

# Hyperfine structure constants for singly ionized manganese (Mn II) using Fourier transform spectroscopy

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## ABSTRACT

We expand on the comprehensive study of hyperfine structure (HFS) in Mn II conducted by Holt et al. (1999) by verifying hyperfine magnetic dipole constants ( $A$ ) for 20 levels previously measured by Holt et al. (1999) and deriving  $A$  constants for 47 previously unstudied levels. The HFS patterns were measured in archival spectra from Fourier transform (FT) spectrometers at Imperial College London and the National Institute of Standards and Technology. Analysis of the FT spectra was carried out in XGREMLIN. Our  $A$  constant for the ground level has a lower uncertainty by a factor of 6 than that of Blackwell-Whitehead et al.

**Key words:** atomic data – line: profiles – methods: laboratory: atomic – techniques: spectroscopic.

## 1 INTRODUCTION

The cosmic abundance of manganese is  $5.42 \pm 0.04$  <sup>1</sup>(Scott et al. 2015), and is the fourth highest of the iron-group elements. However, much higher abundances of manganese are found in some chemically peculiar stars of late B spectral types. An example is given by the HgMn star HD 175640, in which the Mn abundance of 7.8 exceeds that of any element heavier than oxygen (Castelli & Hubrig 2004). The high abundance of manganese in this star gives rise to many lines of Mn II that are not seen in laboratory spectra (Castelli, Kurucz & Cowley 2015).

Manganese has one stable isotope with a mass number of 55. The ground configuration of Mn II is  $3d^5(^6S)4s$  (Sansonetti & Martin 2005). Since manganese has a nuclear spin of 5/2 and a nuclear magnetic moment of 3.4687, spectral lines of Mn II show hyperfine structure (HFS). HFS is of importance in astronomy because it broadens the lines observed in stellar spectra, giving incorrect abundances if it is not taken into account and potentially confusing the line identification. Jomaron, Dworetzky & Allen (1999) showed that the chemical abundance of Mn II in HgMn stars can be overestimated by up to 3 orders of magnitude if HFS is neglected. Even if a rough estimate is made of the HFS pattern, the abundance can be overestimated by up to a factor of 4 in stars. Fig. 3 in Castelli & Hubrig (2004), shows two examples of the importance HFS plays in broadening the width of lines in the spectra of HgMn star HD 175640. For these lines the HFS constants needed to model the line shape have been measured previously. However, there are many

other lines that exhibit broader HFS where the HFS constants for one or both levels are not known. For three notable lines in Castelli & Hubrig (2004) at 9407.0 Å, 9408.7 Å, and 9446.8 Å, the  $A$  constants for the upper levels,  $3d^5(^6S)4p z^5P_{2,3,4}^o$ , were known but the lower levels,  $3d^5(^4P)4s b^5D_{2,3}$  were not. The resulting synthetic spectra are a poor fit to the observed stellar spectrum. Hyperfine structure constants are also needed to obtain a more accurate value for the wavelength of a transition, particularly for close-lying levels where it may be difficult to distinguish between HFS and fine-structure components in the observed spectral lines, and second-order hyperfine mixing may be of importance.

Previous work on the HFS of Mn II began with Villemoes et al. (1991) who used laser spectroscopy to measure HFS constants for the three levels of the  $3d^5(^6S)4p z^5P_j^o$  term and  $3d^5(^6S)4s a^5S_2$ . Holt, Scholl & Rosner (1999) later expanded on this study by independently measuring the HFS constants of 59 levels, including the 3 levels in the  $z^5P_j^o$  term measured previously by Villemoes et al. (1991). Neither of these studies measured the HFS of the ground level in Mn II. Blackwell-Whitehead et al. (2005b) derived HFS constants for the ground level  $3d^5(^6S)4s a^7S_3$  and upper levels in the  $3d^5(^6S)4p z^7P_j^o$  term using Fourier transform (FT) spectroscopy.

In this paper, we discuss the previously measured spectra that were used in this work, describe our analysis of the spectra and the derivation of our uncertainties, compare our results with previous measurements by (Holt et al. 1999), Villemoes et al. (1991), and Blackwell-Whitehead et al. (2005b), and present new HFS constants for 47 levels in Mn II.

## 2 EXPERIMENT

The Mn II spectra analysed were obtained from the National Institute of Standards and Technology 2 metre FT spectrometer (NIST

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<sup>1</sup>Abundance is on a logarithmic scale relative to a hydrogen abundance of 12.

