Near-Earth Supernovae in the Past 10 Myr: Implications for the Heliosphere

Synopsis:
We live in a dynamic star-forming galaxy, and as a result the solar neighborhood changes constantly. One of the most spectacular events that inevitably occurs is the explosion of a supernova near the Earth. Remarkably, a wealth of evidence now shows that at least two supernovae occurred during the past 10 Myr within $\sim 100$ pc of Earth. We summarize these data, most notably the detection of live radioactive $^{60}$Fe in the deep sea, Antarctic snow, and the Moon. Analytic estimates and hydrodynamic simulations show that heliospheric response was dramatic, with the heliopause pushed to $\sim 20$ au.

These supernovae and their impact on the solar system have wide implications beyond heliophysics, including the possibility of damage to Earth’s biosphere, and open a new tool to probe supernova element production and dust evolution. The wide scope of these implications illustrates the close and complementary relationship between heliophysics and other areas of science, and provides a compelling case for a cross-cutting, interdisciplinary research program. This white paper advocates for strengthening cross-disciplinary research on nearby supernova impacts on the heliosphere, interstellar dust, and cosmic rays. We urge for support of investigation via theoretical work, direct exploration of the outer heliosphere and very local interstellar medium, and study of extrasolar astrospheres.
Evidence For Nearby Supernovae in the Past 10 Myr

The environment surrounding the Sun changes constantly in our journey around the Milky Way, and the heliosphere constantly evolves in response. Müller et al. (2006, 2009) demonstrate how the heliosphere’s size depends greatly on its local Galactic environment, largely depending on the density, velocity, and ionization state of the surrounding medium. Recently, Opher & Loeb (2022) simulated the effect of the Sun’s passage through a dense, cold cloud, showing how the heliopause would shrink to a mere 0.22 au and expose the Earth to interstellar material. In this white paper, we focus on the other most dramatic disturbance to the heliosphere: the explosion of a near-Earth supernova.

Supernova explosions mark the deaths of massive stars (Branch & Wheeler, 2017), and launch powerful blast waves that sculpt the interstellar medium (ISM). Nuclear reactions deep in the star before and during its death forge heavy elements, principally species from carbon through the iron peak. The explosion launches these freshly synthesized elements into the surroundings.

How would we know if a supernova exploded near Earth in the geologic past? If the explosion is close enough, supernova debris is delivered to Earth and literally rains down, accumulating in natural archives such as deep-sea sediments. To confirm the supernova origin of such debris, one must look for live (undecayed) radioactivity from species too short-lived to have survived from the birth of the Earth 4.6 Gyr ago (Ellis et al., 1996). Remarkably, such a signal has been found, in the form of live $^{60}$Fe (half-life 2.6 Myr) and $^{244}$Pu (half-life 81 Myr).

Fig. 1 shows the profile of $^{60}$Fe recovered from deep-sea and lunar samples analyzed by several groups (Knie et al., 1999, 2004; Fitoussi et al., 2008; Ludwig et al., 2016; Wallner et al., 2016; Fimiani et al., 2016; Wallner et al., 2021). All measurements agree on the large peak $\sim$ 3 Myr ago. Furthermore, Wallner et al. (2021) indicates the presence of a preceding supernova that exploded around 8 Myr ago, and measured $^{244}$Pu from periods around these peaks.

The $^{60}$Fe found in these terrestrial samples came from a core-collapse or electron-capture supernova, as other extrasolar options (e.g., thermonuclear supernovae or kilonovae) cannot produce sufficient $^{60}$Fe without being close enough to also inflict major biological damage (Fry et al., 2015). While super-asymptotic giant branch (AGB) stars expel $^{60}$Fe in their winds, their velocity is likely too slow to reach the Earth. Based on $^{60}$Fe production rates in supernovae, Fry et al. (2015) estimated the distance to the recent event 3 Myr ago as $D_{SN} \sim 60 - 130$ pc.

Further evidence of $^{60}$Fe has been found in freshly-deposited (< 20 yr) Antarctic snow (Koll et al., 2019), indicating that supernova deris still falls upon the Earth, though at a reduced flux. Besides $^{60}$Fe, other isotopes have been identified as potential tracers of supernova activity. Of these, $^{244}$Pu arrived concurrently with $^{60}$Fe (Wallner et al., 2021), and a claim of elevated $^{53}$Mn has been made (Korschinek et al., 2020).

