Live Radioisotopes as Signatures of Nearby Supernovae

Vasiliki Pavlidou, BDF *U. Illinois*
John Ellis *CERN*
Peter McCullough *Space Telescope*

Astronomy with Radioactivities IV
May 26, 2003

Live Radioactivities and Nearby Supernovae

- ⋆ *Nearby Supernovae*
  a unique laboratory

- ⋆ *Geological Signatures*
  sea sediments as telescopes

- ⋆ *Gamma-Ray Line Signatures*
  probing SN nucleosynthesis & astrophysics

Nearby Supernovae

Nearby SN: $\ll 1$ kpc $\rightarrow$ unique laboratory

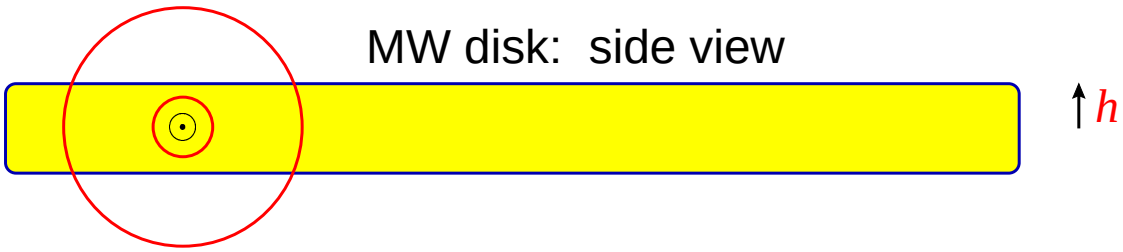
$\star$ inside 100-200 pc: γ-ray lines bright
$\Rightarrow$ radioiotope inventory of SN remnants

$\star$ inside 10-30 pc: terrestrial contamination?
$\Rightarrow$ holy grail: mass extinction?!?

How often? Depends on how far!

Supernova rate $\lambda(< R)$

- Galactic NS rate today: $\mathcal{R}_{\rm SN} \sim (30\ {\rm yr})^{-1}$
- in homog. disk, scale height $h \sim 100$ pc:



$$\lambda(< R) = \frac{V_{\rm disk}(< R)}{V_{\rm disk,total}} \mathcal{R}_{\rm SN}$$

$$\sim \begin{cases} (10\ {\rm Myr})^{-1} \left(\frac{R}{30\ {\rm pc}}\right)^3 & r < h \\ (0.3\ {\rm Myr})^{-1} \left(\frac{R}{100\ {\rm pc}}\right)^2 & r > h \end{cases}$$

- corrections: spiral arms, molecular clouds, exponential disk... Kroupa talk

Multiple events within a few pc in 4.5 Gyr!

Geological Signatures

Terrestrial Signatures of Nearby SNe

Ellis, BDF, Schramm 96

Transport

★ *Cosmic Rays*

diffusive: precede blast wave Biermann talk

spallation in atmosphere: $\rightarrow$ ^{14}C, ^{10}Be, ^{36}Cl, ^{129}I

Surface density $\propto \Phi_{\rm cr} \propto 1/R^2$

★ *Direct Deposit*

if blast wave $\Rightarrow$ earth: all SN products

$\rightarrow$ ^{26}Al, ^{60}Fe, ^{244}Pu

Surface density $\sim M_{{\rm ej},i}/R^2$

▷ Distance cutoff: $P_{\rm blast} \gtrsim P_{\rm solar\ wind} \Rightarrow R < R_{\rm max} \sim 30$ pc

Terrestrial Signatures of Nearby SNe

Ellis, BDF, Schramm 96

Observables

Signature: Isotope Anomalies

Medium: Gelogical Sediments – "Natural Archives"

- *Ice Cores*
- *Sea Sediments*

Measure: Specific concentration

$$\Lambda_i = \frac{n_i}{\rho_{\rm sed}} \sim \frac{M_{{\rm ej},i}/R^2}{({\rm sed\ rate})\Delta t_{\rm dep}}$$

