1-1-1993

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Mark D. Leising
Clemson University, lmark@clemson.edu

D Hartmann
Clemson University

Lih-Sin The
Clemson University

G Mathews
Lawrence Livermore National Laboratory

S E. Woosley
University of California

Recommended Citation

Please use publisher's recommended citation.

1993A&AS...97..219H

ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

JANUARY 1993, PAGE 219

Astron. Astrophys. Suppl. Ser. **97**, 219-220 (1993)

Gamma ray constraints on the galactic supernova rate

D. Hartmann[1], L.-S. The[1], D. D. Clayton[1], M. Leising[1], G.Mathews[2] and S. E. Woosley[3]

[1] Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, U.S.A.
[2] Department of Physics, Lawrence Livermore National Laboratory, Livermore, CA 94550, U.S.A.
[3] UCO/Lick Observatory, University of California, UCSC, Santa Cruz, CA 95064, U.S.A.

Received June 3; accepted June 19, 1992

Abstract. — Most Galactic optical supernovae are hidden due to severe extinction in the disk, but could be detectable through their γ-ray afterglow. ^{44}Ti is among the potentially detectable isotopes in supernova ejecta. HEAO 3 and SMM sky surveys have not detected gamma-ray lines from the decay of ^{44}Ti, thus constraining SN rates and nucleosynthesis. We perform Monte Carlo simulations of the γ-ray signatures of SN occuring during the last millenium to interprete the γ-ray paucity.

Key words: Gamma-rays — nucleosynthesis — stars: supernovae.

1. Introduction.

Consider the γ-ray signal from the decay $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$ with a mean life of 78.2 years (Frekers *et al.* 1983). Because of this short lifetime, detection of a γ-ray signal from ^{44}Ti involves either very recent or very near supernovae. The decay of ^{44}Ti generates γ-ray photons with energies 78.4 keV, 67.9 keV, and 1.157 MeV. The line flux at earth is $F_\gamma \sim 1 \times 10^{-2}\ M_{-4}\ e^{-t/78.2}$ where M_{-4} is the ejected ^{44}Ti mass in units of $10^{-4}\ M_\odot$ and distance, D, is measured in kpc. The detectability of such emission from a recent supernova and perhaps from a few older, nearby remnants make this nucleus a prime γ-ray target. It is clear, however, that the search for a ^{44}Ti signal deals with few events of the past couple of centuries, so that the interpretation of detection, or lack thereof, is similar in nature to that of ^{22}Na from novae (Higdon & Fowler 1987). Searches for ^{44}Ti line emission have been carried out with HEAO 3 (Mahoney *et al.* 1991, 1992) and SMM (Leising & Share 1992). No signal was detected with either experiment.

2. Monte carlo simulation.

^{44}Ti synthesis occurs predominantly in alpha-rich freeze-out, expected when low density matter falls out of NSE while cooling so rapidly that free alpha particles have insufficient time to reassemble to more massive nuclei. The abundance of ^{44}Ti is sensitive to pre-explosive details of stellar evolution as well as the explosion mechanism. For SN 1987A Woosley & Pinto (1988) estimate Ti production near $10^{-4}\ M_\odot$. Parametrized nucleosynthesis studies (Woosley & Hoffman 1991) find a Ti production ratio $P_{44} = {}^{44}\mathrm{Ti}/{}^{56}\mathrm{Fe} \sim P_{44\odot} \sim 1.2 \times 10^{-3}$. We randomly select the ejected ^{44}Ti mass in SNII as $M_{\mathrm{ej}} = \zeta P_{44\odot} M_{56}$, where ζ is randomly chosen between 0.5 and 2.0, and the ejected mass of ^{56}Fe varies between $2\times10^{-3} M_\odot$ and 0.3 $M_\odot$ for stars with initial mass between 10 $M_\odot$ and 35 $M_\odot$, respectively. Stellar masses are randomly drawn from a Salpeter IMF. The same prescription is used for SNIb, but the amount of ejected ^{56}Fe is fixed at $0.3 M_\odot$. For SNIa we use an iron mass between 0.25 $M_\odot$ and $0.75 M_\odot$, and ζ varies between 0.03 and 0.08. Galactic nucleosynthesis of ^{44}Ti could be dominated by SNII and SNIb, but from the point of view of γ-ray searches for individual Galactic events only the product $\zeta P_{44\odot}\ M_{56}$ counts.

The spatial distribution of Type Ia supernovae is assumed to resemble that of blue light (Higdon & Fowler 1987; Mahoney *et al.* 1991), with contributions from two distinct populations: disk and spheroid. Using the Bahcall-Soneira Galaxy model Mahoney *et al.* (1991, 1992) argue that the spheroid fraction of SNIa is about 1/6. The remaining two classes of events are thought to be associated with massive stars. We assume that their birth places are exponentially distributed in height above the plane with scale length of 50-100 pc, and ignore spiral structure.

