The End of Amnesia: Measuring the Metallicities of Type Ia SN Progenitors with Manganese Lines in Supernova Remnants

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Abstract. The Mn to Cr mass ratio in supernova ejecta has recently been proposed as a tracer of Type Ia SN progenitor metallicity. We review the advantages and problems of this observable quantity, and discuss them in the framework of the Tycho Supernova Remnant. The fluxes of the Mn and Cr Kα lines in the X-ray spectra of Tycho observed by the Suzaku satellite suggests a progenitors of supersolar metallicity.

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MN/CR AS A TRACER OF METALLICITY IN TYPE IA SN PROGENITORS

The recent detection of the Cr and Mn Kα lines in the X-ray spectrum of the Tycho Supernova Remnant (SNR) by the Japanese satellite Suzaku [1] has opened the possibility to study secondary Fe-peak nuclei in the shocked ejecta of Type Ia SNRs. The presence of Mn in particular, which has an odd atomic number, has important implications for constraining several properties of Type Ia progenitors, as described by Badenes et al. in [2]. Under the appropriate conditions, the Mn to Cr mass ratio in the ejecta of Type Ia SNe (M_{Mn}/M_{Cr}) can be used to calculate the metallicity of the SN progenitor. In these Proceedings, we expand on the information presented in [2], providing more details on the models, the advantages and limitations of M_{Mn}/M_{Cr} as a tracer of progenitor metallicity, and the applicability of the method to current and future X-ray observations of SNRs.

The rationale for the use of M_{Mn}/M_{Cr} as a tracer of progenitor metallicity Z was explained in detail in [2]. It is based on an argument by Timmes et al. [3] that connects

Here and in [2], we define Z as the mass fraction of all elements heavier than He. Note that the correspondence between this theoretical quantity and a given observational tracer of metallicity (like [Fe/H], for instance) is not necessarily trivial.
the amount of C, N, and O in the progenitor star (and hence its Z) to the trace amount of $^{22}$Ne that is present in the CO white dwarf (WD) that will eventually explode as a SN Ia. During the explosion itself, both $^{55}$Co and $^{52}$Fe (the parent nuclei of $^{55}$Mn and $^{52}$Cr, respectively) are synthesized in the incomplete Si burning regime. These nuclides belong to a quasi-statistical equilibrium group dominated by $^{56}$Ni. While $^{52}$Fe is linked to $^{56}$Ni by the reaction $^{52}$Fe($\alpha$, $\gamma$)$^{56}$Ni, which is not sensitive to $\eta$, $^{55}$Co is linked to $^{56}$Ni by the $^{55}$Co(p,$\gamma$)$^{56}$Ni reaction. In this last reaction, the proton abundance is strongly dependent on $\eta$, with larger values of $\eta$ leading to lower proton abundances, which favors the synthesis of $^{55}$Co in progenitors with high metallicity. In this context, it is worth mentioning the work of [4], who find evidence for a metallicity dependent yield of Mn in SN Ia, with Mn synthesis appearing enhanced in high metallicity stellar systems like the Galactic bulge.

In [2], the nucleosynthetic output of 36 Type Ia SN models calculated with different trace amounts of $^{22}$Ne in the CO WD was examined to quantify the relationship between Z and $M_{Mn}/M_{Cr}$ (Figure 1). In these calculations, the inner 0.2 M$_{\odot}$ of ejecta were not included in the final Mn/Cr ratio. Inside this region, neutron-rich nuclear statistical equilibrium (NSE) takes place, and minor quantities of Mn and Cr are produced at a mass ratio that is independent of the value of Z. Removal of the n-rich NSE products is justified by the fact that the reverse shock in most ejecta-dominated Type Ia SNRs in our Galaxy has not reached the inner 0.2 M$_{\odot}$ of ejecta, and this material does not appear to mix into the outer layers either during the SN phase [5] or the SNR phase [6]. Another argument that supports the exclusion of the n-rich NSE products from an observational point of view is the absence of the K\alpha line from Ni in the same exposure of the Tycho SNR that revealed the Mn and Cr lines [1]. If a large amount of n-rich NSE material (or for that matter, of any kind of NSE material) had been thermalized by the reverse shock, this line would show up at 7.5 keV in the Suzaku spectrum. Fitting a power law to the points shown in Figure 1 yields the relation $M_{Mn}/M_{Cr} = 5.3 \times Z^{0.65}$ [2], which is virtually independent of the details of the explosion dynamics.