Beyond these radioisotope deposits, cosmic ray measurements suggest recent nearby supernovae. Binns et al. (2016) measured $^{60}$Fe in cosmic rays and inferred it must have been present at the source, thus pointing to a recent and nearby event. Measurements of anomalous Fe cosmic rays at low energies (Boschini et al., 2021) and high-energy positrons and antiprotons (Savchenko et al., 2015; Kachelrieß et al., 2015, 2018) could also point to recent local sources.

Core-collapse supernovae are the end state of massive star evolution. Massive stars are overwhelmingly born in clusters, and are usually in binaries, often with other massive stars (Duchêne & Kraus, 2013; Motte et al., 2018). Thus, we expect nearby supernovae are likely to occur as multiple events, and likely should be associated with massive star clusters. The Wallner et al. (2021)
Figure 1: Evidence for recent near-Earth supernovae: compilation of radioactive $^{60}\text{Fe}$ measurements in the deep sea and lunar regolith, from Ertel et al. (2022). All measurements show a pulse 2–3 Myr ago, and recent data confirm a pulse 6–7 Myr ago. Nonuniform fallout and uptake on Earth are reflected in $^{60}\text{Fe}$ abundance variations.

confirmation of a distinct second $^{60}\text{Fe}$ pulse is thus consistent with expectations for massive star formation.

Indeed, prior to the $^{60}\text{Fe}$ discoveries, evidence for recent nearby supernovae was literally all around us, in the form of the Local Bubble—a cavity of low-density, high-temperature plasma in which the solar system is embedded (Frisch et al., 2011). The Local Bubble has been mapped in gas via UV metal lines (Gry & Jenkins, 2014), optical lines (Welsh et al., 2010) and diffuse X-rays (Galeazzi et al., 2014; Snowden et al., 2015); it has also been mapped in dust via observations of diffuse interstellar bands (Farhang et al., 2019) and interstellar reddening (Lallement et al., 2019). The Local Bubble is irregular in shape, and the boundaries are not precise, but it extends 50 pc or more in all directions. Models of this large, hot cavity have invoked two or more supernovae (e.g., Smith & Cox, 2001; Frisch et al., 2011; Breitschwerdt et al., 2016; Schulreich et al., 2017; Frisch & Dwarkadas, 2017; Zucker et al., 2022). These supernovae likely arose in massive star clusters that may have stars remaining to this day (Maíz-Apellániz, 2001). These are also candidates for the origin of the $^{60}\text{Fe}$, and include the Scorpius-Centaurus Association at $\sim$ 130 pc (Benítez et al., 2002) and Tucanae-Horologium at $\sim$ 50 pc (Mamajek, 2016). There have been attempts made to identify the $^{60}\text{Fe}$ neutron star with a nearby pulsar, and to associate it kinematically with a potential companion runaway star by tracing back their paths over time to the Sco-Cen Association (Neuhäuser et al., 2020).

The Local Bubble thus sets the gross features of the interstellar environment around the Sun. In
short, we reside in a so-called “superbubble” created by up to $\sim 20$ supernovae (Schulreich et al., 2017). The very local interstellar medium that controls the heliosphere should be understood in this larger context. This means that direct probes of interstellar space immediately beyond the Sun also open a new window into a superbubble interior. Interestingly, the model of Zucker et al. (2022) suggests that the solar system entered the Local Bubble $\sim 5 \text{ Myr}$ ago. This date is uncertain, but is intriguing in light of the earlier $^{60}\text{Fe}$ pulse dating to $\gtrsim 8 \text{ Myr}$ ago; this may probe our entry into the Local Bubble. Moreover, the radioisotope data as well as the astronomical data on the Local Bubble together reveal the recent nearby supernova history of our interstellar neighborhood, and consequently, the extreme environments our solar system has travelled through.

### Implications for the Heliosphere

A near-Earth supernova would dramatically alter the heliosphere for many thousands of years. The full implications of such an event are wide-ranging and many remain to be explored. But the major dynamical effects have begun to come into focus.

