Astro2020 Science White Paper

Near-Earth Supernova Explosions: Evidence, Implications, and Opportunities

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Executive Summary

There is now solid experimental evidence of at least one supernova explosion within 100 pc of Earth within the last few million years, from measurements of the short-lived isotope ^{60}Fe in widespread deep-ocean samples, as well as in the lunar regolith and cosmic rays. This is the first established example of a specific dated astrophysical event outside the Solar System having a measurable impact on the Earth, offering new probes of stellar evolution, nuclear astrophysics, the astrophysics of the solar neighborhood, cosmic-ray sources and acceleration, multi-messenger astronomy, and astrobiology. Interdisciplinary connections reach broadly to include heliophysics, geology, and evolutionary biology. Objectives for the future include pinning down the nature and location of the established near-Earth supernova explosions, seeking evidence for others, and searching for other short-lived isotopes such as ^{26}Al and ^{244}Pu. **The unique information provided by geological and lunar detections of radioactive ^{60}Fe to assess nearby supernova explosions make now a compelling time for the astronomy community to advocate for supporting multi-disciplinary, cross-cutting research programs.**

Geological and Lunar Detections of Radioactive Iron-60 as Evidence for Near-Earth Supernovae

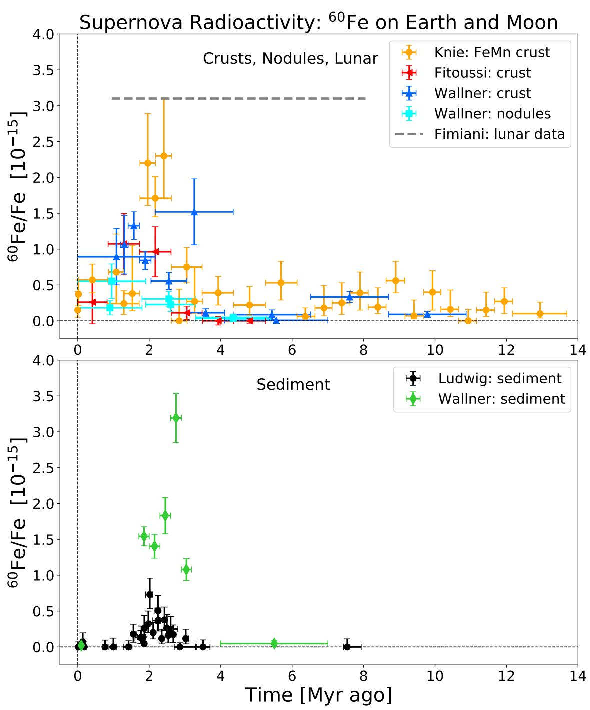

Figure 1: Global and lunar detections of ^{60}Fe, not corrected for decay. All data show a signal around ∼2–3 Myr. Amplitude differences may reflect iron uptake variations, or latitude variations in iron fallout. *Upper panel:* ^{60}Fe/Fe ratios in deep-ocean Fe-Mn crusts. *Lower panel:* ^{60}Fe/Fe in deep-ocean sediments, showing signal duration $\gtrsim 1$ Myr. Data: refs. [40, 23, 70, 22, 46].

Near-Earth supernovae are inevitable. Supernovae explode in our Milky Way roughly every ~ 30 yr on average [15, 2]. This suggests that within the past billion years, one or more supernovae may have exploded ≤ 10 pc of the Earth, with drastic effects on the biosphere, possibly producing a mass extinction [60, 58, 33, 41]. Alvarez et al. [3] hypothesized that such a nearby supernova explosion would have deposited a detectable live (not decayed) radioisotope layer on Earth. Searching for it, they found the iridium layer near the K/Pg boundary, associated instead with a bolide impact responsible for the demise of the dinosaurs.

