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ON THE PERILS OF HYPERFINE SPLITTING: A REANALYSIS OF MN AND SC ABUNDANCE TRENDS

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ABSTRACT

We investigate the impact of hyperfine splitting on stellar abundance analyses of Mn and Sc, and find that incorrect hfs treatment can lead to spurious abundance trends with metallicity. We estimate corrections to a recent study by Nissen et al. (2000), and find: (1) [Mn/Fe] is described by a bimodal distribution, with [Mn/Fe] ~ -0.3 for stars [Fe/H] < -0.7, and [Mn/Fe] ~ -0.05 for stars at higher metallicity, suggestive of a transition between halo/thick disk and thin disk populations. (2) The large majority of stars show nearly solar [Sc/Fe] ratios; although important deviations cannot be ruled out.

Subject headings: stars: abundances – Galaxy: abundances – nucleosynthesis

1. INTRODUCTION

A fundamental goal of stellar abundance studies is to investigate and identify the nucleosynthetic origin and evolution of individual elements in various stellar populations. Observed abundance ratios may be used to constrain theoretical nucleosynthesis yields (e.g. Woosley & Weaver 1995), and gain insight into the formation and chemical enrichment history of galactic systems. Tinsley (1979) developed a paradigm of chemical evolution to explain early observations (Wallerstein 1962; Conti et al. 1967) which showed that oxygen and other α-elements (e.g. Mg, Si, Ca) are enhanced in metal-poor halo stars relative to iron, but not in solar-metallicity disk stars (for more discussion see McWilliam 1997). Based on this simple idea one expects certain trends of [α/Fe] with [Fe/H] for systems with different formation time scales (i.e. SFR, IMF, and binary fractions); thus the measurement of [α/Fe] can be used to probe these parameters, and our understanding of chemical evolution. This also suggests that additional diagnostics of the Galactic star formation history may be obtained by careful abundance studies of other elements. In the following, we consider the abundance trends of Sc and Mn, two so-called iron-peak elements.

Wallerstein (1962) first noted that Mn is deficient relative to Fe in low metallicity stars, consistent with the odd-even effect for iron-peak elements suggested by Helfer et al. (1959) and Arnett (1971). These early observations were later confirmed by Gratton (1989), who found that Mn behaves in an opposite sense to the α-elements: a steady decline to [Mn/Fe] ~ -0.34 from solar metallicity to [Fe/H] ~ -1.0 dex, followed by a plateau at [Mn/Fe] ~ -0.34 between [Fe/H] = -1.0 to -2.4 dex. Gratton concluded that Mn is under-produced in early massive stars, and over-produced in type Ia SN. Below [Fe/H] ~ -2.5, McWilliam et al. (1995) showed that the [Mn/Fe] ratio declines rapidly, and suggests the presence of a distinct early population II, or population III in the Galactic halo. More recently, Nissen et al. (2000; N00) published a comprehensive study of $\approx$120 [Mn/Fe] measurements from F and G dwarf stars in the metallicity interval $-1.4 <$ [Fe/H] $< +0.1$. Their results found the same gradual decline in [Mn/Fe] as Gratton (1989), but to lower [Mn/Fe] values and with the suggestion of a drop in [Mn/Fe] at [Fe/H] ~ -0.7 dex.

If Mn is a type Ia SN product, we expect sub-solar [Mn/Fe] in the Galactic bulge and giant elliptical galaxies, which are enhanced in type II SN products (e.g. Worthey et al. 1992; McWilliam & Rich 1994). For the LMC and dwarf galaxies excesses of elements produced by type Ia SN are anticipated (Wyse & Gilmore 1992). The behavior and origin of Mn is also relevant to interpretation of the abundance patterns in damped Lyα systems (Lu et al. 1996; Prochaska & Wolfe 1997; Pettini et al. 2000). In nearly every damped system where Mn is observed, one finds an underabundance of Mn relative to Fe which suggests an underlying type II SN enrichment pattern independent of dust depletion. This interpretation, however, hinges on the fact that Mn is primarily produced in type Ia SN. Identification of the formation processes for Mn, therefore, has direct bearing on the nucleosynthetic history of these protogalaxies.

