Radioactivity of the Key Isotope $^{44}$Ti in SN 1987A

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Abstract. We investigate radioactivity from the decay sequence of $^{44}$Ti in a young supernova remnant SN 1987A. We perform Monte-Carlo simulations of degradation of the nuclear lines to explain a late-time bolometric luminosity which is estimated from optical and near-infrared observation at 3600 days after the explosion. Assuming the distance to LMC in between 45.5 and 52.1 kpc, we have obtained the initial $^{44}$Ti mass of $(0.82 \pm 2.3) \times 10^{-4} M_\odot$ within the current uncertainty of the physical quantities. The resulting fluxes of $\gamma$- and hard X-rays emerged from the $^{44}$Ti decay are estimated and compared with the line sensitivity of the INTEGRAL/SPI on board and that of NeXT X-ray satellite planned to be launched in 2010. The effect of $^{44}$Ti ionization on the estimated fluxes is briefly remarked.

INTRODUCTION

To detect the nuclear $\gamma$-rays from the decay sequence of $^{44}$Ti is one of the prime target in the current and future $\gamma$-ray and X-ray satellites. In particular, SN 1987A, appeared 16 years ago in the Large Magellanic Cloud (LMC), is providing us with a challenge as the one of such targets.

The important feature of detecting $^{44}$Ti nuclear lines from young supernova remnants can be summarized as follows: The initial yield of $^{44}$Ti that is synthesized by a single event of a core-collapse supernova explosion is very crucial to constrain dynamics of core-collapse supernova nucleosynthesis. This is because $^{44}$Ti is synthesized at the vicinity of the so-called mass cut, that divides the matter which accretes on a compact object and the ejecta which is scattered into interstellar space. For this, the initial mass of $^{44}$Ti depends sensitively on 1) the location of the mass cut, 2) the maximum temperature and the maximum density behind the shock wave, and 3) the internal structure ($\lesssim 2 M_\odot$ from the center) of a progenitor.

So far, 1.16 MeV nuclear line that is emitted from the decay-chain of $^{44}$Ti (see below) was detected from Cassiopeia A with COMPTEL/CGRO experiment [1,2] and this was confirmed with BeppoSAX by detecting associated 67.9 and 78.4 keV nuclear lines [3]. It should be noted here that RXJ0852-4622, the “Vela Junior” remnant, was first discovered by the 1.16 MeV $\gamma$-ray line as a point source [4], and then discovered in X-rays [5]. In the near future, $^{44}$Ti nuclear lines are expected to be detected from the

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other young (≲ a few × 1000 yrs) galactic supernova remnants and SN 1987A in LMC. Further, galactic survey of $^{44}$Ti nuclear lines may dig out unknown supernova remnants which is difficult to be caught in the other electromagnetic wavelengths, and may give us even a scrap of information on the galactic supernova rate.

The decay sequence of the radioactive $^{44}$Ti is the following: $^{44}$Ti decays by orbital electron capture mainly to the second excited state of $^{44}$Sc (branching ratio of 99.3%). The decay is soon followed by the emissions of 67.9 keV and 78.4 keV nuclear de-excitation lines to the ground state of $^{44}$Sc. Although until recently the half-life of $^{44}$Ti showed a large uncertainty in those measured in laboratories, compilation of recent 8 experiments which were performed after 1998 (see., e.g., [6] and references therein; [7]) gives weighted mean half-life of $t_{1/2} = 60 \pm 1$ yr (the error is 1 σ, statistical). The daughter nucleus, $^{44}$Sc, then decays almost exclusively by positron emission to the first excited state of $^{44}$Ca, which emits 1.16 MeV deexcitation line to the ground state. The ground state of $^{44}$Ca is stable. The emitted positron in the above sequence ends up with 511 keV annihilation line. It is noted that the halflife of $^{44}$Sc is merely 3.93 hrs, so that the timescale and hence the radioactivity of the whole decay chain is regulated by the halflife of $^{44}$Ti.

We note that laboratory experiments measure the halflife of neutral $^{44}$Ti. The crucial point here is that $^{44}$Ti decays only by orbital electron capture. This is because the decay Q-value from the ground state of $^{44}$Ti to the second excited state of $^{44}$Sc is less than twice the electron rest mass, which is at least required for positron emission to be allowed by producing two 511 keV $\gamma$-photons when a positron annihilates with an electron (and so does that to the first excited state of $^{44}$Sc for the rest of the minor fraction of the branch). Actually the halflife of highly ionized $^{44}$Ti becomes longer than that of neutral $^{44}$Ti and this affects the radioactivity. Thus, we should be careful to apply the experimental halflife to this problem: The electric environment of $^{44}$Ti in a young supernova remnant may be different from that in laboratories.

