When Stars Attack!
Radioactive Evidence for Near-Earth Supernova Explosions

Brian Fields
Astronomy and Physics, University of Illinois

Saturday Physics for Everyone
Sept. 9, 2017
Inga Karliner
Founder and Godmother
★ Jedi Master bringing Physics to the People
★ 25 years of Saturday Physics!
★ >15,000 total attendance!!

Thank you Inga!
Who Saw the Eclipse?

We are citizens of the cosmos
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When Stars Attack!

★ Brighter than One Billion Suns
Supernova explosions now and in the past

★ Celebrities of the Cosmos
Lifestyles and death throes of massive stars

★ Too Close for Comfort
Supernova explosions near the Earth

★ Supernova Archaeology
Explosion debris from the bottom of the sea
Supernova Explosions Observed
The Fate of Stars

Fact: Stars constantly lose energy

Fact: Stars have finite \((\neq \infty)\) mass
  = finite fuel supply
  = limited energy

Fact: Energy is conserved:
  No free lunch!

Therefore...?

🌟 Stars can’t live forever
🌟 All stars must die!
🌟 Stars have life cycles!

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Supernova Explosions

The Death of Massive Stars
- mass > 10 suns

- Spectacular
- Rare
- Crucial for life
  ...but don’t get too close...

What do we see?
- Bright: can outshine galaxy
- Rapid changes in time:
  - max in days
  - dims over weeks
- Shock wave launched
  Fast, ultra-hot gas

Light from a single supernova
Historical Supernovae

Supernova explosions are rare:
- Deaths of massive stars: $> 10$ Msun
- Fewer than 1% of stars die this way
- None seen in our Galaxy for 300 years

The Sun will die…
- But not this way (not an explosion!)
- And not for billions of years
- Sleep well tonight!
Supernova Explosions in Recorded History

1054 AD

- Europe: no record
- China: “guest star” 天闕客星
- Anasazi people
  Chaco Canyon, NM: painting

Modern view of this region of the sky:
Crab Nebula—remains of a supernova explosion
Supernova Explosions in Recorded History

November 11, 1572
Tycho Brahe

A “new star” ("nova stella")

Modern view (X-rays): remains of a supernova explosion
On the 11th day of November in the evening after sunset ... I noticed that a new and unusual star, surpassing the other stars in brilliancy, was shining ... and since I had, from boyhood, known all the stars of the heavens perfectly, it was quite evident to me that there had never been any star in that place of the sky ...

I was so astonished of this sight ... A miracle indeed, one that has never been previously seen before our time, in any age since the beginning of the world.

What did Tycho get right?
Where was he wrong?
Questions so far?
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Supernova Explosions: Getting Under the Hood
The James Dean of Stars

Live Fast

Star life is struggle vs gravity
Nuclear fires keep hot, pressurized, stable

Q: what happens when fuel runs out?

Die Young

- Fuel exhaustion     collapse
- Core becomes dense, "bounce"
- Shock wave launched       explosion!

Demo: AstroBlaster

Leave a Beautiful Corpse

- Ultradense "cinder" neutron star/black hole
- Most material ejected at high speed

Million-degree gas seen in X-ray vision; 300 yrs old

Hot, shocked gas; > 5,000 yrs old

Demo: Liquid Nitrogen - 321 F
We are made of nuclear ashes of stars
Ashes of Nuclear Furnaces

Most nuclear reactions in stars produce healthy, stable atoms

But…

Some unstable, radioactive atoms are always produced

- then decay after a certain time

For example:

- Solar system born 4.5 billion years ago with traces of radioactivity
- Today, our Galaxy contains traces of radioactivity

...which can be observed by the high-energy gamma-rays it emits!

The radioactive sky: gamma-rays from decays of unstable aluminum-26 atoms
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Near-Earth Supernovae
Supernova Explosions Near Earth

Cosmic WMD

In our Milky Way galaxy:

- About 1 SN/century
- Most far away: spectacular but harmless

Now: no nearby massive stars

Sleep well tonight!

But over the 4.5 billion year history of Earth:

Many nearby events!
Surgeon General’s Warning: Supernovae are Dangerous to Your Health!

Biological damage if too close
(\text{un})\text{holy grail}: \text{mass extinction due to SN}
\text{Q: ill effects of cosmic WMD?}

Direct
DNA damage due to high-energy particles (neutrinos)

Indirect
Radiation damage to atmosphere
- Destruction of ozone layer, which is bad because?...
- \text{Sun’s UV unfiltered}
  \text{ill plants/bacteria at bottom of} \text{in}
- Damage all the way up

Minimum safe distance: 30 light years
Questions?
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Supernova Archaeology
Nearby Supernovae Rain Ejecta on Earth

Explosion launched at speed few% speed of light
SN debris plows thru interstellar matter

Earth shielded by solar wind

If blast close enough:
- pushes to inner Solar System
- rains on Earth
- SN debris accumulates in deep ocean
BDF, Athanassiadou, & Johnson 2006

1 AU = Earth’s orbit

Incoming blast

Sun
The Smoking Gun: Radioactivity

Q: How would we know?