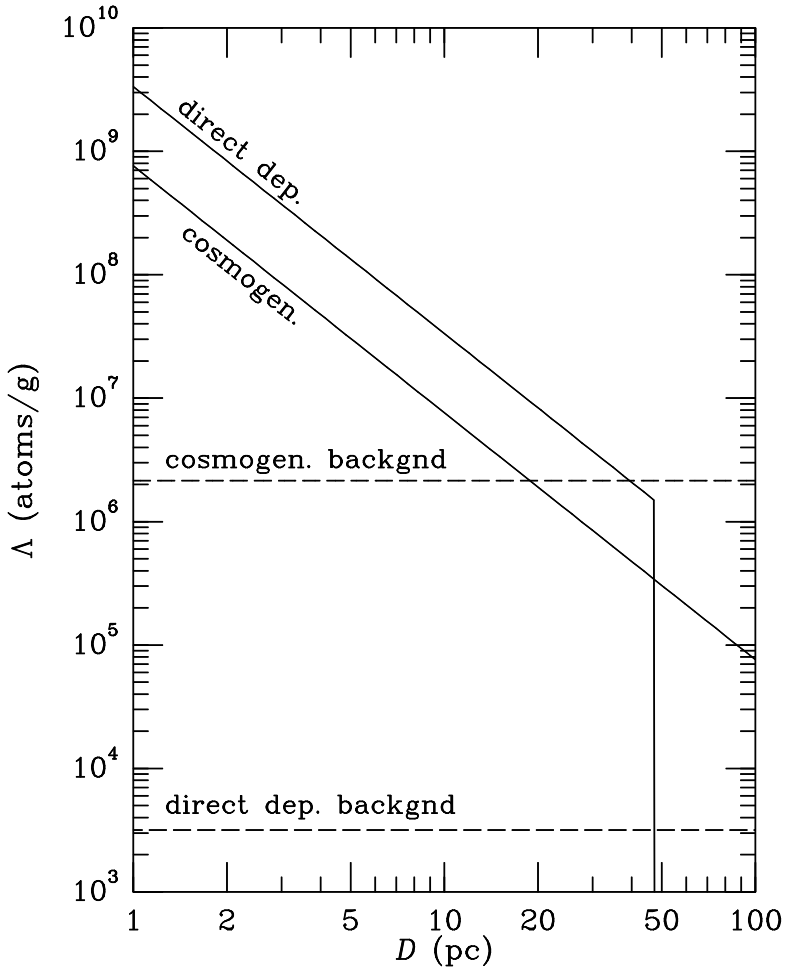
$$= 5\times 10^7\ {\rm atoms\ g}^{-1} \left(\frac{X_{{\rm ej},i}}{10^{-5}}\right)\left(\frac{1\ {\rm kyr}}{\Delta t_{\rm dep}}\right)\left(\frac{10\ {\rm pc}}{R}\right)^2$$

Terrestrial Signatures of Nearby SNe

Ellis, BDF, Schramm 96

Small counts:

- activity too small ⇒ AMS
- stable isotopes, extinct rad
  lost in natural bkgnd
  need short-lived radioisotopes



Backgrounds:

- meteorites: cosmic ray exposure
  → radioisotopes Mostefaoui talk
- normal CR in atmosphere
- natural (& anthropogenic) fission
- bioturbation: creepy crawlies!

Geological Case Study
Antarctic ice

Cosmic rays + atm $\rightarrow$ ^{10}Be ($\tau = 2.2$ Myr)
- stored in polar ice
- moderate fluctuations: solar variation

Antarctic ice: large excursions $\sim 35, 60$ kyr ago

Raisbeck etal 87

also Greenland ice, Pacific, Meditteranean

Beer etal 92; McHargue etal 95; Cini Castagnoli etal 93

$\Rightarrow$ global enhancement

A Supernova Signature?

Raisbeck etal 87; Sonnet etal 87; Ramadurai 93

If so: very recent, very local $\lesssim 40$ pc Ellis etal 96

Whodunit: *Geminga*?
- spin-down age ~ 100 kyr
- HST parallax: $d = 157^{+57}_{-34}$ pc
- multiple peaks: shock ensemble? Ammosov 91

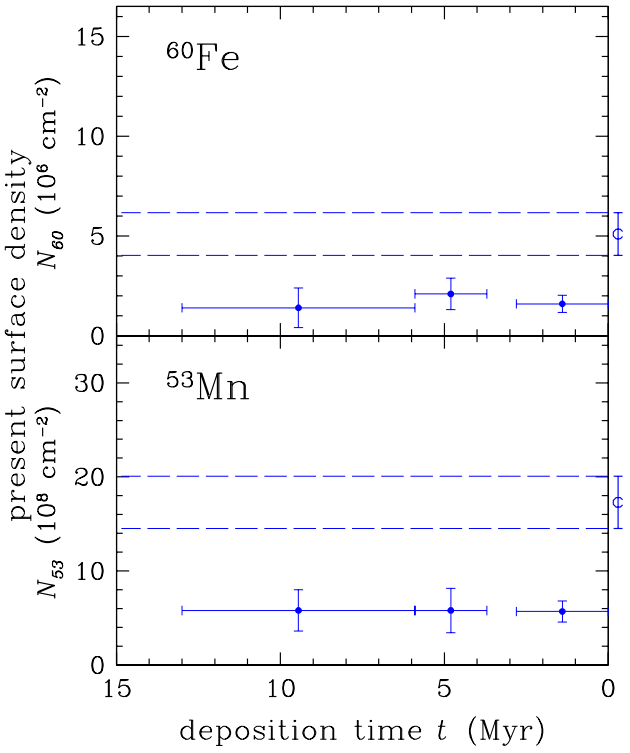
But: not yet confirmed with other isotopes
solar variations? geomagnetic reversals?

