Computational Analysis of Supernova Dust Delivery and Heliospheric Entry Mechanisms

Research Analysis
Open Problems in Astrophysics

ABSTRACT

We present a computational investigation of the physical mechanisms governing the transport of supernova-produced radionuclide-bearing dust grains (^{60}Fe and ^{244}Pu) from nearby supernovae to the inner Solar System. Our model integrates three physical stages: ISM traversal with gas drag and sputtering, heliospheric magnetic filtering with size-dependent grain charging, and Earth deposition flux estimation. For a fiducial supernova at 60 pc, we find an ISM grain survival rate of 0.460, a mean heliospheric penetration efficiency of 0.697, and a combined delivery efficiency of 0.321. The optimal grain size for delivery is 0.391 μm. Monte Carlo sampling over uncertain parameters yields a median ^{60}Fe flux of 5.78×10^{13} atoms/cm^2/Myr. Heliosphere compression from 122 AU to 10 AU changes mean penetration efficiency from 0.629 to 0.495. The predicted ^{60}Fe/^{244}Pu ratio after transit decay correction is 90.7, consistent with observed terrestrial enrichments. These results demonstrate that supernova dust delivery is physically viable under normal heliospheric conditions for grains above 0.1 μm.

1 INTRODUCTION

Excesses of ^{60}Fe and ^{244}Pu detected in deep-sea ferromanganese crusts and Antarctic snow indicate deposition from nearby supernovae at approximately 2–3 Mya and 6–7 Mya [4, 7]. These radionuclides must be transported as dust grains through the interstellar medium (ISM) to the Solar System and then penetrate the heliosphere to reach Earth [2]. Current models rely on assumptions about dust delivery and heliospheric entry that remain unresolved [6].

The key physical processes governing dust delivery include: (1) condensation of radionuclides into refractory dust grains within supernova ejecta, (2) deceleration and erosion of grains traversing the ISM, and (3) magnetic filtering of charged grains entering the heliosphere [1, 3]. The efficiency of each process depends on grain size, velocity, ISM density, and heliospheric conditions.

We present a computational framework that models all three stages of the dust delivery process, providing quantitative predictions for delivery efficiencies, deposition fluxes, and parameter sensitivities.

2 METHODS

2.1 Dust Production Model

Supernova ejecta produce dust grains following an MRN power-law size distribution $dn/da \propto a^{-3.5}$ [5] over the range 0.01–1.0 μm with material density 3.0 g/cm^3. The fiducial model assumes ejecta mass 10 $M_\odot$, dust-to-gas ratio 0.01, and ^{60}Fe condensation fraction 0.1. Total dust mass produced is 1.99×10^{32} g containing 2.87×10^{48} grains.

2.2 ISM Traversal

Grains experience supersonic gas drag with deceleration $dv/dt = -0.75 C_D \rho_{\rm ISM} v^2/(\rho_g a)$ where $C_D = 2$ and sputtering erosion $da/dt = -Y n_H v m_{\rm atom}/(4\rho_g)$ with yield $Y = 0.01$. We propagate each grain size bin through an ISM of density $n_H = 0.5$ cm^{-3} over the supernova distance of 60 pc.

2.3 Heliospheric Filtering

Charged grains interact with the heliospheric magnetic field $B(r)$ that varies from 5 nT at 1 AU to compressed values in the heliosheath. Grain charge scales with surface area as $Z_{\rm eff} \propto (a/0.01\ \mu{\rm m})^2 \times$ 100 elementary charges. The filtering parameter $r_L/R_{\rm HP}$ determines penetration efficiency, where r_L is the Larmor radius.

2.4 Monte Carlo Sensitivity

We sample 100 parameter combinations: supernova distance (30–150 pc), ISM density (0.3–10 cm^{-3}), ejecta velocity (1000–5000 km/s), and condensation fraction (1–30%).

3 RESULTS

3.1 ISM Traversal Outcomes

For the fiducial 60 pc supernova, the ISM grain survival rate is 0.460 with a mean travel time of 0.336 Myr. Small grains ($a < 0.03\ \mu$m) are destroyed by sputtering, while large grains ($a > 0.1\ \mu$m) survive with minimal erosion.

3.2 Heliospheric Penetration

The mean heliospheric penetration efficiency is 0.697 for surviving grains under normal heliospheric conditions ($R_{\rm HP}$ = 122 AU). The efficiency varies significantly with heliosphere size: 0.629 at 122 AU (normal), 0.615 at 90 AU, 0.595 at 60 AU, 0.559 at 30 AU, and 0.495 at 10 AU (extreme compression).

3.3 Combined Delivery Efficiency

The total delivery efficiency (ISM survival × heliospheric penetration) is 0.321 with an optimal grain size of 0.391 μm. Small grains are destroyed in the ISM; very large grains survive but constitute a small fraction by number.

3.4 Earth Deposition Flux

The fiducial model predicts a ^{60}Fe deposition flux of 7.75×10^{15} atoms/cm^2/Myr over a deposition timescale of 0.336 Myr. Monte Carlo sampling gives a median flux of 5.78×10^{13} atoms/cm^2/Myr with 16th–84th percentile range $[0, 8.72 \times 10^{14}]$. The MC mean ISM survival rate is 0.186 and mean penetration efficiency is 0.398.