Analogously, supernova explosions within 100 pc of Earth are expected to have occurred every few Myr. The Local Bubble surrounding the Sun implies nearby events within 2 Myr [24]. These would probably not have caused a mass extinction, but may have perturbed the biosphere and left a detectable radioisotope signature. Ref. [17] suggested several possible radioisotope signatures of such a supernova, including ^{60}Fe (see also ref. [42]).

Using the spectacular sensitivity of accelerator mass spectrometry (AMS), a layer of ^{60}Fe (half-life 2.6 Myr) was discovered in a ferromanganese (FeMn) crust sample from the Pacific Ocean floor [39], and confirmed with a different FeMn crust from elsewhere in the Pacific [40]. Subsequent FeMn crust measurements further confirmed these pioneering results [23]. A first series of sediment samples from North Atlantic revealed an $^{60}\mathrm{Fe}$ peak, but required a much longer deposition time (> 0.4 Myr) than naively expected for supernovae [23]. This was later confirmed in Indian Ocean sediment samples [19]. Ref. [70] also found an ^{60}Fe signal in different Fe-Mn crusts and nodules, as well as in several deep-ocean sediments. Moreover, ref. [46] detected ^{60}Fe in iron-bearing microfossils found in deep-ocean sediments. All sediment data reveal deposition timescales $\gtrsim 1$ Myr.

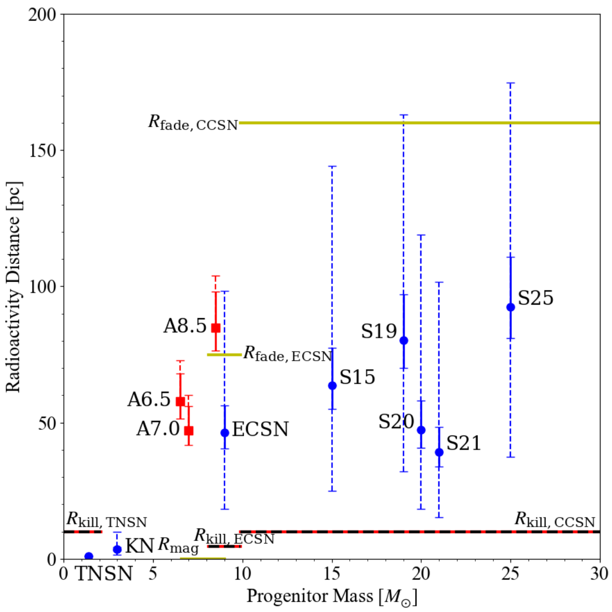

Figure 2: Distances to ^{60}Fe sources estimated from ^{60}Fe data and yields from progenitor models of various masses [28]. Distance $D \propto \sqrt{M_{\mathrm{ej},60}/\mathcal{F}_{60}}$ from the inverse square law assuming: (1) each source spreads its ^{60}Fe ejecta of mass $M_{\mathrm{ej},60}$ isotropically, and (2) these lead to the observed deep-ocean ^{60}Fe decay-corrected fluence $\mathcal{F}_{60}$. The horizontal lines bound possible distances: lower limit is the "kill radius" and excludes Type Ia or thermonuclear supernovae (TNSN) and kilonovae (KN). Upper limit is where supernova remnant fades and fails to deliver ^{60}Fe to Earth. The allowed sources based on distance are AGB stars (red, denoted A) and core-collapse supernovae (blue, denoted S). Of these only core-collapse events are likely to deliver the ^{60}Fe to Earth; a wide range of masses are allowed, with distances $D_{\mathrm{SN}} \sim 30 - 150$ pc.

The time series of these ^{60}Fe measurements are shown in Fig. 1. There is a clear peak at 2 to 3 Myr ago, pointing to at least one nearby supernova at that epoch. Also, there are hints of a second peak around 8 Myr ago.