**Table 1.** Summary of spectra and their conditions used in this study.

Reference number	Date and Serial no.	Current (A)	Pressure (Pa)	Buffer gas	Instrument	Resolution (cm <sup>-1</sup> )	Range (cm <sup>-1</sup> )		Notes <sup>a</sup>
							Lower	Upper	
1	2001/3/21 no. 1	0.2	340	Ne	ICL	0.04	31 596	63 192	mlnl
2	2001/3/21 no. 2	0.45	340	Ne	ICL	0.04	31 596	63 192	mlnh
3	1998/11/12 no. 2	1	133	Ne	VUV	0.06	30 000	53 000	
4	1998/11/12 no. 6	2	133	Ne	VUV	0.06	14 500	45 000	
5	2001/1/16 no. 3	1.7	253	Ne	NIST	0.013	8000	30 000	menh
6	2001/3/22	0.45	340	Ne	ICL	0.04	23 697	47 394	mknh
7	1998/11/12 no. 1	2	133	Ne	VUV	0.06	30 000	53 000	
8	1998/11/10 no. 1	1	667	Ne	VUV	0.06	14 000	45 000	
9	1999/06/16 no. 9	2	150	Ne	VUV	0.07	33 000	66 000	
10	2001/1/12 no. 16	2	253	Ne	NIST	0.02	15 630	29 050	mgnh
11	2001/4/2	0.45	90	Ar	ICL	0.04	31 596	63 192	mlah
12	2001/1/19 no. 4	1.5	253	Ne	NIST	0.009	3800	20 000	mcnh
13	1998/09/24 no. 4	0.5	50	Ne	NIST	0.02	8000	29 000	

<sup>a</sup>File name in Blackwell-Whitehead (2003).

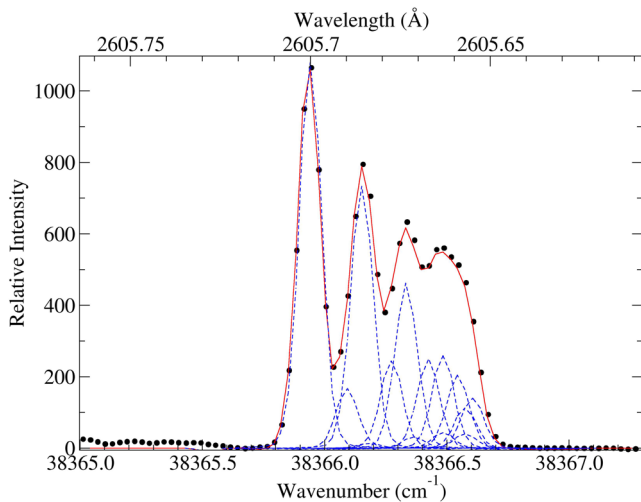
in Table 1), and two vacuum ultraviolet FT spectrometers at NIST (VUV in Table 1) and Imperial College London (ICL in Table 1 (Thorne et al. 1987)). The light source used was a hollow cathode lamp with Mn/Ni or Mn/Cu cathode, run in either neon or argon gas. The spectra were originally taken for the measurement of wavelengths, energy level values, and oscillator strengths and cover wavelengths from 140 nm to approximately 3 μm. Full details of the experimental procedure are given in Kling & Griesmann (2000) and Blackwell-Whitehead et al. (2005a). The spectra used are listed in Table 1 with the wavelength regions and operating conditions. A comparison of spectra taken at different currents enabled us to identify HFS profiles affected by self-absorption as shown in Figs 1 and 2.

### 3 ANALYSIS

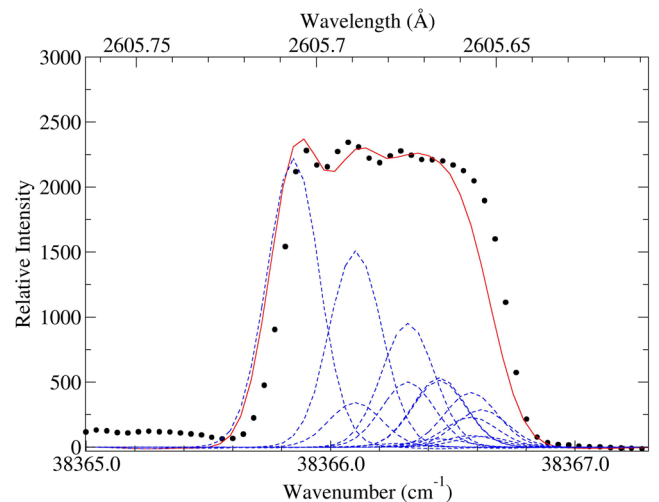
The spectra were analysed with our XGREMLIN software package (Nave et al. 2015), which uses the HFS fitting programs of Pulliam (1977) to determine HFS constants A (magnetic dipole) and B

