THE END OF AMNESIA: A NEW METHOD FOR MEASURING THE METALLICITY OF TYPE Ia SUPERNOVA PROGENITORS USING MANGANESE LINES IN SUPERNOVA REMNANTS

CARLES BADENES,1,2 EDUARDO BRAVO,3 AND JOHN P. HUGHES4

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ABSTRACT

We propose a new method to measure the metallicity of Type Ia supernova progenitors using Mn and Cr lines in the X-ray spectra of young supernova remnants. We show that the Mn-to-Cr mass ratio in Type Ia supernova ejecta is tightly correlated with the initial metallicity of the progenitor, as determined by the neutron excess of the white dwarf material before thermonuclear runaway. We use this correlation, together with the flux of the Cr and Mn Kα X-ray lines in the Tycho supernova remnant recently detected by Suzaku, to derive a metallicity of log (Z) = −1.32^{0.07}_{−0.03} for the progenitor of this supernova, which corresponds to log (Z/Z⊙) = 0.60^{0.67}_{−0.64}, according to the latest determination of the solar metallicity by Asplund and coworkers. The uncertainty in the measurement is large, but metallicities much smaller than the solar value can be confidently discarded. We discuss the implications of this result for future research on Type Ia supernova progenitors.

Subject headings: binaries: close — supernova remnants — supernovae: general — X-rays: ISM

1. INTRODUCTION

Despite decades of continuing effort, the nature of the progenitor systems of Type Ia supernovae (SNe) remains unknown. The most widely accepted theoretical scenarios involve the thermonuclear explosion of a C+O white dwarf (WD) destabilized by accretion of material from a binary companion, either another WD (double degenerate systems, DDs) or a normal star (single degenerate systems, SDs). Observations of supernova rates in distant galaxies suggest at least two different ways to produce Type Ia SNe (Scannapieco & Bildsten 2005): a “prompt” channel associated with young stellar populations and a “delayed” channel associated with old stellar populations. At present, it is not clear what relationship, if any, these channels have with the theoretical scenarios, or even if the proposed scenarios can yield Type Ia SNe at the observed rate ( Maoz 2008). Most attempts to constrain the fundamental properties of the progenitors have been unsuccessful, including direct identification in optical preexplosion images (Maoz & Mannucci 2008), searches for H stripped from the binary companion in SN spectra (Leonard 2007), and searches for prompt emission from circumstellar interaction (Panagia et al. 2006; Hughes et al. 2007). Very recently, the possible identification of the progenitor in a preexplosion X-ray image of SN 2007on by Voss & Nelemans (2008) has been questioned by postexplosion images (Roelofs et al. 2008). Campaigns to look for the surviving companion star to the exploded WD in the nearby Tycho supernova remnant (SNR), known to be of Type Ia origin, have also produced controversial results (Ruiz-Lapuente et al. 2004; Ihara et al. 2007). This lack of clues to the identity of the progenitors in the observations of Type Ia SNe is sometimes referred to as “stellar amnesia.”

One of the most important constraints on the age and nature of the progenitor systems is their metallicity Z. During stellar evolution, the C, N, and O that act as catalysts for the CNO cycle pile up into 14N, which is converted to 22Ne in the hydrostatic He burning phase through the reactions ^14N(α, γ)^18F(γ, e^−)^18O(α, γ)^20Ne. The β− decay of ^18F increases the neutron excess of the WD material, defined as \[ η = 1 - \frac{Z_i}{A} \] (where \( Z_i \) is the atomic number and \( A \) is the mass number), resulting in a linear scaling of \( η \) with metallicity: \[ η = 0.101 \times Z \] (Timmes et al. 2003). This can have an observable impact on Type Ia supernova spectra (Lentz et al. 2000), but the predicted effects are hard to detect in practice (in one case, SN 2005bl, a progenitor of subsolar metallicity has been suggested by Taubenberger et al. 2008). In this Letter, we describe a new direct method to measure the metallicity of Type Ia SN progenitors using Mn and Cr lines from shocked ejecta in the X-ray spectra of SNRs.

2. THE Mn/Cr RATIO AS A TRACER OF PROGENITOR METALLICITY

2.1. Mn/Cr vs. Z

Nuclear burning in Type Ia SNe happens in different regimes depending on the peak temperature reached by the WD material. From higher to lower temperatures, the regimes are nuclear statistical equilibrium (NSE), incomplete Si burning, incomplete O burning, and incomplete C-Ne burning (Woosley 1986). During the explosion itself, electron captures are too slow to change the original value of \( η \) except in the innermost \( ∼0.2 \) M⊙ of ejecta, where nuclear burning happens at higher densities, leading to neutron-rich NSE (Brachwitz et al. 2000). Outside this region, an imbalance between free neutrons and protons does not affect the production of the most abundant species, with the possible exception of 56Ni at supersolar metallicities (Timmes et al. 2003). However, some trace nuclei with unequal numbers of protons and neutrons are very efficient at storing the neutron excess. The most abundant among these nuclei is 55Mn, which is produced during incomplete Si burning as 55Co. When normalized to another product of incomplete Si burning whose nucleosynthesis is insensitive to the neutron excess (Cr is the ideal choice), the yield of Mn becomes an excellent tracer of the progenitor metallicity.

