When Stars Attack!

Confirmation, Identification, and Localization of Recent Near-Earth Supernovae

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Ada Ertel
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Midwest SN @ Chi. 26 Feb 2019
Nearby SNe are Inevitable
Shklovskii 1968; BDF 2004; Krishnan, Sovgut, Trauth, & BDF 2019 in prep

Rate of Supernovae inside $r$:

$$\text{SN Rate}(<r) \sim (10 \text{ Myr})^{-1} \left( \frac{r}{30 \text{ pc}} \right)^3$$
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- multiple events < few pc in the last 4.5 Gyr!
- biological impact can be severe if < 10 pc!

Thomas, Melott, Overholt group; Gehrels 2003
Nearby Supernovae Rain Ejecta on Earth

Ellis, BDF, & Schramm 1996; BDF, Athanassiadou, & Johnson 2008; Fry, BDF, Ellis 2015
Nearby Supernovae Rain Ejecta on Earth

SN eject plows thru interstellar matter

Earth shielded by solar wind
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If blast close enough:
• plasma pushes to inner Solar System

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SN eject plows thru interstellar matter

Earth shielded by solar wind

If blast close enough:
- plasma pushes to inner Solar System
- dust decouples, rains on Earth
- SN dust accumulates in deep ocean
Q: How would we know?
The Smoking Gun: Radioactivity

Ellis, BDF, & Schramm 1996; BDF, Athanassiadou, & Johnson 2008; Fry, BDF, Ellis 2015

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Need observable SN “fingerprint”

Nuclear Signature
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★ Stable nuclides: don’t know came from SN
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$^{60}\text{Fe}$ $t_{1/2} = 2.6 \text{ Myr}$

also, e.g., $^{26}\text{Al}$, $^{97}\text{Tc}$, $^{244}\text{Pu}$?
Radioactivity Detection: $^{60}$Fe

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Ferromanganese crust
Pacific Ocean
✓ slow growth ~ 1 mm/Myr
✓ accelerator mass spectrometry:
  live $^{60}$Fe!
Radioactivity Detection: $^{60}\text{Fe}$

Knie et al. (2004)

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$^{60}\text{Fe}$ abundance

time before present [Myr]
Radioactivity Detection: $^{60}$Fe


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Background: $^{60}$Ni

$^{60}$Fe abundance vs. time before present [Myr]

$^{60}$Fe/Fe
Radioactivity Detection: $^{60}$Fe


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$t = 2.8 \pm 0.4$ Myr

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Woo hoo!
Radioactivity Detection: $^{60}\text{Fe}$


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Note AMS sensitivity!
Explosion Distance

Ellis, BDF, Schramm 1996; BDF & Ellis 1999; BDF, Hochmut & Ellis 2005; Fry, BDF, & Ellis 2015

Observable: surface density/fluence:

\[ N_{60,\text{obs}} \sim \frac{M_{60,\text{eject}}}{D^2} \]
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Turn the problem around:
“radioactivity distance” from \(^{60}\text{Fe}\) yield
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- core-collapse supernova
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Jesse Miller
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Verdict: Core Collapse ~30-150 pc

Jesse Miller
New Data, New Probes, New Sites
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– consistency check
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  – magnetic microfossils!
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★ Lunar cores!
  – $^{60}\text{Fe}$ excess over cosmic-ray production
$^{60}$Fe Sample Sites
Before

$^{60}\text{Fe}$ data, first clear detection

$60\text{Fe/Fe} [1 \times 10^{-15}]$ vs. Time [Myr ago]

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8
Earth and Lunar $^{60}$Fe Data

$60^{Fe}/Fe \times 10^{-15}$

Time [Myr ago]

Ada Ertel
Confirmation of $^{60}$Fe crust signal at 2-3 Myr
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another signal at ~8 Myr? ...now confirmed
$^{60}\text{Fe flux duration } \sim 1 \text{ Myr}$
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far exceeds Sedov prediction!?! Fry+ 2015
$^{60}$Fe flux duration $\sim 1$ Myr

far exceeds Sedov prediction?!? Fry+ 2015

probes dust evolution & dynamics? Fry, Ertel + 2017

![Graph showing Fe concentration over time](image)
CONCLUSION
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THIS IS A THING

new probe for astronomy, astrophysics, geology, biology…
Outlook
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Live $^{60}\text{Fe}$ seen globally and on the Moon
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Live $^{60}$Fe seen globally and on the Moon
- signal in deep ocean crusts, nodules, sediments find
- confirmed pulse $\sim 2$-$3$ Myr ago
- evidence for pulse at $\sim 8$ Myr
- $^{60}$Fe pulse duration $\sim 1$ Myr ??
- evidence for lunar signal—directionality?
- Source of Local Bubble?
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Birth of “Supernova Archaeology”

Implications across disciplines:
- nucleosynthesis, cosmic dust, stellar evolution, bio evolution, astrobiology
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Future Research

‣ Supernova(e) origin and direction
  ★ lunar distribution
  ★ cosmic-ray anisotropies, $^{60}$Fe excess
  ★ neutron star/pulsar correlation
  ★ dust production, evolution, dynamics
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‣ more, different samples:
  ✓ other isotopes
  ✓ other media (fossil bacteria)
  ✓ other sites: back to the Moon!
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- stay tuned…Midwest SN 202x!
Whodunit?
The Moon as a Telescope
Fry, BDF, & Ellis (2016)

★ $^{60}$Fe dust grains nearly undeflected in Solar System
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★ Earth:
Whodunit?
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  – stratosphere scrambles
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★ Moon is airless:
Whodunit?
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★ $^{60}$Fe dust grains nearly undeflected in Solar System
★ Earth:
  – stratosphere scrambles
★ Moon is airless:
  – encodes direction!
  – $^{60}$Fe pattern points to source!