A supernova blast creates a powerful forward shock moving at speeds $v_{\text{SN}} \sim 200 - 1000 \text{ km/s}$ depending on the distance to the explosion and the density of the surrounding medium. The blast is supersonic, so that ram pressure dominates over thermal pressure. At a distance $D_{\text{SN}}$ the pressure is roughly

$$P_{\text{SN}} \approx \frac{E_{\text{SN}}}{D_{\text{SN}}^3}$$

(1)

$$\approx 3 \times 10^{-10} \text{ dyne/cm}^2 \left(\frac{50 \text{ pc}}{D_{\text{SN}}}\right)^3$$

(2)

$$\approx P_{\text{SW}}(10 \text{ au}),$$

(3)

where we have used the canonical supernova explosion energy (excluding neutrinos) of $E_{\text{SN}} = 10^{51} \text{ erg}$. This result holds when the supernova remnant (SNR) is in the Sedov-Taylor phase, as is appropriate for our problem. Conveniently, in this phase the pressure is independent of the density of the medium surrounding the explosion: lower densities lead to higher blast speeds that combine to give the same ram pressure.

Eqn. (1) shows that the supernova pressure is $> 100$ times the present-day pressure of the Local ISM, for supernova distances implied by the $^{60}\text{Fe}$ detections. Thus we expect dramatic effects on the heliosphere accompanied these events. Indeed, eqn. (3) shows that in pressure balance, we expect the blast to penetrate to around 10 au!
To date, the only studies of nearby supernova blasts impacting the heliosphere are Fields et al. (2008) and Miller & Fields (2022). These initial simulations explored a wide range of possible supernova blast distances and interstellar distances in order to characterize the compression of the heliosphere. Fig. 2 shows an example of these simulations for a supernova 63 pc away, a plausible distance for the recent supernovae. The supernova blast has speed 541 km/s and flows from the bottom to top of the figure. We see that the arrival of such a supernova creates a heliosphere with the same structures as the modern version (Baranov & Malama, 1993)—termination shock, heliopause, and bow shock—but extremely compressed. In this case, the supernova material reaches $\sim 20$ au, where we see the heliopause. Miller & Fields (2022) showed that the basic geometry and the locations of the features are similar whether the blast is directed towards the Sun’s equator or the poles; we thus expect that the relative orientation of the Sun and supernova is not a major factor in the compression.

Both Fields et al. (2008) and Miller & Fields (2022) found that force balance is the controlling factor determining the heliospheric compression in these simulations. That is, the closest approach of the supernova is set by the balance of the blast pressure with that of the solar wind. Along the symmetry axis, this gives a stagnation radius

$$r_{\text{stag}} = 24 \text{ au} \left( \frac{D_{\text{SN}}}{100 \text{ pc}} \right)^{3/2} \left( \frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)^{-1/2},$$

in good agreement with the numerical simulation results. As in eqn. (1), $D_{\text{SN}}$ is the distance to the supernova, and $E_{\text{SN}}$ is the supernova explosion energy. For a fixed supernova explosion energy, therefore, the most important parameter controlling the heliospheric compression is the distance to the supernova.

The scaling in eqn. (4) holds for purely hydrodynamic simulations. These simulations were simplified, imposing 2D axisymmetry, adopting the hydrodynamics of a one-component fully ionized and unmagnetized plasma, and using a non-varying solar wind. Further study is needed to illuminate the importance of additional physical effects such as magnetic fields, charge exchange, pickup ions and energetic neutral atoms (e.g., Sokół et al., 2019; Sokół et al., 2022), and cosmic ray and dust propagation (see, e.g., Zank, 1999, for

Figure 3: Location of the stagnation radius (ram pressure balance) over time as a supernova remnant evolves, from Miller & Fields (2022). The distances to the supernovae are labelled, and for reference the Kuiper belt is indicated by the gray region.
a review). These effects are significant for the present-day heliosphere, but are wholly unstudied under a supernova blast regime, which could also have novel effects depending on the density of the impacting gas, such as radiative cooling.

While the initial supernova shock front sweeps rapidly across the solar system, the whole supernova remnant compresses the heliosphere for up to $\sim 100$ kyr until it weakens enough for the heliosphere to rebound. Using pressure balance, and following the propagation of a Sedov-Taylor blast, we can calculate the retreat of the stagnation radius after the supernova forward shock engulfs the solar system. Fig. 3 shows the size of the heliosphere over time for supernovae at distances from 50-100 pc. We see that a significant fraction of the solar system is directly exposed to the blast wave for all plausible supernova distances. Even for a supernova 100 pc away, the entire Kuiper belt is exposed.

This analysis assumes the Sun is at rest relative to the supernova remnant. However, including solar motion has significant effects on the gas profile and $^{60}$Fe deposition. Chaikin et al. (2022) shows how the relative motion of the Sun elongates the $^{60}$Fe deposition timescale to a few Myr, even without dust dynamics analyzed in Fry et al. (2020). This work demonstrates how the gradual rebounding of the heliosphere will not be as smooth as the idealized case in Fig. 3.