(electric quadrupole), defined as in equation 1 of Holt et al. (1999). The program fits the line profiles based on eight parameters: the A and B constants of the upper and lower levels, the centre-of-gravity wavenumber of the line, the maximum intensity of the strongest HFS component, the damping constant which in this program is defined as a ratio of the Lorentzian to the total width of the line, and the full width at half-maximum (FWHM) of the HFS components. In almost all cases the uncertainty of the B constant was similar to or larger than its value. We have thus either set the B constants of both levels to zero in our fits or used the previously-measured B constants from Holt et al. (1999). Since the individual HFS components cannot be fully resolved due to Doppler broadening of the spectral line, it is usually not possible to derive accurate HFS constants by fitting both levels simultaneously. We have thus fixed the value of one A constant and allowed the other to vary in our fitting procedure. An example fit is shown in Fig. 1.

For some levels, none of the spectral lines connecting the level to others with well-determined HFS constants show significant structure and the corresponding lines appear symmetric in our spectra. In these cases both the HFS and Doppler broadening contribute to the width of the spectral lines. These levels may, however, show



**Figure 1.** The  $3d^5(6S)4s a^7S_3 - 3d^5(6S)4p z^7P_2$  transition in Mn II, observed in a spectrum taken at a low current (no. 1 in Table 1, points). The red line shows the total fit of the line using the individual HFS components, shown as blue dashed line. The spectral line is free of self-absorption and gives a low uncertainty for the A constant of the  $z^7P_2$  level.



**Figure 2.** The same line as Fig. 1 observed in a spectrum taken at high current (no. 4 in Table 1). Self-absorption in the line gives an erroneous result for the A constant of the  $z^7P_2$  level.

**Table 2.** Derivation of the magnetic dipole A constant for the ground level,  $3d^5(^6S)4s\ a^7S_3$ .

Upper level	Upper A <sup>a</sup> (10 <sup>-3</sup> Å)	Air wavelength <sup>b</sup> (cm <sup>-1</sup> )	Ref. <sup>c</sup>	align="center">A <sup>d</sup> (10 <sup>-3</sup> cm <sup>-1</sup> )	A <sub>ave</sub> <sup>e</sup> (10 <sup>-3</sup> cm <sup>-1</sup> )	A <sub>ave</sub> <sup>f</sup> (10 <sup>-3</sup> cm <sup>-1</sup> )
z <sup>5</sup> P <sub>2</sub>	-10.36 (2)	2298.9532	2	28 (1)		26.07 (22)
			3		26.02 (0.17)	
			4		26.0 (5)	
z <sup>5</sup> P <sub>3</sub>	-5.01 (1)	2305.0033	1	27 (1)		26.08 (8)
			2		26.2 (4)	
			3		26.11 (9)	
			4		25.7 (3)	
z <sup>7</sup> P <sub>2</sub>	-18.16 (2)	2605.68028	1		26.11 (4)	26.12 (3)
			2		26.14 (6)	

<sup>a</sup>A constant and uncertainty in last digit in parenthesis of upper level from Holt et al. (1999). <sup>b</sup>Ritz wavelength of transition taken from Kramida & Sansonetti (2013). <sup>c</sup>Reference number of spectrum from column 1 of Table 1. <sup>d</sup>Measured A constant and uncertainty in the last digit in parenthesis of a<sup>7</sup>S<sub>3</sub>. <sup>e</sup>Weighted average and uncertainty over all measured A constants in column 5 for each transition in column 4. Uncertainty, given in the last digit in parenthesis, is calculated from the quadrature sum of the uncertainty derived from uncertainties in column 4 using equations (2) and (3) and the uncertainty of the upper level A constant in column 2 (see Section 3.2). <sup>f</sup>Weighted average and uncertainty of values in column 6 (see Section 3.2). Uncertainty, given in the last digit in parenthesis, is sum of uncertainties in column 6 using equations (2) and (3) and estimated systematic uncertainty of upper level A constants in column 2 of  $0.013 \times 10^{-3} \text{ cm}^{-1}$ .