**THE IMPACT OF C SIMMERING ON THE MN/CR RATIO**

Before a slowly accreting WD explodes as a SN Ia, there is a $\sim$ 1000 yr long phase of slow C fusion in its core. The energy input from this ’simmering’ creates a more or less extended convective region inside the WD. It was pointed out by [8] that the weak interactions which take place during this simmering phase can increase the value of $\eta$ in the WD material, albeit only by $\Delta \eta = 0.0015$ [9]. The impact that this increase of $\eta$ will have on the $M_{Mn}/M_{Cr}$ ratio will depend on the extent of the overlap between the convective core and the explosive Si burning region of the ejecta where Mn and Cr are synthesized. Unfortunately, the extent of the convective core in a pre-explosion CO WD is not known, and cannot be calculated self-consistently without sophisticated simulations [7].

To estimate this impact, we consider two limiting cases. If the entire WD is convective, all the explosive Si burning products are affected by simmering, and the $M_{Mn}/M_{Cr}$ ratio has a lower bound of 0.4, which does not allow to measure metallicities below solar (see Figure 1). Another possibility is that the size of the convective core is limited by the
Ledoux criterion to the central C-depleted region created during hydrostatic He-burning, as proposed by [10]. There are a number of reasons why this seems plausible (see [2]), but there is no way to prove that it is indeed the case. In this scenario, the impact of simmering is only large for subluminous Type Ia SNe, whose Si-rich regions reach deeper into the SN ejecta. The effect is also stronger at lower Z, because metal-poor stars have larger C-depleted cores [11]. Two examples of simmering-modified models with limited convection are shown in Figure 1. Under these conditions, the impact of C simmering should be of no concern for the Tycho SNR, because we know both from the historical light curve [13] and the X-ray emission of the SNR [14] that the SN of 1572 was not subluminous, but rather normal or slightly overluminous.

OBSERVATIONS: TYCHO AND BEYOND

Assuming no impact from C simmering, the metallicity of the Tycho SN progenitor would be $Z = 0.048^{+0.051}_{-0.036}$ (from [2], see Figure 1). The $M_{\text{Mn}}/M_{\text{Cr}}$ ratio is too large to be explained by C simmering alone, which suggests a solar or supersolar metallicity for the progenitor, regardless of the size of the convective core. The large uncertainties in the measured values of $M_{\text{Mn}}/M_{\text{Cr}}$ make it very difficult to completely discard some impact from simmering, specially in the most pessimistic case of unlimited convection. This underlines the importance of improving the $M_{\text{Mn}}/M_{\text{Cr}}$ measurements, both by using adequate atomic data for Mn and Cr (in [2], the specific emissivities had to be interpolated, which introduced a large uncertainty in the measurement) and by calculating line fluxes from deeper observations that can reduce the statistical errors. Determining accurate fluxes for such weak lines represents a challenge for the present generation of X-ray telescopes. An improvement on the measurements presented here is certainly possible for bright SNRs, but more distant objects will require either much larger collecting areas or a new type of detectors, such as the microcalorimeters being planned for the NeXT/ASTRO-H mission [15]. Another exciting prospect for the future is the extension of this method to other Type Ia SNRs. Suzaku has recently detected lines from Mn and Cr in the spectrum of the Kepler SNR (S. Park, private communication), and the prospects for finding at least Cr in the Galactic SNR G337.2−0.7 are good [12], so more measurements will be available soon.

CONCLUSIONS

In [2], the $M_{\text{Mn}}/M_{\text{Cr}}$ ratio was introduced as a tracer of SN Ia progenitor metallicity. It might be more appropriate to say that it is a tracer of neutron excess in the explosive Si burning region of Type Ia SNe. This is interesting in its own right, because it also opens a window into the extent of the convective core of pre-explosion WDs. We hope that more and better observations will let us disentangle the contributions of metallicity and C simmering to the neutron excess in Type Ia SNe, and that this can help us to understand the lingering mystery of Type Ia progenitors.
FIGURE 1. The $M_{Mn}/M_{Cr}$ ratio vs. $Z$ in Type Ia (red circles) and core collapse (blue triangles) SN models \cite{2,6}, together with the observed $M_{Mn}/M_{Cr}$ for Tycho, adapted from \cite{2}. Some simple models for the impact of simmering are also shown. The solid green plot represents the most pessimistic case of a fully convective WD. The dash-dotted and dotted green plots represent the more optimistic case of a convective core limited to the C-depleted region of the WD, for a subluminous ($\Delta m_{15} = 1.8$), and a normal, but faint ($\Delta m_{15} = 1.4$) Type Ia SN. In the models with limited convection, it has been assumed that the WD progenitor had a ZAMS mass of $5M_\odot$.

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