$\Delta \theta = \Delta \phi = 10.0^\circ$, $\eta = 155.0^\circ$, $\Delta t_{\text{signal}} = 100.0$ kyr
"radioactivity distance" from $^{60}\text{Fe}$ yield

$$D \sim \sqrt{\frac{M_{60,\text{eject}}}{N_{60,\text{obs}}}}$$
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What makes $^{60}\text{Fe}$?
- core-collapse supernovae
- Type Ia supernovae
- AGB stars
- kilonovae
- impactor Wallner+ 16; Miller & BDF 18
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\[\text{Mass of Progenitor} [M_\odot]\]

\[\text{Estimated distances for possible progenitors, for }^{60}\text{Fe yields and the fact that the fission recycling sources are }\sim 10-100 \text{ times larger than }^{244}\text{Pu atom detected}\]

\[\text{More likely, }^{60}\text{Fe never arrives}\]

\[\text{60Fe never arrives}\]
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$^{60}$Fe never arrives

![Graph showing the relationship between radioactivity distance and mass of progenitor.](image)

**Mass of Progenitor**

- A6.5
- A7.0
- A8.5
- $R_{\text{fade, CCSN}}$
- $R_{\text{fade, ECSN}}$
- S15
- S19
- S20
- S21
- S25

We are dead

$^{60}$Fe isotope fraction

- $^{60}$Fe yield
- $^{60}$Fe anomaly.

$^{60}$Fe from various source candidates

- $^{60}$Fe yields from various source candidates
- $^{60}$Fe never arrives

Whodunit?

Fry, BDF, & Ellis 2015
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What makes $^{60}$Fe yield?

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Using the decay-corrected Knie et al. (2004) and fit to us sie et al. (2008), we have solved Equation (6). Of particular note are the TNSN. Consequently, a biohazard argument cannot rule out what makes $^{60}$Fe?

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\[ \text{Figure 2. The Astrophysical Journal} \]
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D ∼ $\sqrt{M_{60,\text{eject}} / N_{60,\text{obs}}}$

"radioactivity distance" from $^{60}$Fe yield

$^{60}$Fe yields due to nuclear reaction $\gamma$ and fitting sources. (2013-2015)

What is the $^{60}$Fe anomaly?
What makes $^{60}$Fe?

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**“radioactivity distance” from $^{60}$Fe yield**

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SN distance:

![Graph](image-url)
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SN distance:

$$d(^{60}\text{Fe}) \sim 30 - 150 \text{ pc}$$

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Encouraging:
★ astronomical distances not built in!

`Whodunit?`
Fry, BDF, & Ellis 2015

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\end{figure}
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Encouraging:
- † astronomical distances not built in!
- † $d(^{60}\text{Fe}) \approx d(\text{SN} \rightarrow \text{Earth}) \approx d_{\text{SN}}(3 \text{ Myr})$

Yellow: nontrivial consistency!
Nachbarsternsupernovaexplosionsgefahr
or
Attack of the Death Star!
Nachbarsternsupernovaexplosionsgefahr
or
Attack of the Death Star!

Ill efects if a supernova too close
possible source of mass extinction

- Shklovskii; Russell & Tucker 71; Ruderman 74; Melott group
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Ionizing radiation
- initial gamma, X, UV rays destroy stratospheric ozone
  Ruderman 74; Ellis & Schramm 94
- solar UV kills bottom of food chain
  Crutzen & Bruhl 96; Gehrels et al 03;
  Melott & Thomas groups; Smith, Scloa, & Wheeler 04
- cosmic rays arrive with blast, double whammy
- ionization damage, muon radiation
Nachbarsternsupernovaexplosionsgefahr

or

Attack of the Death Star!

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  Melott & Thomas groups; Smith, Sclao, & Wheeler 04
- cosmic rays arrive with blast, double whammy
- ionization damage, muon radiation

Neutrinos

- neutrino-nucleon elastic scattering:
  “linear energy transfer”
  DNA damage
  Collar 96, but see Karam 02
Nachbarsternsupernovaexplosionsgefahr

or

Attack of the Death Star!

Ill effects if a supernova too close
possible source of mass extinction

- Shklovskii; Russell & Tucker 71; Ruderman 74; Melott group

Ionizing radiation

- initial gamma, X, UV rays destroy stratospheric ozone
  Ruderman 74; Ellis & Schramm 94
- solar UV kills bottom of food chain
  Crutzen & Bruhl 96; Gehrels et al. 03;
  Melott & Thomas groups; Smith, Sclao, & Wheeler 04
- cosmic rays arrive with blast, double whammy
- ionization damage, muon radiation

Neutrinos

- neutrino-nucleon elastic scattering
  “linear energy transfer”
  DNA damage

Minimum safe distance: ~8 pc