In addition to these time-resolved terrestrial data, ref. [22] report an ^{60}Fe excess in undated Apollo return samples of the lunar regolith. This ties in with the discovery of ^{60}Fe in cosmic rays [8], which would require a supernova origin in the last $\sim$ 2.6 Myr within $\sim$ 1 kpc of Earth, based on the ^{60}Fe lifetime and models of cosmic-ray diffusion. This is consistent with studies [37, 59, 38] that used cosmic-ray spectra to argue for an injection of cosmic rays by a supernova occurring $\sim$ 2 Myr ago.

Interpretation

The production site of the observed ^{60}Fe signal must have been a core-collapse supernova (CCSN). For any given ^{60}Fe nucleosynthesis source, supernova or other, one can use the measured fluence to estimate the distance to the progenitor. Fig. 2 shows the result of one such analysis [28] that used models with a variety of progenitor masses for supernovae, but also considered ^{60}Fe production in AGB stars, Type Ia (thermonuclear) supernovae, and kilonovae. The last two are ruled out by the implausibly and dangerously small distance required by their small ^{60}Fe yields. AGB stars do exist at the allowed distances, but it is unlikely ^{60}Fe from AGB winds could reach Earth prior to decay. CCSN emerge as the only viable candidates, and Fig. 2 shows CCSN models suggest a distance ~ 100 pc, reassuringly beyond the possible 'kill radius' for a mass extinction, but still close enough to possibly affect the biosphere [67, 51]. We note in this connection the existence of young nearby pulsars that might be candidates for its compact remnant [66].

The firm ^{60}Fe detection at $2-3$ Myr and possible additional signal at ~ 8 Myr is consistent with the Sun's being surrounded by the Local Bubble, the low-density, high-temperature region that is thought to arise from a number of recent nearby supernova explosions. The Local Bubble model of ref. [9] is compatible not only with terrestrial and lunar detections of ^{60}Fe [61], but also with two soft X-ray emitting cavities present in the dust distribution of the local interstellar medium, matching the sites of the two most recent supernova explosions in their model with respect to both distance and direction: see refs. [10, 62].

Ref. [17] suggested several other radioisotopes besides ^{60}Fe as possible signatures of a nearby supernova. Of these, ^{26}Al (half-life 0.73 Myr) and ^{244}Pu (half-life 81 Myr) have been the subjects of AMS searches in deep-ocean samples. Recent ^{26}Al data are, however, compatible with terrigenic production, which could point to low supernova yields [20] or to differences in Fe-bearing vs Al-bearing supernova dust [28]. Intriguingly, ref. [69] found ^{244}Pu in the same crusts as the ^{60}Fe detections, but the results lie far below what one would expect from continuous production in the Galaxy. This suggests that plutonium sources are rare, so that a steady-state equilibrium is not achieved over the ^{244}Pu lifetime. Rather, ^{244}Pu sources are few and far between, likely being neutron-star mergers [1]. It remains, however, a critical test to probe more sensitively the ^{244}Pu signal *contemporary* with the ^{60}Fe which will test whether the recent near-Earth event(s) included r-process production. Confirming that some supernovae produce *r*-process elements [12, 6], and quantifying the yields would provide a major new probe of supernova explosion physics and nucleosynthesis.

An important issue in interpreting terrestrial signatures of a nearby supernova is modeling radioisotope transport from the source to an ocean floor. Transport through the interstellar medium is thought to be via dust particles, which will also interact with their natal supernova remnant and possibly interstellar material. Important questions are the duration of this process, and whether the arrival directions of the dust particles are correlated with the direction of the source. The latter seems unlikely [30], but could be tested with the lunar distribution of radioisotopes. On Earth, atmospheric and oceanic effects are expected to destroy any information on the source latitude and may cause variations in the density of deposition on the Earth's surface, concentrating ^{60}Fe in certain areas of the ocean floor.