Nucleosynthesis calculations (e.g. Timmes et al. 1995) predict deficient [Sc/Fe] ratios in metal-poor stars. This contrasts starkly with the observations of Zhao & Magain (1990, 1991) who found +0.3 dex Sc enhancements. However, Gratton & Sneden (1991), Peterson et al. (1990), and McWilliam et al. (1995) found no evidence for a deviation from [Sc/Fe]=0.0, and Gilroy et al. (1988) found Sc deficient by $\approx$0.2 dex. The recent analysis of N00 supports the enhancements found by Zhao & Magain, with the surprising conclusion that Sc behaves like an α-element; particularly convincing is the fact that N00 find relatively deficient Sc in their sub-sample of α-element poor stars.

While one of us (JXP) was pursuing an analysis of Mn for a sample of thick disk stars (Prochaska et al. 2000), we became concerned about the N00 Mn analysis due to their use of the incorrect hyperfine splittings of Steffen (1985; S85). In particular, we were concerned that an incorrect hfs treatment and the change in line-strength with metallicity could lead to an artificial trend of [Mn/Fe] versus [Fe/H]. In the course of this work we also worried about the N00 treatment of Sc II lines; the large S85 hfs splittings seem to have caused N00 to derive large hfs abundance corrections in contrast to previous work (McWilliam & Rich

Table 1
HYPERFINE SPLITTING OF Mn I AND Sc II LINES[a]

Mn I λ6013		Mn I λ6016		Mn I λ6021		Sc II λ5526		Sc II λ5657		Sc II λ6245		Sc II λ6604	
$\Delta\lambda$[b]	$\log gf$[c]	$\Delta\lambda$	$\log gf$	$\Delta\lambda$	$\log gf$	$\Delta\lambda$	$\log gf$	$\Delta\lambda$	$\log gf$	$\Delta\lambda$	$\log gf$	$\Delta\lambda$	$\log gf$
.478	−0.766	.619	−1.460	.746	−2.668	.770	−3.051	.886	−1.229	.621	−1.736	.582	−2.505
.499	−0.978	.645	−1.297	.772	−1.451	.775	−2.648	.888	−1.799	.629	−2.476	.590	−2.347
.518	−1.251	.647	−0.682	.774	−2.316	.779	−2.436	.893	−1.799	.631	−1.907	.594	−1.936
.527	−1.455	.667	−1.292	.795	−1.275	.779	−1.838	.894	−1.627	.636	−3.476	.596	−2.358
.533	−1.661	.668	−0.945	.798	−2.191	.783	−2.326	.895	−1.641	.638	−2.293	.599	−2.333
.538	−1.309	.684	−1.276	.804	−0.533	.783	−1.633	.901	−2.323	.640	−2.114	.602	−2.531
.547	−1.330	.685	−1.394	.813	−1.249	.786	−1.567	.902	−1.652	.644	−3.058	.604	−3.029
.552	−1.485	.696	−1.723	.817	−2.271	.787	−2.305	.904	−1.652	.646	−2.260	.607	−4.455
.562	−1.807	.696	−1.460	.821	−0.673	.788	−1.571	.906	−1.825	.647	−2.385	.609	−2.707
.566	−1.853	.698	−1.656	.827	−1.316	.789	−0.909	.906	−3.749	.650	−2.824	.611	−2.505
.566	−2.409	.704	−2.422	.834	−0.831	.790	−2.414	.908	−1.825	.651	−2.319	.613	−2.347
.567	−2.029	.707	−1.297	.837	−1.492	.790	−1.632	.909	−2.001	.652	−2.803	.615	−2.531
		.713	−1.292	.843	−1.015	.791	−1.030			.655	−2.678	.615	−2.358
		.714	−1.656	.846	−1.522	.792	−1.754			.656	−2.502		
		.716	−1.394	.847	−1.237	.793	−1.937			.657	−2.581		
						.793	−1.166						
						.794	−1.322						
						.795	−2.083						
						.795	−1.741						
						.795	−1.507						