Geological Case Study
Deep Ocean Crust

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

Knie talk

AMS $\rightarrow$ live ^{60}Fe, $\tau = 2.2$ Myr !
and ^{53}Mn, $\tau = 5.3$ Myr
63 atoms total
$\star$ ^{60}Fe and ^{53}Mn found in *all* layers!?!



Geological Case Study
^{60}Fe & ^{53}Mn in Deep Ocean Crust

Estimated background
^{60}Fe: $\sim$ 100 times below signal
^{53}Mn: background?

A Supernova Signature?
But why not a single "spike" in time?
- SN dust spread widely?
- mixture in the sample itself?

If SN, signal is *sum* over layers
^{60}Fe: surface density $N_{60,\mathrm{obs}} \sim M_{\mathrm{ej},60} e^{-t/\tau}/R^2$

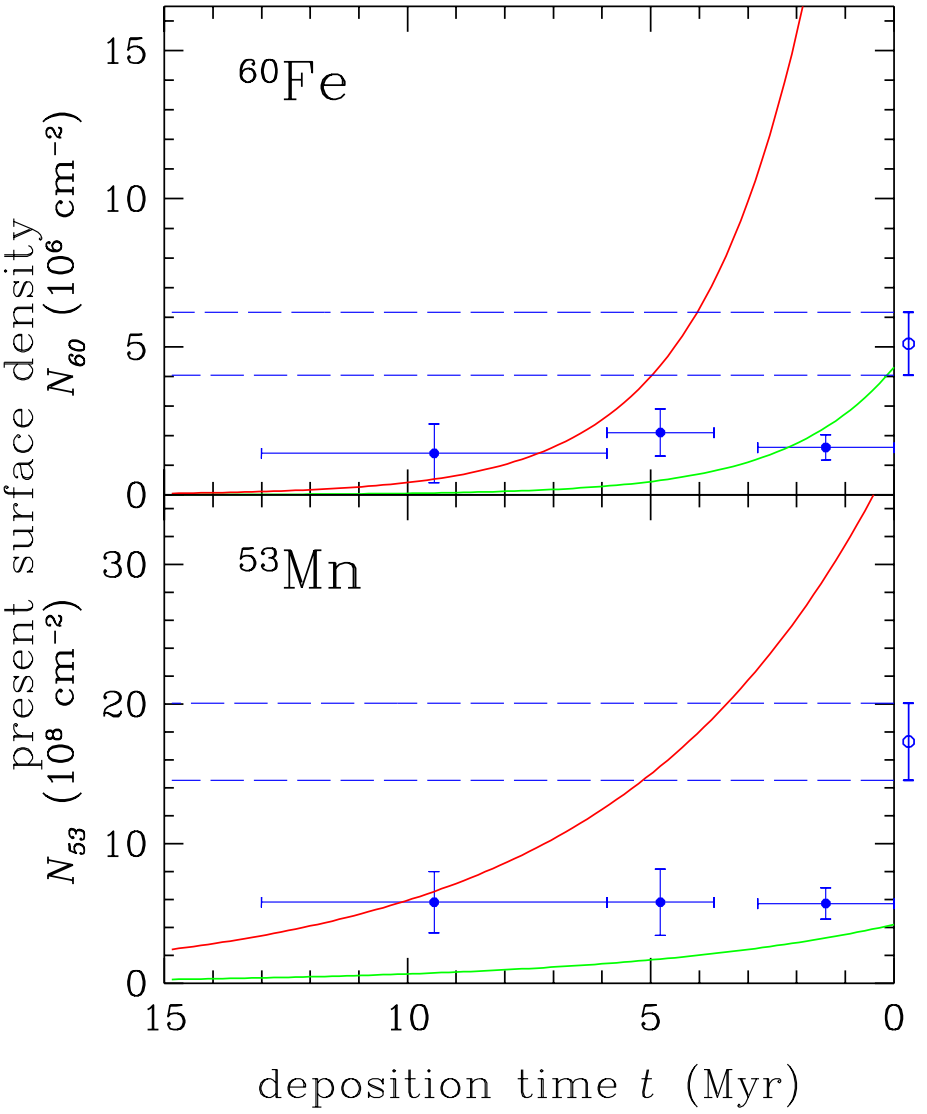
$\boxed{R = 29\ e^{-t/2\tau}\ \mathrm{pc}}$ BDF & Ellis 99