Previous studies on the $^{44}$Ti ionization effect on its radioactivity are found in references [8, 9]; these mainly discuss Cassiopeia A. A recent paper [10] includes a linear analysis in order to simply show why and how the $^{44}$Ti ionization affects its radioactivity. As we shall see later, there is a clear possibility of ionization of $^{44}$Ti ongoing in SN 1987A. In this article, we first derive the expected nuclear fluxes without consideration of the $^{44}$Ti ionization. We then briefly discuss how the possibly-ongoing $^{44}$Ti ionization may change this estimate in the near future, using the result of the linear analysis presented in [10].

**$^{44}$Ti Radioactivity in SN 1987A**

Figure 1 depicts observation-based data of bolometric luminosity and theoretically calculated light curves. The observed light curve in early time is first governed by the radioactive decay of $^{56}$Ni ($t_{1/2} = 6.1$ d) and then that of its daughter $^{56}$Co ($t_{1/2} = 77.3$ d). The synthesized $^{56}$Co nuclide decays mainly by positron emission to stable $^{56}$Fe. Until ≈ 800 days after the explosion, the light curve observed in the wavelength ranging from ultraviolet to infrared has been successfully modeled with the energy supply from the
FIGURE 1. Evolution of the bolometric luminosity of SN 1987A. Observed luminosity data are shown (see the text). The thick solid line denotes a theoretical light curve with the $^{44}$Ti half-life of $t_{1/2} = 63$ yrs and the short-dashed line denotes that with $t_{1/2} = 57$ yrs. The long-dashed line shows a theoretical contribution from the $^{57}$Co decay, and the dash-dotted line that from the $^{56}$Co decay. The dotted and thin solid lines denote the contributions from the $^{44}$Ti decays that correspond to $t_{1/2} = 57$ yrs and 63 yrs, respectively.

decay of $^{56}$Co (see [11] for details).

Afterwards, the decline of the observed light curve apparently slowed down, suggesting the presence of the other heating source. As the next source, $^{57}$Co ($t_{1/2} = 272$ d) plays a role in the luminosity. This epoch does not last long, however. The slowness of the decline of the observed light curve becomes distinguished in particular after $\sim 1500$ days (see Fig. 1). The dominant energy source at this moment is believed to be the $^{44}$Ti decay.

Suntzeff [12] reported a bolometric luminosity at 3600 days, i.e., 10 years after the explosion. He used the bolometric corrections to the optical colors VK to estimate a bolometric magnitude under the assumption that the flux distribution was indeed frozen. Under this assumption, he obtained a bolometric luminosity, $L_{97} = (1.9 \pm 0.6) \times 10^{36}$ erg sec$^{-1}$, at 3600 days after the explosion. In the following, this bolometric luminosity $L_{97}$ is referred to as the S97 bolometric luminosity. The author also estimated a bolometric luminosity of $\sim 1.0 \times 10^{36}$ erg sec$^{-1}$ at 4151 days after the explosion under the assumption that the same bolometric corrections from day 1800 [13].
The above-mentioned observational data and observation-based values of bolometric luminosity are shown in Fig. 1.

To explain the upper and the lower bound of the S97 bolometric luminosity at 3600 days after the explosion [12], we performed Monte-Carlo simulations of Compton degradation of the nuclear $\gamma$-photons of $^{57}$Co (14 keV, 122 keV, 136 keV, etc.) and $^{44}$Ti (68 keV, 78 keV, 511 keV, 1.16 MeV). The UV, optical, and IR photons originate from the energy loss of the emitted $\gamma$-rays during the radiative transfer in the ejecta.

To determine the velocity distribution of particles, we adopt the explosion model 14E1 [14] whose main-sequence mass, the ejecta mass, and the explosion energy are 20 $M_\odot$, 14.6 $M_\odot$ (4.4 $M_\odot$ core material plus 10.2 $M_\odot$ hydrogen-rich envelope), and $1 \times 10^{51}$ erg, respectively. This model was derived from a detailed analysis of the plateau shape of the light curve of SN 1987A which was observed until 120 days after the explosion, and well accounts for the earlier optical, X-ray, and $\gamma$-ray light curves of SN 1987A [15]. Note that the $^{56}$Ni mass in SN 1987A has been constrained as 0.07 $M_\odot$ from the intensity during the observed exponential decline.