Possible Biological Effects

The spectacular optical display of a nearby supernova would not be very dangerous to life if the explosion is ~ 100 pc away. The outburst would also bring higher-energy ionizing radiation, including extreme UV, X-rays and gamma rays, yet even these are not catastrophically harmful from ~ 100 pc. However, charged cosmic rays would arrive later with the supernova blast that accelerates them, and linger for many thousands of years. They would deplete the Earth's ozone layer, which would in turn allow more solar UVB radiation to reach the Earth's surface and upper ocean layers for an extended period [16, 52]. Increases in ionizing radiation can damage DNA, harm tissues in animals, and degrade photosynthesis in plants. Penetrating cosmic-ray muons may also be a hazard, as well as other effects of increased atmospheric ionization by cosmic rays [51, 50, 53]. However, no 'smoking gun' effect of a supernova at ~ 100 pc on the Earth's biosphere has yet been identified. A supernova at 10 pc would surely be very dangerous for the biosphere, but a distinctive signature remains to be found in the geological record.

Outlook: Interdisciplinary Opportunities for the Coming Decade

Following the large infusion of new data in 2016, this field has evolved from speculation and pioneering results to becoming a growing science, ripe with opportunity for surprise and discovery. It has become a *bona fide* part of astrophysics, which is akin to and has many links with meteoritic studies, particularly studies of extinct radioactivities in meteorites [54, 5] and pre-solar grains that seek to identify nucleosynthesis products from individual events [11].

Supernova Astrophysics: Detection of or strong limits on other radioisotopes will be particularly useful in identifying the progenitor and potentially its non-isotropic element production and dispersal. Detection of *r*-process species would offer the first concrete evidence that supernovae produce these species. Detection of the third-peak element $^{244}\mathrm{Pu}$ would require a major revision of our current picture of the physics in typical core-collapse events.

Cosmic Dust: At distances $\gtrsim 10~\mathrm{pc}$, the supernova blast does not reach within 1 AU, instead radioactive debris rains on Earth in the form of dust [7, 4]. The existing detection of $^{60}\mathrm{Fe}$, and future detections or limits to other radioisotopes, thus directly probe the formation and evolution of supernova dust. This provides new insight into critical questions about the formation and distribution of dust in our Galaxy as well as supernovae at high redshift [57, 32].

Nuclear Astrophysics: The terrestrial detection of supernova debris offers a new laboratory probe of element formation in the cosmos. It is complementary to other aspects of astronomy with radioactivities, particularly gamma-line telescopes that have detected $^{60}\mathrm{Fe}$ [71, 14] and mapped $^{26}\mathrm{Al}$ [15] in our Galaxy (see MeV line White Paper [31]), and the growing field of multi-messenger studies of kilonovae. In particular, it casts direct experimental light on galactic nucleosynthesis, demonstrating the role of supernovae in making specific isotopes [68, 43, 65].

Cosmic-Ray Astrophysics: Local supernovae have been suggested as explanation for spectral anomalies [37, 59, 38] and $^{60}\mathrm{Fe}$ detections [8] in cosmic rays. Cosmic-ray disturbance of the biosphere and atmosphere can lead to damage [51, 52] or even benefits [40, 18]. Detailed study of cosmic rays inside the Local Bubble and heliosphere will be an important to test this scenario.

Solar Neighborhood: Our Galactic environment depends on the frequency of nearby supernovae. The recent explosion(s) subject models of the Local Bubble to new experimental constraints [27, 9, 26]. Also, because stars are generally born in clusters, there is the opportunity to identify the natal cluster of the $^{60}\mathrm{Fe}$ supernova(e). Candidates include the Scorpius-Centaurus association ($\sim 120~\mathrm{pc}$ away 3 Myr ago [7]) and the Tucana-Horlogium association ($\sim 50~\mathrm{pc}$ away [48]), and others [36, 64].

Solar System Formation: Live radioactivities are known to have been present at the formation of the Solar System, likely implying a nearby supernova [54, 5]. The commonalities between early-Solar and recent nearby supernova studies merit further exploration and connection [45, 35].