wide HFS patterns when combining with higher levels in the term system, so it is useful to derive some estimate of their HFS constants from lines connecting them to lower levels, even though these lines show little structure. Values for the A constant for these lines were derived by fixing the FWHM of the HFS components to various values and allowing the A constant to vary. The uncertainty of the A constant was determined by varying the FWHM of the components and determining the values for the A constant at each width where the standard deviation of the constant started to increase, indicating that the value no longer gave an optimum fit to the line. In some cases, e.g. the  $3d^6\ a^5D_4$  level, changing the FWHM by up to 10 per cent had little effect on the fitted A constant. For other levels, e.g. the  $3d^6\ a^5D_3$  level, the fitted A constant varied by more than its value when changing the FWHM and the uncertainty of the constant is thus large.

Since we cannot derive accurate HFS constants by fitting both levels simultaneously, we require previous values derived from laser spectroscopy for at least one level to begin our analysis. We chose as a starting value the A constant for the  $3d^5(^6S)4p\ z^5P_3^o$  level obtained by Holt et al. (1999). Their value for this level agrees within the joint uncertainty with the less accurate value obtained by Vиллемoes et al. (1991). From this level we obtained the A constant of the  $3d^5(^6S)4s\ a^5S_2$  level, which in turn was used to verify the  $z^5P_2^o$  and  $z^7P_2^o$  constants of Holt et al. (1999). Their A and B constants for the  $z^5P_{2,3}^o$  and  $z^7P_2^o$  levels were then used to obtain the A constant of the ground level,  $3d^5(^6S)4s\ a^7S_3$ , as shown in Table 2. Allowing the B constant of the ground level to vary in the fit resulted in an uncertainty greater than its value and it was thus set to zero when fitting higher levels. From these levels, A constants for almost all of the known septet and quintet levels below  $86\ 000 \text{ cm}^{-1}$  in Mn II could be derived using either the more accurate HFS constants of Holt et al. (1999) where available or our new constants. Our results, together with a comparison with Holt et al. (1999), are given in Table 3.

### 3.1 Uncertainty derivation

The A constants for most of the levels reported in Table 3 were derived from multiple spectral lines with each line being observed

in multiple spectra. A two-step process was used to derive the A constants for each level and their standard uncertainty.

First, we take a weighted average of the A constants,  $A_{\text{avg}}$ , for each transition derived from the observed line in spectrum  $i$  using:

$$A_{\text{avg}} = \frac{\sum_i^n A_i \delta_i^{-2}}{\sum_i^n \delta_i^{-2}} \quad (1)$$

Here  $A_i$  is the A constant determined from the line,  $\delta_i$  is its standard deviation obtained from a least squared fit of the line, and  $n$  is the number of spectra used for each line. Having obtained a weighted average for each line from multiple spectra, we estimate a one standard uncertainty for each line,  $\Delta A_{\text{avg}}$ , using the greater of:

$$\Delta A_{\text{avg}} = \sqrt{\frac{\sum_i^n \left[ (A_i - A_{\text{avg}})^2 \delta_i^{-2} \right]}{(n-1) \sum_i^n \delta_i^{-2}}} \quad (2)$$

and

$$\sqrt{1 / \sum_i^n \delta_i^{-2}} \quad (3)$$

Equation (3) prevents a misleading low uncertainty that can arise from a small number of measured HFS constants being in coincidentally good agreement. Using this procedure takes into account both the measured standard deviations and the actual distribution of the measured A constants from equation (2).

Next, we add the uncertainty of the A constant of the other level involved in the transition in quadrature to the result from equations (2) and (3) to give the uncertainty determined from all measurements using that particular transition. We then use equations (1), (2) and (3) again, but this time summing over all transitions,  $i$ , that can be used to determine the A constant of the level, with  $n$  now being the number of transitions. Finally, we add an estimate of the systematic uncertainty in Holt et al. (1999) to the result from equations (2) or (3). Our estimate of  $0.013 \times 10^{-3} \text{ cm}^{-1}$ , was obtained by taking the minimum uncertainty of any level in their table 1. We report this combined uncertainty in Table 3. This process is shown in Table 2 for the ground level and is described below.