This diagnostic can be quantified with Type Ia SN explosion models. We have used the model grid from Badenes et al. (2003,
2005) complemented with other models calculated with the code described in Bravo et al. (1996). Physical inputs and initial conditions are as in Badenes et al. (2003) except in the cases noted below. We consider examples of several explosion mechanisms: deflagrations, delayed detonations, and pulsating delayed detonations. For the present work, we have recalculated the nucleosynthesis of four delayed detonation models (DDTa, DDTc, DDTe, and DDTf) at different metallicities by altering the value of $X(^{20}\text{Ne})$ in the preexplosion WD from the canonical 0.01 (corresponding to $Z = 9.0 \times 10^{-5}$). We have also calculated one deflagration model starting from a central density twice as large as the other models, and one delayed detonation model with the C to O mass ratio $M_c/M_O = 1/3$ in the WD instead of the usual 1. In spite of these fundamental differences in explosion mechanisms and initial conditions, we find a very tight correlation between the Mn to Cr mass ratio outside the neutron-rich NSE region in the SN ejecta, $M_{\text{Mn}}/M_{\text{Cr}}$, and the progenitor metallicity $Z$ (see Fig. 1). A power-law fit yields the following relation (with a correlation coefficient $r^2 = 0.9975$):

$$M_{\text{Mn}}/M_{\text{Cr}} = 5.3 \times Z^{0.65}.$$ \hfill (1)

Removal of the inner 0.2 $M_\odot$ of neutron-rich NSE material from this relation is justified because (1) there is observational evidence that this material does not mix outward during the explosion (Gerardy et al. 2007; Mazzali et al. 2007) or its aftermath (Fesen et al. 2007); and (2) the dynamical ages of most ejecta-dominated Type Ia SNRs are too small for the reverse shock to have reached so deep into the ejecta. For illustration, we have plotted in Figure 1 the core-collapse SN models from Woosley & Weaver (1995) which also show some correlation between $M_{\text{Mn}}/M_{\text{Cr}}$ and $Z$, albeit with a much larger spread and a much shallower slope.

2.2. The Impact of C Simmering

In order for equation (1) to hold, the value of $\eta$ set by the progenitor metallicity must remain unchanged between the formation of the WD and the SN explosion. This should be true for DD progenitors if the final merger and runaway happen on dynamical timescales. In slowly accreting WDs, $\eta$ can be modified through electron captures during the so-called simmering phase of nonexplosive C burning that takes place in the $\sim 1000$ yr prior to the explosion (Piro & Bildsten 2008). The impact of this additional neutronization on the $M_{\text{Mn}}/M_{\text{Cr}}$ ratio will depend on the extent of the convective region over which the neutronized material is mixed ($M_{\text{conv}}$), and its overlap with the portion of the WD that will undergo incomplete Si burning where Mn and Cr are synthesized.

Some previous studies (Kuhlen et al. 2006; Piro & Bildsten 2008; Chamulak et al. 2008) have found large values for $M_{\text{conv}}$ by assuming a homogeneous chemical composition for the WD, effectively applying the Schwarzschild criterion for convection. We will adopt the hypothesis that the convective region is limited by the Ledoux criterion to the C-depleted core of the WD created during hydrostatic He-shell burning, $M_{\text{core}}$ (Höflich & Stein 2002). In the absence of a self-consistent picture for convection inside WDs, this must remain an open issue (see Piro & Chang 2008 for a discussion), but we believe that our hypothesis is reasonable given the existence of other processes that can reduce the extent of $M_{\text{conv}}$ and limit the mixing of neutronized material. These include the presence of Urca shells (Stein & Wheeler 2006) and the long thermal diffusion timescale for buoyant bubbles larger than $\sim 100$ m (Garci-Senz & Woosley 1995), which prevents them from mixing completely with their surroundings during convection.