[a] Line data taken from http://cfaku5.harvard.edu
[b] The correct wavelength equals $\lambda + \Delta\lambda$
[c] The absolute gf values have no bearing on our analysis

1994; McWilliam et al. 1995) which found only small hfs corrections for scandium. In this paper, we estimate the error in derived Mn and Sc abundances due to use of the S85 hfs lists and consider the effects of the corrections on the abundance trends found by N00. The focus of this paper is to warn the reader of the uncertainties associated with hyperfine splitting. While we make an estimate of the true Mn and Sc abundances from the N00 sample, our analysis is limited by the fact that neither the microturbulent velocities or the iron equivalent widths were available to us.

2. HFS ANALYSIS

Similar to other odd-Z elements (e.g. V, Co, Cu), hyperfine interactions between nuclear and electronic wavefunctions split the absorption lines of Mn and Sc into multiple components. For the majority of the Mn I and Sc II lines, the hyperfine components have typical splittings of up to a few tens of mÅ. In terms of stellar abundance studies, the hyperfine splitting de-saturates strong absorption lines resulting in features with larger equivalent widths than single lines with no hfs components. Thus, if the splittings are ignored, or under-estimated, the computed abundances will be over-estimated for strong lines. Because the size of the abundance over-estimate increases with line-strength, it is important to treat hfs effects correctly for strong lines; otherwise spurious abundance trends may result. For weak lines the hfs treatment is not so critical because they are already unsaturated. To derive an abundance from a line affected by hfs one must perform a spectrum synthesis over the hfs components; thus the number of components, the wavelength splittings, and the relative strengths must be known. The number of components and their relative strengths are readily computed with the equations in Condon & Shortly (1935). To compute wavelengths it is necessary to have splitting constants (A and B) for each electronic level, preferably from laboratory measurements.

In this analysis we adopt the hfs line lists of Kurucz (1999). For the Mn I lines of N00 the hfs constants are from Handrich et al. (1969), based on laboratory measurements, and for the Sc II lines the measured hfs constants are from Mansour et al. (1989). Typical 1σ uncertainties for measured Sc II A and B constants are less than 0.2% and 0.5% respectively. For the 5526Å line the uncertainty in hfs component wavelengths are nearly all less than 0.001Å, with a maximum uncertainty of 0.003Å for the weakest components; these values are much smaller than the velocity widths ($\sim$ 0.02Å), and far too small to significantly affect the computed abundance. The Mn I lines have rms errors $<$ 0.5% in the A constants but larger uncertainties in the B constants. As with the Sc II lines, these uncertainties are insignificant.