On the other hand, even for reasonably close supernovae (50 pc), interstellar material does not reach Earth’s orbit. Therefore, the $^{60}$Fe observed in deep sea samples could not have arrived as a plasma, but must have come in the form of dust in order to not be deflected by the heliosphere. Measurements of the $^{60}$Fe pulse show that supernova radioisotopes rained on Earth for a long time, $\gtrsim 1$ Myr. The $^{60}$Fe flux is significantly longer than the gas profile of $\sim 100$ kyr (Ertel et al., 2022, also seen in Fig. 3): $^{60}$Fe-bearing dust must decouple from the gas. Fry et al. (2020) built a model for dust propagation in an evolving supernova remnant that naturally reproduced the 1 Myr timescale. Similarly, Slavin et al. (2020) and Sarangi & Slavin (2022) evolve models of supernova-formed dust with various compositions, though not focusing on $^{60}$Fe. Supernova dust models continue to be relevant for the present heliosphere because of the ongoing infall of $^{60}$Fe-bearing dust today (Koll et al., 2019).

The continued infall of $^{60}$Fe onto Earth today points to the presence of $^{60}$Fe-bearing dust in the very local ISM and its successful propagation to 1 au. This raises questions that link heliophysics and astrophysics and requires further study. Initial models of supernova dust grain propagation into the magnetized solar wind were promising (Athanassiadou & Fields, 2011; Fry et al., 2016), but were simplistic in their treatment of the dust and of the solar wind. A more complete picture of dust transport through the heliosphere is necessary for the last stage of the dust’s journey (Linde & Gombosi, 2000; Mann, 2010). Closely linked are issues of the astrophysics of supernova dust: its production and survival (Andersen et al., 2011; Kirchschlager et al., 2020, 2019; Slavin et al., 2020), and the composition and sizes of $^{60}$Fe-bearing grains (Slavin, 2020; Fry et al., 2015).

In a different approach, Opher & Loeb (2022) simulated the heliosphere in the presence of a cold cloud, showing that the heliosphere could shrink to a paltry 0.22 au. If supernovae had seeded the cloud with $^{60}$Fe, the $^{60}$Fe would not have to be a component of dust in order to reach Earth.

If a supernova explodes too close to our solar system, it would be potentially harmful to life. X-rays and cosmic rays (CRs) weaken the ozone layer, allowing solar UV radiation to cause significant biological damage (Ruderman, 1974; Ellis & Schramm, 1995; Gehrels et al., 2003). The canonical “kill distance” is approximately 8 pc (Gehrels et al., 2003). However, more distant supernovae may also have severe consequences. Fields et al. (2020) postulated that a supernova about $\sim 20$ pc away triggered the mass extinction in the end-Devonian 360 Myr ago. Even at 100
pc, some biological damage may still occur (Thomas et al., 2016; Melott et al., 2018). The time period around 3 Myr ago was a critical period for human evolution, and astronomical factors may have played a role in this process (Melott & Thomas, 2019; Opher & Loeb, 2022).

Looking outwards, supernova remnants also provide an intriguing new interpretation for astrospheres. Currently, surveys have found bow shocks of astrospheres around high-velocity stars (Peri et al., 2012) and in dusty regions like the Galactic plane (Kobulnicky et al., 2016). The observation of astrospheres in SNRs would provide a novel form of stellar-interstellar interaction.

Opportunities for Heliophysics

Motivated by abundant evidence for near-Earth supernova activity, we can re-contextualize many of the present-day heliosphere questions with the supernova-triggered Local Bubble replacing the a generic picture of the local ISM. Of the many questions this raises, some with direct impact on heliophysics are as follows.

**How does supernova-forged dust propagate through the solar system to Earth, and how does this change as the SNR evolves and weakens?** The detection of $^{60}$Fe in modern Antarctic snow (Koll et al., 2019) shows that supernova dust continues to enter the heliosphere and propagate to Earth. The time is ripe for a careful theoretical study of the dust trajectory in the magnetized solar wind, to be tested against experimental searches for supernova-like interstellar dust in the solar system. Such work would be guided by studies of interstellar dust trajectories in the present heliosphere, which reveal a rich dependence on grain size, charge-to-mass ratio, and solar wind polarity (Slavin et al., 2012; Sterken et al., 2012; Alexashov et al., 2016; Krüger et al., 2019). This work is directly relevant for the present-day $^{60}$Fe influx, which is arriving from the Local Interstellar Cloud. But the material at early times is not from this cloud, and would arrive on supernova grains with speeds and properties that could be quite different from the present.