Need observable SN “fingerprint”

Nuclear Signature

★ Stable nuclides: don’t know came from SN
★ Live radioactive isotopes: none left on Earth
   If found, must come from SN!

$^{60}\text{Fe}$ half-life $t_{1/2} = 2.6 \text{ Myr}$

also, e.g., $^{26}\text{Al}$, $^{97}\text{Tc}$, $^{244}\text{Pu}$?
Evidence? Deep Ocean Crust

Knie et al. (1999) ferromanganese (FeMn) crust
Pacific Ocean
growth: ~ 1 mm/Myr

Ultra-high sensitivity measurements
accelerator mass spectrometry:
“needles in haystacks”
discovered live radioactivity: $^{60}\text{Fe}$!

Q: What pattern expected in sediment?
Expect: one radioactive layer
1999: $^{60}\text{Fe}$ in multiple layers!?
$^{60}$Fe Confirmation


Advances
- New crust from new site
- Better geometry (planar)
- Better time resolution
- $^{10}$Be ➞ radioactive timescale

Isolated Signal
- $t = 2.8 \pm 0.4$ Myr
- A Landmark Result
  - Isolated pulse identified
  - Epoch quantified
  - Consistent with original crust

Note fantastic AMS sensitivity!

Background: $^{60}$Ni
New Data, New Probes, New Sites

★ New crust data  Wallner+ 2016
- consistency check

★ Ocean sediment data  Ludwig+ 2016; Wallner+ 2016
- faster growth rate ~ 1 mm/kyr
- much improved time resolution
- magnetic microfossils!

★ Lunar cores!  Fimiani+ 2016
- $^{60}$Fe excess over cosmic-ray production

★ Cosmic rays  Binns+ 2016
- $^{60}$Fe detected, requires local source
BEFORE

Current $^{60}$Fe Data, Decay Corrected

Ratio of $^{60}$Fe/Fe [1e-15]

Time [Myr ago]
AFTER
Current $^{60}$Fe Data, Decay Corrected

Ratio of $^{60}$Fe/Fe [1e-15]

Time [Myr ago]

Fimiani: lunar data
Ludwig: microfossils
Knie: FeMn crust
Hitoussi: crust
Wallner: sediment
Wallner: FeMn crust
Wallner: nodules
★confirmation of $^{60}$Fe crust signal at 2-3 Myr
★another signal at ~8 Myr? …now confirmed
$^{60}$Fe flux duration $\sim$1 Myr
★ far longer than expected!?! Fry+ 2015
★ probes SN dust evolution? Fry, Ertel + 2017

![Graph showing the ratio of $^{60}$Fe/Fe vs. time (in Myr ago) with a duration marked as 1 Myr.](image)
Aftermath: The Local Bubble?

★ The Sun lives in region of hot, rarefied gas
- The Local Bubble
- huge hot cavity ~150 light yrs

★ Nearby SN needed to blow bubble!
- we live inside SN remains
- bubble: ~10 SN in past 10 Myr
  Smith & Cox 01
- $^{60}$Fe from nearest massive star cluster?
  Benitez et al 00
A Near Miss?

Supernova debris more dispersed at greater distance
can relate measured amount to distance!  \[ \#^{60}\text{Fe atoms} \sim \frac{1}{d^2} \]

➡ find range \( d=60-300 \) light years

So \( d>d_{\text{kill}} \) ...but barely: "near miss"

- Climate change from radiation?
- bump in extinctions?

If true: implications for astrobiology tightens Galactic habitable zone

Image: Mark Garlick
www.markgarlick.com
CONCLUSION

THIS IS A THING

new probe for astronomy, astrophysics, geology, biology…
Outlook

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Live radioactive iron (\(^{60}\)Fe) seen globally and on Moon

Signals 3 Myr and 7 Myr ago

Birth of "Supernova Archaeology"

Implications across disciplines: astronomy, physics, astrobiology, evolutionary biology

Future Research

- better model SN debris delivery
- improved SN radioactive synthesis models
- more, different samples:
  - other kinds of radioactive atoms (isotopes)
  - other sites (lunar samples?)
- other epochs? Mass extinction correlations?

Stay tuned...

We are citizens of the cosmos

Brian Fry
John Ellis
Ada Ertel
Jesse Miller