Note also that at the period of the S97 observation the ionization of $^{44}$Ti was not relevant. Later, the supernova blast shock crashed into the dense inner ring, and the shock heating started to ionize the elements (see below). We therefore use the experimental halflife of neutral $^{44}$Ti: $t_{1/2} = 60 \pm 3$ yrs (3$\sigma$ deviation) to explain the S97 bolometric luminosity. The distance to SN 1987A is adopted to be 48.8 $\pm$ 3.3 kpc (3$\sigma$, see [16]). Other details of our calculation are found in [11]; in the present study, the adopted nuclear decay parameters have been updated.

In Fig. 1, two calculated bolometric light curves which stick to the upper bound of the S97 luminosity are also shown. The difference of the two theoretical curves is in the adopted halflife of neutral $^{44}$Ti; the one is calculated with $t_{1/2} = 57$ yrs and the other with $t_{1/2} = 63$ yrs. One sees in Fig. 1 that the current uncertainty in the $^{44}$Ti halflife no longer produces a remarkable difference in the light curve.

The upper-bound light curve gives $<^{44}$Ti/$^{56}$Ni$>$ = 2.9, where $<^{44}$Ti/$^{56}$Ni$>$ is defined as $<^{44}$Ti/$^{56}$Ni$> = [X(44Ti)/X(56Ni)]_{87A}/[X(44Ca)/X(56Fe)]_{87A}$, i.e., the ratio of $^{44}$Ti/$^{56}$Ni in amount in SN 1987A to $^{44}$Ca/$^{56}$Fe in the solar neighborhood. The obtained value 2.9 for the upper bound is considered to be acceptable. One of the reasons for this is that the synthesized amount of $^{44}$Ti theoretically tends to be more abundant in aspherical supernovae than in spherical ones; actually recent Hubble Space Telescope images and spectroscopy have revealed that SN 1987A has an aspherical geometry [17]. Translated from the obtained $<^{44}$Ti/$^{56}$Ni$>$ values, we find the initial $^{44}$Ti mass of $(0.82 - 2.3) \times 10^{-4} M_\odot$ within the known uncertainty of the experimental values mentioned above.

Figure 2 shows the expected nuclear fluxes at 6000 days after the explosion (i.e., in 2003) for both the obtained upper and the lower bounds of the initial $^{44}$Ti mass. It is worthwhile to mention here that the obtained $^{44}$Ti masses depend on the assumed distance to SN 1987A, but the expected fluxes do not. In Fig. 2, the line sensitivity of INTEGRAL/SPI on board and that of the planned NeXT mission are also shown for comparison.

We see in Fig. 2 that, with $10^6$ sec observation time, it might be difficult for INTEGRAL/SPI to detect the $^{44}$Ti nuclear lines from SN 1987A. We note that our upper
Predicting the nuclear fluxes associated with the $^{44}$Ti decay in SN 1987A at 6000 days after the explosion (i.e. in 2003). The line sensitivity of INTEGRAL SPI on board for the typical observation time $10^6$ sec and that of the NeXT mission for the typical observation time of $10^5$ sec are also shown for comparison. The NeXT satellite is planned to be launched in 2010.

The bound estimate relies on the upper bound of the S97 bolometric luminosity, which was estimated under the assumption described previously and corresponds to usual $1\sigma$ deviation: There is a possibility that the starting point, the bolometric luminosity itself, may be larger. Theoretically, on the other hand, the larger bolometric luminosity corresponds to the larger $<^{44}\text{Ti}^{56}\text{Ni}>$ value. The feasibility of the largest $<^{44}\text{Ti}^{56}\text{Ni}>$ value remains to be solved, but too large a value could not be naturally adopted.

Finally, we point out that the ionization process of $^{44}$Ti is considered to be well underway in SN 1987A, due to shock heating caused by the collision of the supernova blast shock with the dense inner ring: H-like and He-like ionization stages of O, Ne, Mg, and Si have been already observed, and also SN 1987A is observed to be a very rapidly evolving remnant (see [18, 19]). If $^{44}$Ti reaches the high-ionization stages in the future, the expected fluxes shown in Fig. 2 will become smaller, as discussed in the linear analysis presented in [10]. To get a rough idea, if all $^{44}$Ti should be in the He-like (H-like) ionization state, the radioactivity of SN 1987A would suffer a $\sim 9$ (45) \% reduction (see Table 1 of [10]). Under the realistic situation in which the ionization of the elements evolves by the shock heating, various ionization stages will be led. Even in such a case, 68, 78, 511 keV lines appear to be detectable with a planned detector.
on a future mission such as NeXT (see Fig. 2). Actual conclusion of the effect of the ionization on the radioactivity requires the knowledge of the temperature and the density evolution of the supernova remnant, and this will be a future subject for SN 1987A.

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