Secondary Fe-peak nuclei in the Tycho Supernova Remnant: A Promising Tracer of Type Ia Progenitor Metallicity

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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 two Galactic supernova remnants: the well known Tycho SNR and W49B, an older object that has been tentatively classified as Type Ia. The fluxes of the Mn and Cr Kα lines in the X-ray spectra of these SNRs observed by the *Suzaku* and *ASCA* satellites suggest progenitors of supersolar metallicity for both objects.

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1. 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] [1]. It is based on an argument by Timmes et al. [3] that connects 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 η, ^{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 η, with larger values of η 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 Kα 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.

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[1]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.

2. The Impact of C simmering on the Mn/Cr ratio

Before a slowly accreting WD explodes as a SN Ia, there is a ~ 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 [7] that the weak interactions which take place during this simmering phase can increase the value of η in the WD material, albeit only by $\Delta\eta = 0.0015$ [8]. The impact that this increase of η 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 [9].

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 [12] and the X-ray emission of the SNR [13] that the SN of 1572 was not subluminous, but rather normal or slightly overluminous.

3. Observations: Tycho, W49B 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). Here we also present the case of the Galactic SNR W49B, another object which has Mn and Cr lines in its X-ray spectrum [14], but whose Type Ia origin and age are uncertain (see discussion in [15]). In this case, the measured $M_{Mn}/M_{Cr} = 0.66 \pm 0.50$ translates into $Z = 0.041^{+0.056}_{-0.036}$, also without simmering impact (Figure 1). This metallicity value should be considered with caution, because (a) the SN that originated SNR W49B might have been subluminous, making the impact of simmering important even in the case of limited convection; and (b) given the unknown age, the reverse shock may have propagated into the n-rich NSE region, which would contaminate the measured M_{Mn}/M_{Cr}.

These two test cases can serve to illustrate several points. First, both Tycho and W49B have a larger M_{Mn}/M_{Cr} that can be explained by C simmering alone, which suggests a solar or super-solar metallicity for both events, regardless of the size of the convective core. Second, the large uncertainties in the measured values of M_{Mn}/M_{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_{Mn}/M_{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
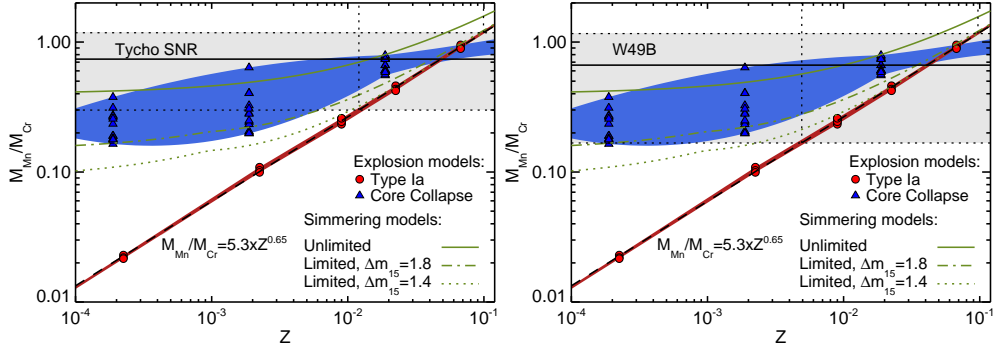
Figure 1: The M_{Mn}/M_{Cr} ratio vs. Z in Type Ia (red circles) and core collapse (blue triangles) SN models [2, 17], together with the observed M_{Mn}/M_{Cr} for Tycho (left panel, adapted from [2]) and W49B (right panel, calculated from the line fluxes given in [14]). Some simple models for the impact 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 $5 M_\odot$.

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 [16].

4. Conclusions

In [2], the M_{Mn}/M_{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.

Acknowledgments

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