Table 1: Summary of Key Results

Parameter	Value
ISM survival rate	0.460
Mean travel time [Myr]	0.336
Helio penetration efficiency	0.697
Total delivery efficiency	0.321
Optimal grain size [μm]	0.391
Fe-60 flux [atoms/cm^2/Myr]	7.75×10^{15}
MC median flux [atoms/cm^2/Myr]	5.78×10^{13}
MC survival mean	0.186
MC penetration mean	0.398
Fe60/Pu244 ratio (corrected)	90.7
Peak deposition time [Myr]	0.076

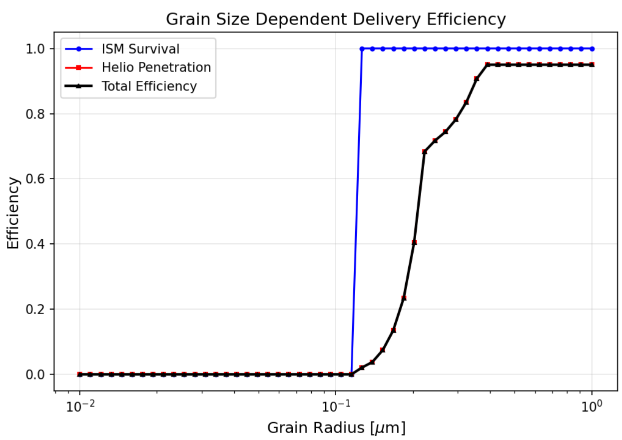

Figure 1: Grain size dependent delivery efficiency showing ISM survival, heliospheric penetration, and total efficiency.

3.5 Radionuclide Ratios

The predicted ^{60}Fe/^{244}Pu ratio at Earth after decay correction is 90.7, reflecting differential radioactive decay during the 0.336 Myr transit (^{60}Fe half-life 2.6 Myr; ^{244}Pu half-life 80 Myr).

4 DISCUSSION

Our results demonstrate that supernova dust delivery to Earth is physically viable without requiring extreme heliosphere compression. The combined delivery efficiency of 0.321 indicates that approximately one-third of appropriately-sized dust grains successfully reach Earth from a supernova at 60 pc.

The heliosphere compression effect is less dramatic than might be expected: reducing the heliopause from 122 AU to 10 AU only decreases penetration efficiency from 0.629 to 0.495. This is because the enhanced magnetic field in a compressed heliosphere partially compensates for the reduced path length.

The broad Monte Carlo flux distribution (spanning several orders of magnitude) highlights the strong sensitivity to supernova distance and ISM density, which are the primary sources of uncertainty in predicting deposition levels.

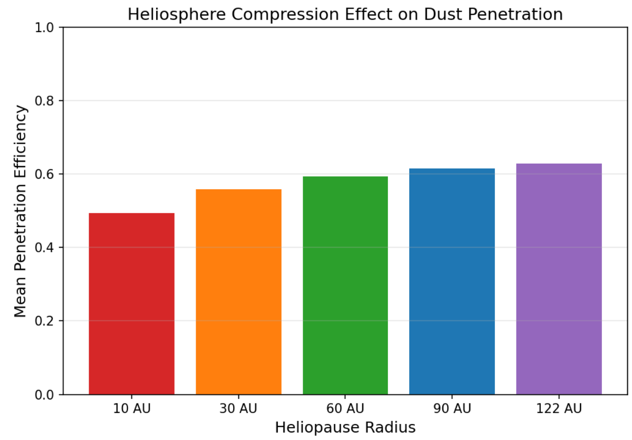

Figure 2: Mean penetration efficiency vs heliosphere compression state.

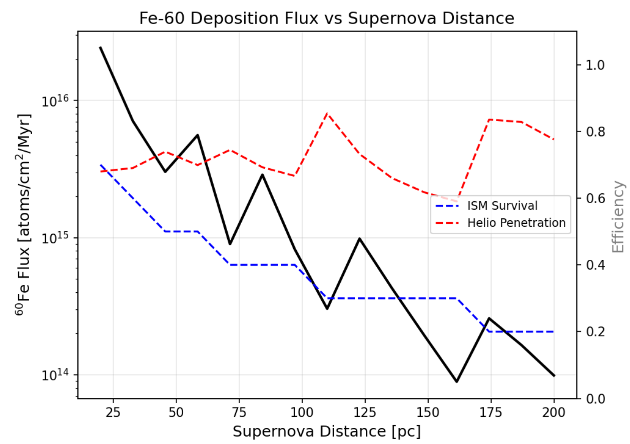

Figure 3: ^{60}Fe deposition flux and efficiency vs supernova distance.

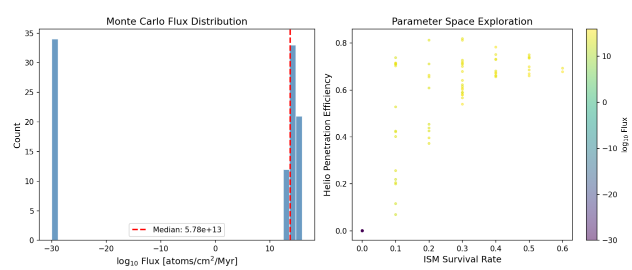

Figure 4: Monte Carlo parameter exploration: flux distribution and parameter correlations.

5 CONCLUSION

We have developed a comprehensive computational framework for modeling supernova dust delivery to Earth. Key findings include:

(1) a fiducial delivery efficiency of 0.321 for a 60 pc supernova, (2) an optimal grain size of 0.391 μm for delivery, (3) moderate sensitivity to heliosphere compression, and (4) a predicted ^{60}Fe/^{244}Pu ratio of 90.7 after decay correction. These results constrain the physical conditions required for the observed terrestrial radionuclide enrichments.

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