According to Mazzali et al. (2007) Si-rich ejecta in Type Ia SNe lie between Lagrangian mass coordinates 1.05 and 1.55 $M_\odot$, with main-sequence progenitor masses of 3 and 6 $M_\odot$, respectively (see § 2.2). The horizontal solid and dotted lines represent the estimated $M_{\text{Mn}}/M_{\text{Cr}}$ ratio in the Tycho SNR from the Suzaku observations (0.74 ± 0.047, shaded in gray), which corresponds to log $(Z) = -1.32$ (Asplund et al. 2005) into the incomplete Si burning region, in a proportion equivalent to the extent of overlap between $M_{\text{conv}}$ and the Si-rich ejecta depends on the main-sequence mass $M_{\text{MS}}$ and initial metallicity of the WD progenitor (which determine $M_{\text{core}}$, Domínguez et al. 2001) and the SN brightness (see Fig. 2). This overlap is only significant for subluminous ($\Delta m_{15} \geq 1.6$) Type Ia SNe originated by progenitors with either large $M_{\text{MS}}$ or low $Z$, or both. Chamulak et al. (2008) find an upper limit for the increase of $\eta$ during the simmering phase of $\Delta \eta = 0.0015$, which is comparable to the value of $\eta$ in solar material. The impact of simmering on the $M_{\text{Mn}}/M_{\text{Cr}}$ ratio can then be estimated by mixing material with $M_{\text{Mn}}/M_{\text{Cr}} = 0.3$ (appropriate for the value of $Z_0$ derived by Asplund et al. 2005) into the incomplete Si burning region, in a proportion equivalent to the extent of overlap shown in Figure 2. The green and orange plots in Figure 1 are two examples of such “simmering modified” models for very subluminous ($\Delta m_{15} = 1.8$) Type Ia SNe, illustrating our conclusion that C simmering will only modify the $M_{\text{Mn}}/M_{\text{Cr}}$ ratio in the SN ejecta for very subluminous SNe, and then only in cases where $M_{\text{MS}}$ is large or $Z$ is low, or both.

3. MEASURING THE $M_{\text{Mn}}/M_{\text{Cr}}$ RATIO IN SNRS

The work in this Letter is motivated by the recent Suzaku detection of Mn and Cr in the X-ray spectrum of the Tycho SN reported by Tamagawa et al. (2008) (see Fig. 3). This observational result opens the possibility of studying the $M_{\text{Mn}}/M_{\text{Cr}}$ ratio in Type Ia SN ejecta, which cannot be done using optical SN spectra due to the 2.7 yr half-life of $^{55}\text{Fe}$ in the decay chain $^{55}\text{Co} \rightarrow ^{55}\text{Fe} \rightarrow ^{55}\text{Mn}$. Since Mn and Cr are
for different plots \( (M_\text{s}/F) \) (2001) (for at, we have taken the average between \( E \) from the faint Mn and Cr lines, and it will be reduced in an is dominated by the statistical uncertainties in the X-ray fluxes SNR [\( \text{[Fe/H]} \)]. The large error bar in this result gives . This mass ratio translates into a metallicity of for the progenitor of the Tycho SNR gives . This mass ratio translates into a metallicity of for the progenitor of the Tycho SNR.

of the plane plotted in Figure 4, we find( interpolated values for the ratio. For the larger region of the parameter space that is populated by young( timescale and electron temperature \( kT \) al. 2001) to retrieve \( K \). We have used the ATOMDB database (Smith et et al. 2004). This combination of Galactocentric radius and metallicity suggests a young progenitor age (a few Gyr or less), which would make Tycho a candidate for the “prompt” channel

4. DISCUSSION AND CONCLUSIONS: THE METALLICITY OF TYCHO’S PROGENITOR

From the Suzaku observation, \( F_{\text{Mn}}/F_{\text{Cr}} = 0.46 \pm 0.21 \), which gives \( M_{\text{Mn}}/M_{\text{Cr}} = 0.74 \pm 0.47 \). This mass ratio translates into a metallicity of \( Z = 0.048^{+0.053}_{-0.030} \) for the progenitor of the Tycho SNR \( \log (Z) = -1.32^{+0.33}_{-0.37} \). The large error bar in this result is dominated by the statistical uncertainties in the X-ray fluxes from the faint Mn and Cr lines, and it will be reduced in an upcoming, approved deeper Suzaku observation. At present, we find a strong indication for a supersolar metallicity \( \log (Z/\text{\odot}) = 0.45^{+0.31}_{-0.46} \) with the solar value from Grevesse & Sauval (1998); \( \log (Z/\text{\odot}) = 0.60^{+0.31}_{-0.46} \) with the newer value from Asplund et al. (2005). Our results are compatible with a solar metallicity, but subsolar values can be discarded with confidence. Given this measurement and the fact that Tycho’s SN was probably either normal or slightly overluminous (Badenes et al. 2006; Ruiz-Lapuente 2004), we do not have to concern ourselves with the impact of neutronization during C simmering in this particular case. The Tycho SNR is 59 pc above the Galactic plane at a Galactocentric radius of 9.4 kpc (assuming a distance of 2.4 kpc; Smith et al. 1991). A supersolar metallicity is higher than average for this location, but well within the spread of measured [Fe/H] values (Nordström et al. 2004). This combination of Galactocentric radius and metallicity suggests a young progenitor age (a few Gyr or less), which would make Tycho a candidate for the “prompt” channel