Relative supernova rates are sensitive to galaxy type and the estimated Hubble type of the Milky Way (~ Sbc) implies the breakdown (Ia:Ib:II) = (1:1.6:8) (Tammann 1991). Supernovae are rare events in our Galaxy, only six are known to have occured during the last millenium. We can use historic events to constrain the range of acceptable mean Galactic supernova rates. Classification and peak magnitudes of the historic events are uncertain, but we follow van den Bergh (1990) for their breakdown (Ia:Ib:II) $\sim$ (1:2:3). Each of these events were brighter than $m_v = 0$. We assume that the historic record is complete above this level, but allow for a factor 2 uncertainty.

The absolute magnitude in the *B*-band for Type Ia supernovae is defined well enough to use SNIa as standard candles. Leibundgut & Tammann (1990) suggest $M_B(\max) = -18.3 + C$, where $C = 5 \log(h)$ depends on the choice of the Hubble constant in units of 100 km/s/Mpc. Supernovae of Type Ib are fainter than SNIa (Evans, van den Bergh, & McClure 1989): $M_B(\max) = -16.7 + C$. Still fainter at peak than SNIb's are Type II supernovae (Tammann & Schröder 1990) with $M_B(\max) = -15.7 + C$. To include underluminous SNII we add uniform random fluctuations with amplitude δM_B = 1.2 mag.

The average optical depth of the half disk in spiral galaxies is commonly assumed to be of order $\tau_p = 0.2$ (e.g., Sandage and Tammann 1981; but see Valentijn 1990). In the solar neighborhood the average extinction is $\tau_a = 1$ kpc^{-1} (Mihalas & Binney 1981). To account for the patchiness of the ISM we use a corrected optical depth $\tau_{\text{eff}} = \tau(D)\ (1 - (r - 1/2)\exp(-\tau(D)))$, where r is a uniform random variable. We consider a supernova optically detected if it is brighter than $m_v = 0$.

3. Results and conclusions.

Because of the short life time of ^{44}Ti the associated γ-ray glow is dominated by a few recent events. None of the known historic supernovae is either close or young (or both) enough to be detectable (assuming standard yields). Mahoney *et al.* (1991, 1992) searched the data of the HEAO 3 γ-ray experiment and found no evidence for Galactic ^{44}Ti hotspots. We employ their limiting line flux of $\sim 2 \times 10^{-4}$ photons/cm^2 s. Leising and Share (1992) searched almost ten years of SMM data and also did not detect ^{44}Ti emission. Their 99% confidence upper limits are 10^{-4} photons/cm^2 s for the 1.16 MeV line from arbitrary points near the Galactic center/anticenter and 2×10^{-4} photons/cm^2 s at longitudes $l = \pm 90°$.

Using our procedures for generating Galactic supernova events, we perform Monte Carlo simulations to determine the probabilities for their detection in γ-rays and in the optical band. For given total supernova rate one can then analytically calculate the total probabilities for consistency with the observed historic supernova record and the lack of γ-ray detections. For a typical set of input parameters and optical data alone, a supernova recurrence time of $t_{\text{rec}} \sim$ 10-40 years satisfies the constraints imposed by the historic record. A survey of models with varying total rate and ratio $\epsilon = \text{Ia}/(\text{Ia}+\text{Ib}+\text{II})$ shows that the combined optical/γ-ray data yield values that are consistent with those derived from extragalactic supernova searches. The model dependent "best fit" suggests $\log(t_{\text{rec}}) = 1.3 \pm 0.1$ and $\epsilon = 0.15 \pm 0.05$. We emphasize, that while the optical constraints alone are consistent with the wide range $t_{\text{rec}} \sim 10-40$ years, the addition of the γ-ray constraints reduce the model probability by almost one order of magnitude for t_{rec} as short as 10 years. Constraints on the recurrence time above $\sim$ 40 years are mostly due to the historic record, while below about 20 years they are due to the γ-ray data. The search for ^{44}Ti hotspots with the experiments aboard the recently launched Compton Observatory should either yield detection(s) or at least improved limits. Monte Carlo modeling can then be used to further constrain the rates and/or nucleosynthesis of Galactic supernovae (Hartmann *et al.* 1991).

Acknowledgements.

This research was supported in part by NASA grants NAG 5-1578 and NAGW-2525, NSF grants 8813649 and 9115367, and grants SF-ENG-48 and W-7405-ENG-48.

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