**Table 3.** Magnetic dipole (A) constants for Mn II.

Configuration	Level	Energy (cm <sup>-1</sup> ) <sup>a</sup>	This study A <sup>b</sup>	Previous work A <sup>b, c</sup>	Levels used in derivation	Spectra used
3d <sup>5</sup> ( <sup>6</sup> S)4s	a <sup>7</sup> S <sub>3</sub>	0	<b>26.11 (4)</b>	26.6 (3)*	z <sup>7</sup> P <sub>2</sub> , z <sup>5</sup> P <sub>2</sub> , z <sup>5</sup> P <sub>3</sub>	1,2,3,4
	a <sup>5</sup> S <sub>2</sub>	9472.993	<b>-39.97 (3)</b>	-40.09 (7)**	z <sup>5</sup> P <sub>1</sub> , z <sup>5</sup> P <sub>2</sub> , z <sup>5</sup> P <sub>3</sub> , z <sup>7</sup> P <sub>2</sub>	1,2,6
3d <sup>6</sup>	a <sup>5</sup> D <sub>4</sub>	14325.866	<b>2.47 (10)<sup>d</sup></b>	-	z <sup>5</sup> P <sub>3</sub>	5,10
	a <sup>5</sup> D <sub>3</sub>	14593.835	0.4 (4) <sup>c</sup>	<b>0.19 (3)</b>	z <sup>5</sup> P <sub>2</sub> , z <sup>5</sup> P <sub>3</sub>	5,6
	a <sup>5</sup> D <sub>2</sub>	14781.205	-1.08 (6)	<b>-1.17 (3)</b>	z <sup>5</sup> P <sub>1</sub> , z <sup>5</sup> P <sub>2</sub> , z <sup>5</sup> P <sub>3</sub>	5
	a <sup>5</sup> D <sub>1</sub>	14901.203	-1.77 (15)	<b>-1.97 (7)</b>	z <sup>5</sup> P <sub>1</sub> , z <sup>5</sup> P <sub>2</sub>	5, 6
3d <sup>5</sup> ( <sup>4</sup> G)4s	a <sup>5</sup> G <sub>6</sub>	27547.260	<b>27.68 (4)</b>	-	z <sup>5</sup> F <sub>5</sub>	2,4,8
	a <sup>5</sup> G <sub>5</sub>	27571.250	<b>24.07 (5)</b>	-	z <sup>5</sup> F <sub>4</sub> , z <sup>5</sup> F <sub>5</sub>	2,4,8
	a <sup>5</sup> G <sub>4</sub>	27583.590	<b>19.35 (6)</b>	-	z <sup>5</sup> F <sub>3</sub> , z <sup>5</sup> F <sub>4</sub>	2,4,8
	a <sup>5</sup> G <sub>3</sub>	27588.530	<b>11.8 (4)</b>	-	z <sup>5</sup> F <sub>2</sub> , z <sup>5</sup> F <sub>3</sub>	2,8
	a <sup>5</sup> G <sub>2</sub>	27589.360	<b>-6.21 (15)</b>	-	z <sup>5</sup> F <sub>1</sub> , z <sup>5</sup> F <sub>2</sub>	2,4,8,11
3d <sup>5</sup> ( <sup>4</sup> P)4s	a <sup>5</sup> P <sub>3</sub>	29889.534	-	<b>33.683 (13)</b>	-	-
	a <sup>5</sup> P <sub>2</sub>	29919.444	-	<b>43.43 (2)</b>	-	-
	a <sup>5</sup> P <sub>1</sub>	29951.434	-	<b>53.50 (3)</b>	-	-
3d <sup>5</sup> ( <sup>4</sup> D)4s	b <sup>5</sup> D <sub>4</sub>	32787.900	<b>29.27 (10)</b>	-	z <sup>5</sup> P <sub>3</sub> , z <sup>5</sup> D <sub>4</sub>	4,8
	b <sup>5</sup> D <sub>3</sub>	32857.270	<b>30.8 (2)</b>	-	z <sup>5</sup> D <sub>3</sub> , z <sup>5</sup> D <sub>4</sub> , z <sup>5</sup> F <sub>3</sub>	4,8
	b <sup>5</sup> D <sub>2</sub>	32859.150	<b>31.0 (3)</b>	-	z <sup>5</sup> D <sub>1</sub> , z <sup>5</sup> D <sub>3</sub>	4,8
	b <sup>5</sup> D <sub>1</sub>	32836.74	<b>30.9 (5)</b>	-	z <sup>5</sup> D <sub>1</sub> , z <sup>5</sup> D <sub>3</sub>	2,8
3d <sup>5</sup> ( <sup>6</sup> S)4p	z <sup>7</sup> P <sub>2</sub>	38366.232	-	<b>-18.16 (2)</b>	-	-