FIG. 2.—Upper limits to \( M_{\text{Mn}} \) during the simmering phase (left axis, black plots) and its overlap with the Si-rich region of ejecta (right axis, colored plots) as a function of \( Z \). The black plots represent quadratic interpolations for different \( M_{\text{Mn}} \): 3 \( M_\odot \) (dashed curves), 5 \( M_\odot \) (dotted curves), and 6 \( M_\odot \) (solid curves), with the symbols indicating the values from Domínguez et al. (2001) (for \( M_{\text{Mn}} = 6 M_\odot \) at \( Z = 0.02 \), we have taken the average between \( M_{\text{Mn}} = 7 M_\odot \) and \( M_{\text{Mn}} = 5 M_\odot \)). The colored plots represent the overlap (in %) between \( M_{\text{Mn}} \) and the Si-rich region of ejecta, for very subluminous \( \Delta m_{\text{Mn}} = 1.8 \) (red), mildly subluminous \( \Delta m_{\text{Mn}} = 1.6 \) (orange), and normal, but faint \( \Delta m_{\text{Mn}} = 1.4 \) (blue), Type Ia SNe.

FIG. 3.—X-ray spectrum of the Tycho SNR observed by Suzaku in the vicinity of the Fe Kα line. The Kα lines of Cr and Mn are detected at \( >10 \) and 7 \( \sigma \) confidence levels, with fluxes of \( 2.45^{+0.33}_{-0.43} \times 10^{-5} \) and \( 1.13^{+0.38}_{-0.43} \times 10^{-5} \) photons cm\(^{-2}\) s\(^{-1}\), respectively (Tamagawa et al. 2008).

FIG. 4.—Interpolated Mn-to-Cr specific Kα emissivity ratio as a function of \( n_T \) and \( kT \). The dotted box encompasses the values of \( n_T \) and \( kT \) found in the Si-rich ejecta of six young Type Ia SNRs by Badenes et al. (2007): \( 9.49 \) cm\(^{-3}\) s\(^{-1}\) \( \leq \log (n_T) \leq 11.94 \) cm\(^{-3}\) s\(^{-1}\); \( 1.0 \) keV \( \leq kT \leq 10.0 \) keV. The striped area corresponds to the region of parameter space appropriate for the Tycho SNR, \( 10.23 \) cm\(^{-3}\) s\(^{-1}\) \( \leq \log (n_T) \leq 10.99 \) cm\(^{-3}\) s\(^{-1}\); \( 1.0 \) keV \( \leq kT \leq 10.0 \) keV.
of Type Ia SNe, but the scatter in the age-metallicity relations and the uncertainties in our measurement are too large to be more specific on this point.

In this Letter, we have proposed a new method to measure the metallicity of Type Ia progenitors using Mn and Cr lines in the X-ray spectra of their SNRs. We have applied it to the Tycho SNR and obtained a strong indication that its progenitor had a solar or supersolar metallicity. The main strength of our method is its simplicity: it is based on well-known nuclear physics and observable parameters that are easy to measure. Detection of Mn and Cr lines in other young Type Ia SNRs in the Galaxy should be possible with Suzaku, Chandra, and XMM-Newton observations. A few additional SNRs in the Magellanic Clouds might be reached with deep exposures, bringing the total of potential targets to perhaps a dozen. This number would increase significantly with the inclusion of SNRs in nearby galaxies such as M31 and M33, which may be accessible to next-generation X-ray observatories such as Constellation-X and XEUS. Even with a small sample of objects, we should be able to use this method to verify and complement the indirect metallicity studies of extragalactic Type Ia SNe (Gallagher et al. 2005; Prieto et al. 2008) and test claims about the metallicity dependence of the Type Ia SN rate (Kobayashi et al. 1998). Measurements or upper limits below a certain threshold \((M_{\text{obs}}/M_\odot \leq 0.1)\) would also provide interesting constraints on the extent of the convective region in accreting WDs. We conclude by noting that Mn and Cr lines have already been detected by ASCA in the Galactic SNR W49B (Hwang et al. 2000). The measured line flux ratio also suggests a solar or supersolar progenitor metallicity, but both the age and the SN type of W49B are controversial (Hwang et al. 2000; Badenes et al. 2007). We defer a detailed discussion of this object and the application of our method to other Galactic SNRs to a forthcoming publication.

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