Heliophysics: The confirmation of at least one supernova $\sim 2 - 3~\mathrm{Myr}$ ago provides a unique opportunity to study the heliosphere under conditions dramatically different from the present [21, 26]. Supernova-driven shocks and radiation bursts play pivotal roles in regulating the diffuse interstellar material around the heliosphere and nearby planetary systems. Interstellar ram pressure determines the dimensions of astrospheres [25] and the heliosphere [56], and so the supernova evolution sets the duration and closest approach of the blast. Neutral interstellar atoms penetrate the heliosphere and mass-load the solar wind, see refs. [13, 49], modulating the cosmic-ray flux at Earth [56] and regulating the boundary conditions of the heliosphere [63].

Astrobiology and Planetary Science: Data on terrestrial effects of the recent explosion(s) calibrates the impact of supernovae on the biosphere, informing studies of a supernova-induced mass extinctions. More generally, studies of the location and frequency of supernovae can cast light on which Milky Way regions are suitable for life–the Galactic Habitable Zone [44, 34, 55].

Beyond Astronomy: Across the Sciences. Near-Earth supernovae studies interweave disparate sciences, including the following. *Nuclear Physics:* This area of research has proven to be a novel and fruitful application of accelerator mass spectrometry (AMS) and its exquisite sensitivity (now pushing to levels of $^{60}\mathrm{Fe}/\mathrm{Fe} \sim 3 \times 10^{-17}$). It is therefore encouraging that the pioneering AMS work by the Munich groups has recently been joined in these studies by a group using an AMS facility in Australia. *Geology:* Geochronological and geochemical studies are crucial for testing the atmospheric and climatic and even biological impact of the event. The established existence of supernova(e) at the early Pleistocene offers a unique opportunity to study the Earth's response to such a perturbation.

Open Questions and Future Research: There are many open questions that provide opportunities for future research. What other radioisotopes were deposited on the Earth and Moon, and what do these imply for supernova physics and supernova dust? Can the type of supernova responsible for the event ~ 2.5 Myr ago be identified, including the mass of its progenitor and the likely nature of its ejecta? Can the location of the progenitor be identified, and could one even imagine identifying its remnant? Can one link this supernova to features in the Local Bubble? Were there other nearby supernovae within the past few million years? Can a link be established between any supernova event and some specific perturbation of the biosphere?

Enabling Discovery

The time is therefore ripe to answer these questions through the combined efforts of the astrophysics community and the other disciplines embraced by near-Earth supernova studies.

• **First and foremost, we call for funding agencies to provide mechanisms to support cross-cutting research of this kind.** We emphasize our experience that the novelty and interdisciplinarity of this subject are great strengths, but pose challenges to funding within particular disciplines (e.g., "too geological for astrophysics, too astrophysical for geology").

• **We call for support of theoretical explorations of the astrophysical aspects of this problem**, as individual areas of study and in integrated syntheses. These include supernova nucleosynthesis, supernova dust formation, propagation and evolution, cosmic-ray injection, acceleration and propagation, and supernova impact on the heliosphere.

• **We call for support of MeV gamma-ray observatories** capable of probing nuclear lines from $^{60}\mathrm{Fe}$, $^{26}\mathrm{Al}$, and other supernova radioisotopes [31].

• **We call for support by astrobiology programs** of studies of the direct and indirect impact of ionizing radiation (photons and cosmic rays) on terrestrial biota, and of consequences for exoplanets and the Galactic habitable zone.

• **We call for support of AMS**, not only to understand better the ^{60}Fe signal but also to measure or constrain additional radioisotopes, including known core-collapse supernova products such as ^{26}Al [20], but also other species probing other nucleosynthesis processes, e.g., ^{182}Hf and ^{244}Pu [69] that are key probes of the *r*-process, as well as other isotopes [47].

• **We call for support of geoscience research in this area.** Geochronologic and geochemical studies of terrestrial archives (e.g., of $^{3}\mathrm{He}$) will help to better constrain the timing/duration of the event(s), as well as test their potential impact on changes in climate and even biological evolution.

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