**Given that SNRs produce Galactic cosmic rays, what are the consequences of the injection of freshly accelerated CRs with a different spectrum at the heliosphere boundary?** It is an open question how cosmic rays propagate in the compressed heliosphere, and how this changes as the supernova blast fades. The interplay of the high cosmic ray flux on the solar wind is not known. The particles will have higher energies than at present, and could lead to signatures in natural archives on the Earth. Such explorations will also shed new light on models of CR acceleration in supernovae and their escape into the surrounding medium (Blasi, 2013; Drury, 2011; Vieu et al., 2022; Ellison et al., 2000).

**What signatures of recent near-Earth supernovae persist in the very local interstellar medium surrounding the heliosphere?** What are predictions for in situ measurements of this environment, and how will such data shed light on the heliosphere’s past? Interstellar missions like Voyager and the proposed Interstellar Probe (Brandt et al., 2022; McNutt et al., 2022) will not sample the average Galactic interstellar medium, but a part of the Local Bubble sculpted by the remains of ancient supernovae. Everything within the Local Bubble — including the Local Interstellar Cloud — has been processed by multiple supernova explosions millions of years ago. By examining the interstellar medium untainted by our heliosphere, Interstellar Probe may even contribute to our understanding of how old SNRs evolve and fade away into the Galaxy.

**Beyond $^{60}$Fe-bearing dust, what other effects could supernovae have on Earth and its biosphere?** Could evidence of these traces remain after 3 Myr? The expected high-energy
and high-intensity cosmic-ray flux could lead to traces in the geological record, e.g., in the oldest ice cores and in deep-sea deposits. Such signatures would help to test ideas about biological consequences and biosphere damage. As an extension, it is also interesting to probe the effects of supernovae on the Moon, the outer planets and other bodies that were exposed to the blast.

**What can we learn from observing astrospheres of other stars and comparing with the heliosphere?** Extrasolar astrospheres provide a testbed for stellar wind-ISM collisions under conditions different from our own, testing our understanding and possibly calibrating our models. These may also be probed by studies of the effects of interstellar dust impacting interplanetary dust\(^1\).

**Recommendations**

To realize fully the wide scientific opportunities we have outlined requires a wide range of experimental, observational, and theoretical work. Our specific recommendations are as follows:

- **Strengthen heliophysics links to astrophysics and related fields by encouraging and supporting interdisciplinary research.** Cross-disciplinary research traditionally faces barriers to funding, with funding agents within each discipline often abdicating responsibility to others. Encourage and support interdisciplinary collaboration, workshops, and public outreach.

- **Support present and future missions to the outer heliosphere and beyond, particularly the proposed Interstellar Probe.** Such a mission would provide unique insight via direct detailed measurements of the local interstellar environment, including gas and dust dynamical properties and composition, and magnetic fields.

- **Support present and future missions that perform empirical dust measurements spanning 1 au to the outer solar system and that can identify and characterize interstellar grains.** This would ground our understanding of propagation of interstellar and supernova dust in the heliosphere.

- **Support theoretical study of the heliosphere over time, particularly in concert with the formation and evolution of the Local Bubble and the deposition of supernova-produced radioisotopes.** Address questions we have outlined, including the propagation of supernova dust, supernova-accelerated cosmic rays, the impact on solar system bodies, and signatures of these processes in the present geological and lunar records and across the solar system.

- **Support study of astrospheres of other stars as laboratories of heliophysics under a wide range of conditions.** This can provide illuminating comparisons with the heliosphere today and in the presence of supernovae.

Fortunately, many of these efforts, including outer heliosphere missions such as Interstellar Probe, heliospheric dust measurements and cosmic-ray studies, are central to heliophysics writ large. In addition, we believe that the interdisciplinary approach we advocate also strengthens heliophysics, raising its visibility to other sciences and to the public generally.

The coming decade promises to offer exciting insights into our place in the evolving cosmos. This history is encoded in signatures from deep-sea deposits to the solar system to the stars. We look forward to decoding these signals to unveil the dynamic nature of the heliosphere over time.

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\(^1\)C. Lisse, *in preparation.*
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