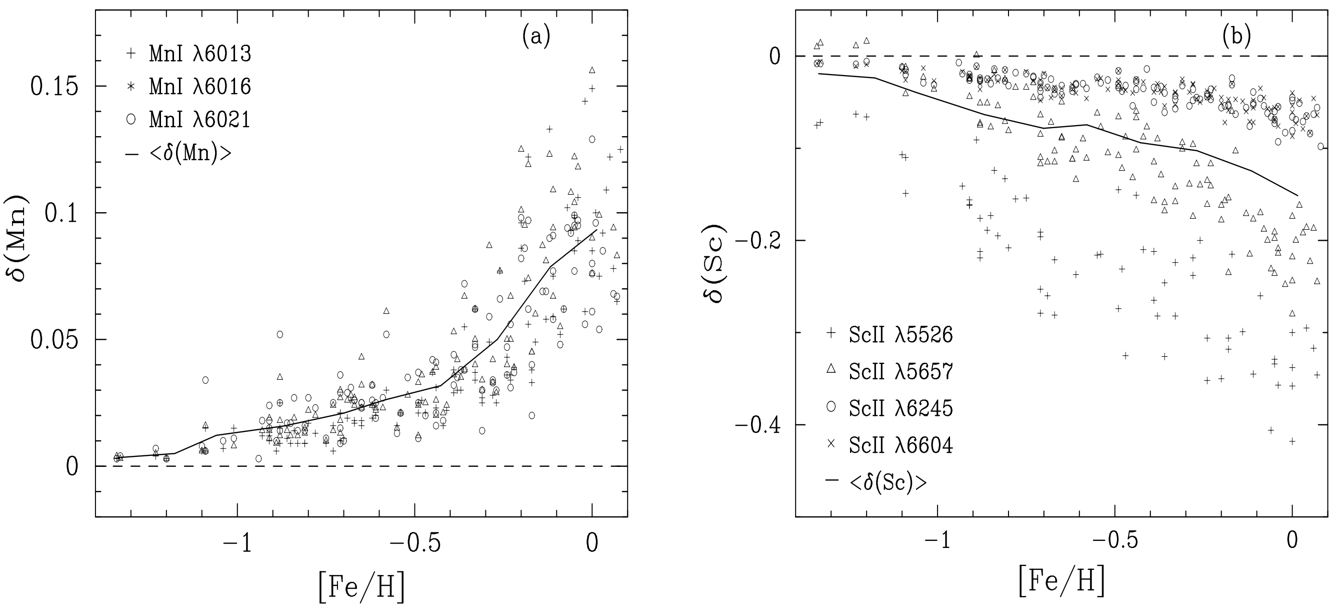

FIG. 1.— Corrections to the Steffen (1985) hfs analysis of (a) Mn I and (b) Sc II when the more accurate hyperfine lines listed in Table 1 are considered. Note that the corrections have a dependence with metallicity such that ignoring them might lead to erroneous trends in the Mn and Sc abundances. In this analysis, we have adopted the microturbulence relation from Nissen & Schuster (1997) with $\xi = 1.15$ km s^{-1} for the Sun.

In a few instances we have checked the Kurucz (1999) hfs line parameters. Table 1 lists the hfs components for the three Mn I absorption lines and four of the five Sc II lines analyzed in N00. Unfortunately there are no A or B constants measured for the Sc II $\lambda5239$ line and we do not consider it in this analysis. Regrettably, N00 and Gratton (1989) did not use the best hfs lists. Gratton (1989) relied upon the incomplete hfs lists of Booth et al. (1983). However, our analysis of the solar Mn I lines shows that use of the Booth et al. (1983) hfs list results in a negligible mean error of ≈0.002 dex. N00 adopted the hfs components published by S85 based on the work of Biehl (1976); unfortunately, S85 grouped together nearby hfs components and applied old, inaccurate, splitting constants. In the case of Mn I lines, the true hfs splittings are larger than indicated by S85 while for Sc II lines the true splittings are much smaller than indicated by Steffen.

In this analysis we investigate the differences between the S85 compilation and the data presented in Table 1 for the N00 sample. Because N00 did not publish iron line equivalent widths or microturbulent velocities, and because of the different model atmospheres and synthesis codes employed we could only calculate the abundance corrections arising from the use of the different hfs line lists. To compute abundances we employed the Kurucz (1993) grid of model atmospheres, interpolated to the stellar parameters (T_{eff}, $\log g$, and [Fe/H]) given by N00 and the synthesis program MOOG of (Sneden 1973). Microturbulent velocities for all stars were adopted based on the relation of Nissen & Schuster (1997). Use of the N00 solar microturbulent velocity, at 1.44 Km/s, would have decreased our corrected [Mn/Fe] data points by 0.06 dex. The Unsold damping approximation, without enhancement, was assumed throughout.