note scale: *parsecs not built into data*!

Limits:
if SN was "yesterday," $t/\tau \sim 0$ $\Rightarrow$ $\boxed{R \lesssim 30\ \mathrm{pc}}$
but if $R \lesssim 10$ pc $\Rightarrow$ too rare, too dangerous!

Ruderman 74, Ellis & Schramm 93

$\Rightarrow$ $\boxed{\tau \lesssim 5\ \mathrm{Myr}}$



red curve: SN at 10 pc

green curve: SN at 30 pc

Fields & Ellis 1999

Geological Case Study
^{60}Fe & ^{53}Mn in Deep Ocean Crust

Whodunit?

IF SN: nearby, recent

$\rightarrow$ OB association may still exist

$\rightarrow$ mabye source of Local Bubble?

Sco-Cen OB Association Benitez et al 2000

$\sim$ 120 pc away now

kinematics $\rightarrow$ closest appraoch $\sim$ 100 pc (40 pc at 2σ)

Gamma-Ray Line Signatures

Gamma-Ray Line Signatures of Nearby SNe

Diffuse line emssion seen (so far) for ^{26}Al

Diehl talk; Oberlack etal 00, Knödlseder etal 99, Diehl etal 95

- Large scales: follows disk, sprial arms seen
  $\rightarrow$ massive stars (SN II, WR) Rauscher, Meynet talks
  Prantzos 91, Timmes etal 95, Knödlseder 99, Lentz & Branch 99
- Powerful diagnostic: SN rate, ^{26}Al nuke
- Supernova remnants: none seen as of Knödlseder etal 96

Expected point source flux

$$\Phi_\gamma = \frac{M_{\mathrm{ej},i} e^{-t/\tau}}{4\pi A_i m_p \tau R^2}$$

$$= 6 \times 10^{-5}\ e^{-t/\tau}\ \mathrm{cm^{-2}\,s^{-1}} \left(\frac{M_{\mathrm{ej},i}}{10^{-4}\,M_\odot}\right) \left(\frac{100\ \mathrm{pc}}{R}\right)^2$$

$\Rightarrow$ within INTEGRAL sensitivity if
$R \lesssim few \times 100$ pc: *nearby!*

Gamma-Ray Line Case Study
The Antlia Supernova Remnant

McCullough, BDF, Pavlidou 02

If SN nearby $\rightarrow$ remnant large on sky

An overlooked supernova remnant

Hα survey of S. Hemisphere:

- feature in Antlia Pneumatica
- filaments, shell structure 24° diameter
- above the Gal plane
- X-ray (ROSAT) feature in shell $\rightarrow$ hot gas

Distance estimates (dust column, diameter < 100 pc):

$100 \text{ pc} \lesssim R \lesssim 240 \text{ pc}$

$\Rightarrow$ nearby!

$\Rightarrow$ γ-line candidate

Gamma-Ray Line Case Study
The Antlia Supernova Remnant

McCullough, BDF, Pavlidou 02

Antila at 1.8 MeV

- $\sim 3\sigma$ significance Oberlack etal 00
- SN II yields Timmes etal 95
- $\Rightarrow$ 110 pc $\lesssim$ R $\lesssim$ 510pc: consistent!

