi.org/10.1130/G45040.1.

**Schlesinger WH and Bernhardt ES** (2013) *Biogeochemistry*. Waltham, MA, USA: Academic Press.

**Shen J, Pearson A, Henkes GA, Zhang YG and Chen K** (2018) Improved efficiency of the biological pump as a trigger for the Late Ordovician glaciation. *Nature Geoscience* **11**, 510.

**Summers D and Chang S** (1993) Prebiotic ammonia from reduction of nitrite by iron (II) on the early earth. *Nature* **365**, 630.

**Thomas BC** (2018) Photobiological effects at earth's surface following a 50 pc supernova. *Astrobiology* **18**, 481.

**Thomas BC and Honeyman MD** (2008) Amphibian nitrate stress as an additional terrestrial threat from astrophysical ionizing radiation events? *Astrobiology* **8**, 731.

**Thomas BC, Melott AL, Jackman CH, Laird CM, Medvedev MV, Stolarski RS, Gehrels N, Cannizzo JK, Hogan DP and Ejzak JM** (2005) Gamma-ray bursts and the earth: exploration of atmospheric, biological, climatic, and biogeochemical effects. *Astrophysical Journal* **634**, 509.

**Thomas RQ, Canham CD and Weathers KC** (2009) Increased tree carbon storage in response to nitrogen deposition in the US. *Nature Geoscience* **3**, 13.

**Thomas BC, Engler EE, Kachelreis M, Melott AL, Overholt AC and Semikoz DV** (2016) Terrestrial effects of nearby supernovae in the early Pleistocene. *Astrophysical Journal Letters* **826**, L3.

**Wallner A, Feige J, Kinoshita N, Paul M, Fifield LK, Golser R, Honda M, Linnemann U, Matsuzaki H, Merchel S, Rugel G, Tims SG, Steier P, Yamagata T and Winkler SR** (2016) Recent near-Earth supernovae probed by global deposition of interstellar radioactive $^{60}$Fe. *Nature* **532**, 69.

https://doi.org/10.1017/S1473550420000117 Published online by Cambridge University Press