	z <sup>7</sup> P <sub>3</sub>	38543.122	<b>-5.47 (8)</b>	-4.8 (3)*	a <sup>5</sup> S <sub>2</sub> , a <sup>5</sup> D <sub>4</sub> , a <sup>7</sup> S <sub>3</sub>	1,2,4,8
	z <sup>7</sup> P <sub>4</sub>	38806.691	<b>-4.52 (8)</b>	-4.1 (5)*	a <sup>7</sup> S <sub>3</sub>	1,2
3d <sup>5</sup> ( <sup>4</sup> F)4s	a <sup>5</sup> F <sub>1</sub>	43311.324	-	<b>-11.71 (3)</b>	-	-
	a <sup>5</sup> F <sub>5</sub>	43528.661	-	<b>28.413 (7)</b>	-	-
	a <sup>5</sup> F <sub>4</sub>	43537.186	-	<b>26.769 (13)</b>	-	-
	a <sup>5</sup> F <sub>3</sub>	43696.217	-	<b>30.311 (13)</b>	-	-
	a <sup>5</sup> F <sub>2</sub>	43850.341	-	<b>10.567 (17)</b>	-	-
3d <sup>5</sup> ( <sup>6</sup> S)4p	z <sup>5</sup> P <sub>3</sub>	43370.537	-	<b>-5.013 (13)</b>	-	-
	z <sup>5</sup> P <sub>2</sub>	43484.664	-10.39 (6)	<b>-10.364 (17)</b>	a <sup>5</sup> S <sub>2</sub>	1,2,6
	z <sup>5</sup> P <sub>1</sub>	43557.175	-24.44 (8)	<b>-24.48 (3)**</b>	a <sup>5</sup> S <sub>2</sub>	1,2,6
3d <sup>4</sup> 4s <sup>2</sup>	c <sup>5</sup> D <sub>1</sub>	54938.213	-	<b>3.94 (3)</b>	-	5,13
	c <sup>5</sup> D <sub>2</sub>	55116.333	5.30 (13)	<b>5.60 (2)</b>	z <sup>5</sup> P <sub>1</sub> , z <sup>5</sup> P <sub>2</sub>	5,13
	c <sup>5</sup> D <sub>3</sub>	55371.693	7.74 (9)	<b>7.979 (17)</b>	z <sup>5</sup> P <sub>2</sub> , z <sup>5</sup> P <sub>3</sub>	5,13
	c <sup>5</sup> D <sub>4</sub>	55697.014	10.79 (4)	<b>10.83 (2)</b>	z <sup>5</sup> P <sub>3</sub>	5,13
	z <sup>5</sup> G <sub>2</sub>	64456.720	<b>24.7 (2)</b>	-	a <sup>5</sup> G <sub>2</sub>	2,4,8
3d <sup>5</sup> ( <sup>4</sup> G)4p	z <sup>5</sup> G <sub>3</sub>	64473.421	<b>14.64 (17)</b>	-	a <sup>5</sup> G <sub>4</sub>	2,4,8
	z <sup>5</sup> G <sub>4</sub>	64494.140	<b>11.64 (9)</b>	-	a <sup>5</sup> G <sub>4</sub> , a <sup>5</sup> G <sub>5</sub>	2,4,8
	z <sup>5</sup> G <sub>5</sub>	64518.890	<b>10.92 (14)</b>	-	a <sup>5</sup> G <sub>5</sub> , a <sup>5</sup> G <sub>6</sub>	2,4,8
	z <sup>5</sup> G <sub>6</sub>	64550.040	<b>11.47 (8)</b>	-	a <sup>5</sup> G <sub>6</sub> , a <sup>5</sup> F <sub>5</sub>	2,4,8,10
	z <sup>5</sup> H <sub>3</sub>	65483.120	<b>25.28 (19)</b>	-	a <sup>5</sup> G <sub>2</sub>	1,2,4,8
	z <sup>5</sup> H <sub>4</sub>	65566.030	<b>16.7 (4)</b>	-	a <sup>5</sup> G <sub>3</sub> , a <sup>5</sup> G <sub>4</sub>	2,8
	z <sup>5</sup> H <sub>5</sub>	65658.650	<b>12.4 (2)</b>	-	a <sup>5</sup> G <sub>4</sub> , a <sup>5</sup> G <sub>5</sub>	2,4,8
3d <sup>5</sup> ( <sup>4</sup> G)4p	z <sup>5</sup> H <sub>6</sub>	65754.820	<b>10.87 (8)</b>	-	a <sup>5</sup> G <sub>5</sub>	1,2,4,8
	z <sup>5</sup> H <sub>7</sub>	65847.030	<b>10.56 (9)</b>	-	a <sup>5</sup> G <sub>6</sub>	1,2,4,8