Figure 1a plots the hfs difference, $\delta(\mathrm{Mn}) \equiv \epsilon(\mathrm{Mn})|_{Nissen} - \epsilon(\mathrm{Mn})|_{PM}$, for every measured line in N00 as a function of [Fe/H]. The figure clearly demonstrates that the S85 analysis overestimates the Mn abundance and, most importantly, that the effect is largest at high metallicity. In turn, the error leads to an observed trend of decreasing [Mn/Fe] with decreasing metallicity as described by N00. Because we compute differential corrections to the N00 abundances we expect that our results are largely insensitive to errors in the model atmosphere or the exact assumptions of the spectrum synthesis code. While a significantly higher damping or microturbulence parameter lessens the effect described by Figure 1a, qualitatively the picture is unchanged. Analogous to the Mn treatment, we plot $\delta(\mathrm{Sc})$ vs. [Fe/H] in Figure 1b. Here, the S85 hfs compilation leads to a significant overestimate of the hfs correction, particularly for $\lambda5526, 5657$. In turn, this difference could account for the observed enhancement of Sc described by N00.

3. DISCUSSION

We now apply the corrections derived in the previous section in a line-by-line fashion to the N00 compilation and thereby estimate the true [Mn/Fe] and [Sc/Fe] trends. Although our results should qualitatively describe the metallicity dependence of Mn and Sc, a quantitative discussion will await a full reanalysis by the authors of N00.

Figure 2a compares the corrected [Mn/Fe] values based on our hfs calculations versus the N00 results. The corrected analysis offer a considerably different picture from that of N00. The most robust change is the systematic increase of ≈ 0.15 dex in [Mn/Fe] for the most metal-poor stars. This [Mn/Fe] shift arises from the substantial hfs corrections to the solar Mn abundance. One also notes that the trend toward lower [Mn/Fe] values from