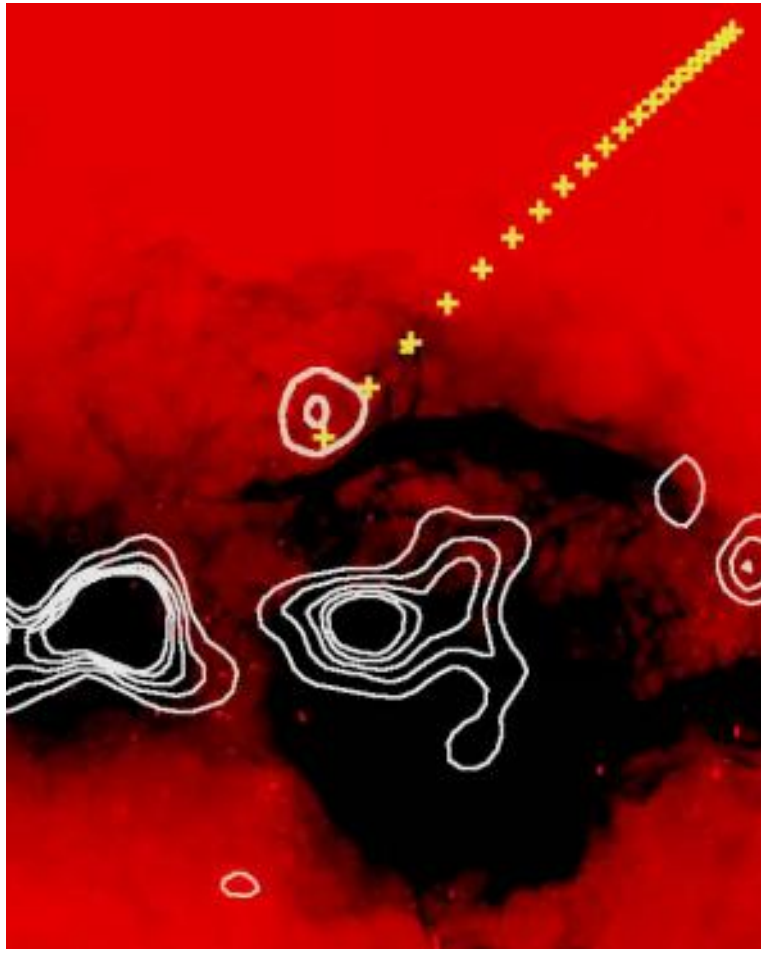
A juicy target for INTEGRAL!

- confirm ^{26}Al: first in SN remnant!
- spatially resolve?
- find ^{60}Fe $\rightarrow$ dist&age/yields

Nearby SN $\rightarrow$ high proper motion NS

- seek nearby, high-μ pulsar
- $\Rightarrow$ B0950+08 Pilkington 68
- backtrack: hits ^{26}Al "bulls-eye"!
- combine with COMPTEL ^{26}Al:

$R = 62 - 140$ pc, $t = 1.1 - 2.5$ Myr



Gamma-Ray Line Case Study
Vela Junior

1.16 MeV emission: ^{44}Ti ($\tau = 60$ yr)

- found in Cas A (age 320 yr) Iyudin etal 94, 97
- also in "Vela Junior" Iyudin etal 98

  expansion age ~ 680 yr

  $\Rightarrow$ distance ~ 200 pc

A Terrestrial Connection

NO_3^- in Antarctic ice: noise + spikes

produced in upper atm–measure ionizing radiation

large spikes $\Leftrightarrow$ SN1604, SN1572, SN1181 ?!

due to X-rays from nearby SN? Rood et al 79

unidentified spike ~ 1300 AD

$\Rightarrow$ maybe Vela Junior? Burgess & Zuber 00

Live Radioactivities: Outlook

Geological Signatures:

an emerging window to nucleosynthesis

Top priority: *Verify* ^{60}Fe *anomaly*

⋆ other samples

⋆ other isotopes

⋆ time resolution

⋆ verify null signal prior to event

Gamma-Ray Line Signatures:

an established, increasingly powerful tool

Top priority for nearby supernovae:

⋆ Identify (or limit) in remnants

⋆ multiple species (e.g., ^{26}Al and ^{60}Fe)

⋆ *r*-process? (e.g., ^{126}Sn)

Qian, Vogel, Wasserburg 98

The future is promising!

Nachbarsternsupernovaexplosionsgefahr
or
When Stars Attack!

Ill effects of a supernova too close
$\Rightarrow$ possible source of mass extinction

Russell & Tucker 71; Ruderman 74

Ionizing radiation

- initial γ, X, UV rays
  subsequent diffusive cosmic rays
- destroy ozone in atmosphere

  Ruderman 74; Ellis & Schramm 94

  $\longrightarrow$ solar UV kills bottom of food chain
  but true hazard unclear

  Crutzen & Brühl 96; Gehrels etal 03
- seeds cloud formation Svensmark 98; BDF & Ellis 99
  $\longrightarrow$ cosmic ray winter?

Neutrinos

- $\nu A \longrightarrow \nu A$ elastic scattering: DNA damage

  Collar 96