	z <sup>5</sup> D <sub>1</sub>	66645.116	11.4 (3)	<b>11.01 (3)</b>	a <sup>5</sup> P <sub>1</sub>	7,9
	z <sup>5</sup> D <sub>2</sub>	66676.833	8.9 (9)	<b>9.56 (2)</b>	a <sup>5</sup> P <sub>3</sub>	8
	z <sup>5</sup> D <sub>3</sub>	67009.217	6.41 (7)	<b>6.374 (17)</b>	a <sup>5</sup> P <sub>2</sub> , a <sup>5</sup> P <sub>3</sub>	2,4,8
	z <sup>5</sup> D <sub>4</sub>	67295.446	3.26 (6)	<b>3.209 (13)</b>	a <sup>5</sup> P <sub>3</sub>	2,4,8
	z <sup>5</sup> F <sub>5</sub>	66542.539	9.50 (20)	<b>9.340 (7)</b>	a <sup>5</sup> D <sub>4</sub> , a <sup>5</sup> F <sub>5</sub>	4,9,10
3d <sup>5</sup> ( <sup>4</sup> G)4p	z <sup>5</sup> F <sub>4</sub>	66643.296	8.93 (17)	<b>8.646 (10)</b>	a <sup>5</sup> D <sub>3</sub> , a <sup>5</sup> D <sub>4</sub> , a <sup>5</sup> F <sub>4</sub>	9,10
	z <sup>5</sup> F <sub>3</sub>	66686.739	9.1 (2)	<b>9.110 (13)</b>	a <sup>5</sup> D <sub>2</sub> , a <sup>5</sup> D <sub>3</sub> , b <sup>5</sup> D <sub>3</sub>	4,8,9
	z <sup>5</sup> F <sub>2</sub>	66901.494	3.4 (3)	<b>3.379 (17)</b>	a <sup>5</sup> P <sub>1</sub> , a <sup>5</sup> P <sub>3</sub> , a <sup>5</sup> D <sub>1</sub>	2,8
	z <sup>5</sup> F <sub>1</sub>	66894.130	-	<b>34.89 (3)</b>	-	-
	z <sup>5</sup> S <sub>2</sub>	66929.517	3.0 (2)	<b>2.85 (2)</b>	a <sup>5</sup> P <sub>2</sub>	2,7,8
3d <sup>5</sup> ( <sup>4</sup> P)4p	y <sup>5</sup> P <sub>3</sub>	68284.664	0.94 (15)	<b>0.784 (17)</b>	a <sup>5</sup> P <sub>2</sub> , a <sup>5</sup> P <sub>3</sub> , b <sup>5</sup> D <sub>4</sub>	2,4,8
	y <sup>5</sup> P <sub>2</sub>	68417.697	-7.4 (4)	<b>-7.34 (2)</b>	a <sup>5</sup> P <sub>1</sub> , a <sup>5</sup> P <sub>2</sub> , a <sup>5</sup> P <sub>3</sub>	2,4,11
	y <sup>5</sup> P <sub>1</sub>	68496.694	-16.7 (5)	<b>-17.15 (3)</b>	a <sup>5</sup> P <sub>2</sub> , b <sup>5</sup> D <sub>2</sub> , a <sup>5</sup> D <sub>1</sub> , a <sup>5</sup> D <sub>2</sub>	2,4,9,11
3d <sup>5</sup> ( <sup>4</sup> D)4p	y <sup>5</sup> F <sub>5</sub>	70657.595	<b>6.38 (10)</b>	-	b <sup>5</sup> D <sub>4</sub>	2,4,8
	y <sup>5</sup> F <sub>4</sub>	70497.790	<b>10.30 (17)</b>	-	a <sup>5</sup> P <sub>2</sub> , a <sup>5</sup> P <sub>3</sub> , b <sup>5</sup> D <sub>4</sub>	2,4,8
	y <sup>5</sup> F <sub>3</sub>	70342.936	<b>10.5 (3)</b>	-	b <sup>5</sup> D <sub>2</sub> , b <sup>5</sup> D <sub>3</sub>	2,8
	y <sup>5</sup> F <sub>2</sub>	70231.468	<b>17.4 (4)</b>	-	b <sup>5</sup> D <sub>2</sub>	2,4,8
	y <sup>5</sup> F <sub>1</sub>	70150.76	<b>44.0 (3)</b>	-	b <sup>5</sup> D <sub>0</sub> , b <sup>5</sup> D <sub>1</sub>	2,4,8
3d <sup>5</sup> ( <sup>4</sup> D)4p	x <sup>5</sup> P <sub>1</sub>	71264.390	<b>-18.7 (7)</b>	-	a <sup>5</sup> P <sub>1</sub> , a <sup>5</sup> P <sub>2</sub> , b <sup>5</sup> D <sub>2</sub>	2,4,8