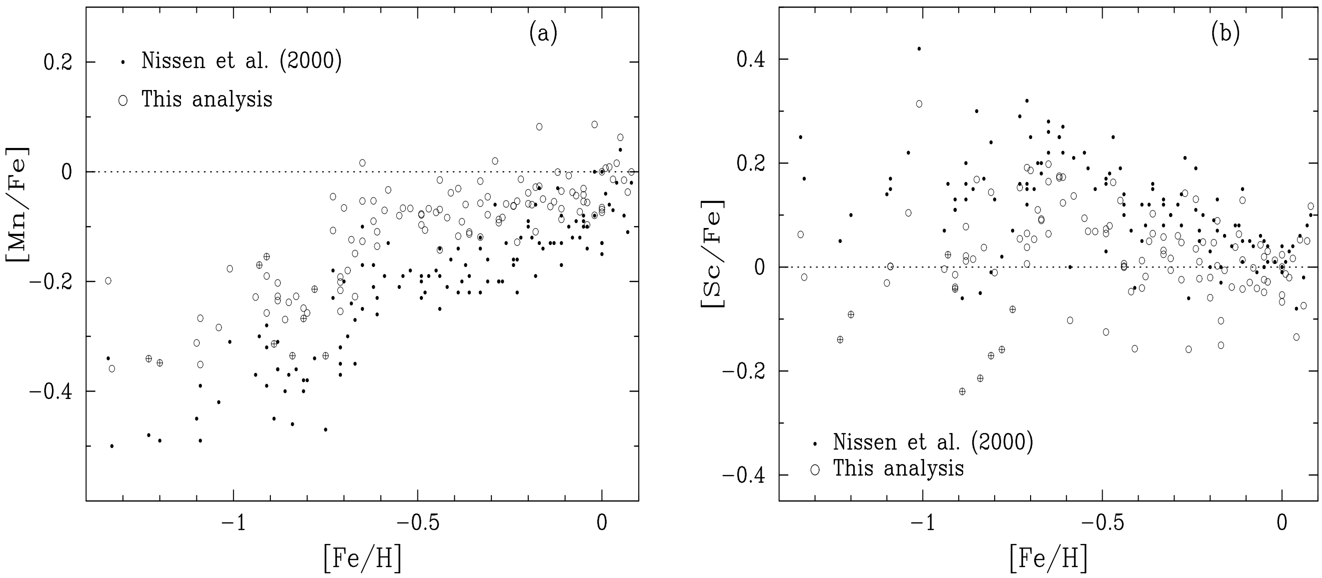

FIG. 2.— A comparison of the Nissen et al. (2000) compilation and our corrected values for the (a) [Mn/Fe] and (b) [Sc/Fe] abundance ratios vs. [Fe/H]. For our analysis, we have applied line-by-line corrections to the Nissen et al. abundances as described in Figure 1. The results show that the trends observed in the Nissen et al. values are quite possibly the result of errors in the Steffen (1985) hfs compilation. The $+$-signs mark α-poor stars identified by Nissen & Schuster (1997).

[Fe/H] $= 0 \rightarrow -0.5$ is no longer evident in the reanalysis. In short the corrected [Mn/Fe] values are bimodal; those stars with [Fe/H] < -0.7 have [Mn/Fe] ~ -0.3 in agreement with Gratton (1989) and the higher metallicity stars show [Mn/Fe] ~ -0.05. The most straightforward explanation for these results is that [Fe/H] ~ -0.7 marks the passing from the thin disk stellar population to the thick disk and halo populations. The Mn/Fe trends are consistent with Mn being produced primarily by type Ia SN and do not require a metallicity dependent yield. We note in passing that the plateau of Mn/Fe for the thin disk stars lies rather uncomfortably below solar: [Mn/Fe] ~ -0.05 dex. While the Sun might have a high Mn abundance relative to the bulk of the thin disk dwarf stars, the offset could be due to a zero-point error in the N00 solar analysis.

Now consider the results for Sc presented in Figure 2b. In short, the corrected values no longer show the α-enhanced trend discussed in the N00 analysis. The solar Sc abundance has been revised upward by ≈ 0.2 dex which, in turn, has eliminated the relative enhancement in the metal-poor stars. Our results agree well with the Sc abundance analysis performed by Gratton & Sneden (1991) indicating that essentially all stars exhibit solar Sc/Fe. There are two sets of stars, however, with reasonably significant departures from [Sc/Fe] $= 0$: (i) the α-poor stars (marked with a $+$) identified by Nissen & Schuster (1997) exhibit sub-solar Sc/Fe, consistent with an origin related to the α-elements; (ii) nearly every star with [Fe/H] ~ -0.6 shows enhanced Sc/Fe. This trend is difficult to explain and we wonder if it is simply a statistical anomaly or perhaps a small error in the original analysis of N00. Finally, we note the two weakest Sc II lines ($\lambda 6245, 6604$) give systematically higher ϵ(Sc) values than the two stronger lines, particularly in the metal-poor stars. This difference may be explained by blends between the strong lines of the Solar spectrum and unidentified neutral metal lines which would lead to erroneously high gf values. To account for this systematic offset, we recommend that future studies on Sc include many more Sc II lines.

In this Letter, we have investigated the effects of miscalculating the hfs correction on elemental abundance trends. We have performed a simple exercise to correct for the erroneous hfs compilation used by N00 in their analysis of Mn and Sc. In turn, we have demonstrated that hfs errors can mimic metallicity-dependent abundance trends. Our results highlight the importance of accurately addressing hyperfine splitting and we encourage the reader to utilize the large database of hfs lines being compiled by R. Kurucz. Having estimated corrections to the Mn and Sc abundances from N00, we find the following: (1) the [Mn/Fe] values are best described by a bimodal distribution with stars at [Fe/H] < -0.7 exhibiting [Mn/Fe] ~ -0.3 and stars at higher metallicity showing [Mn/Fe] ~ -0.05. These trends are consistent with type Ia SN being the principal site for Mn nucleosynthesis; (2) the large majority of stars have nearly solar Sc/Fe ratios consistent with the results of Gratton & Sneden (1991) and McWilliam et al. (1995). There are exceptions, however, namely the α-poor stars of the N00 sample which show systematically low Sc/Fe values and the bulk of stars at [Fe/H] ~ -0.6 which exhibit enhanced Sc.

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