Table 3 – continued

Configuration	Level	Energy (cm <sup>-1</sup> ) <sup>a</sup>	This study A <sup>b</sup>	Previous work A <sup>b, c</sup>	Levels used in derivation	Spectra used
3d <sup>5</sup> ( <sup>4</sup> D)4p	x <sup>5</sup> P <sub>2</sub>	71323.600	<b>-0.1 (5)</b>	–	a <sup>5</sup> P <sub>1</sub> , a <sup>5</sup> P <sub>3</sub>	2,4
	x <sup>5</sup> P <sub>3</sub>	71390.488	<b>2.58 (15)</b>	–	a <sup>5</sup> P <sub>2</sub> , a <sup>5</sup> P <sub>3</sub> , b <sup>5</sup> D <sub>4</sub>	2,4
	y <sup>5</sup> D <sub>4</sub>	72011.05	<b>4.06 (11)</b>	–	a <sup>5</sup> P <sub>3</sub> , b <sup>5</sup> D <sub>3</sub> , b <sup>5</sup> D <sub>4</sub>	2,4,8
	y <sup>5</sup> D <sub>3</sub>	72247.73	<b>3.84 (17)</b>	–	b <sup>5</sup> D <sub>2</sub> , b <sup>5</sup> D <sub>3</sub> , a <sup>5</sup> P <sub>2</sub> , a <sup>5</sup> P <sub>3</sub>	2,4,7,8,9
	y <sup>5</sup> D <sub>2</sub>	72307.23	<b>3.2 (3)</b>	–	b <sup>5</sup> D <sub>2</sub> , b <sup>5</sup> D <sub>3</sub>	2,4,8
3d <sup>5</sup> ( <sup>6</sup> S)5s	y <sup>5</sup> D <sub>1</sub>	72321.02	<b>1.7 (6)</b>	–	b <sup>5</sup> D <sub>2</sub>	2,4,8
	e <sup>7</sup> S <sub>3</sub>	74560.181	<b>-1.15 (8)<sup>d</sup></b>	–	z <sup>5</sup> P <sub>1</sub> , z <sup>5</sup> P <sub>3</sub>	6,8
3d <sup>5</sup> ( <sup>4</sup> F)4p	e <sup>5</sup> S <sub>2</sub>	76374.791	<b>-20.3 (6)<sup>d</sup></b>	–	z <sup>5</sup> P <sub>1</sub> , z <sup>5</sup> P <sub>3</sub>	6,8
	y <sup>5</sup> G <sub>6</sub>	82142.46	<b>8.5 (1)</b>	–	a <sup>5</sup> F <sub>5</sub>	2,4,8
3d <sup>5</sup> ( <sup>6</sup> S)4d	y <sup>5</sup> G <sub>4</sub>	81863.10	<b>9.0 (6)</b>	–	a <sup>5</sup> F <sub>4</sub>	2,4,8
	y <sup>5</sup> G <sub>5</sub>	82117.22	<b>7.82 (12)</b>	–	a <sup>5</sup> F <sub>4</sub>	2,4,8
	y <sup>5</sup> G <sub>3</sub>	81780.73	<b>19 (2)</b>	–	a <sup>5</sup> F <sub>2</sub> , a <sup>5</sup> F <sub>3</sub> , a <sup>5</sup> F <sub>4</sub>	4
	y <sup>5</sup> G <sub>2</sub>	82193.11	<b>15 (2)</b>	–	a <sup>5</sup> F <sub>3</sub>	4
	e <sup>5</sup> D <sub>4</sub>	82136.483	<b>-6.0 (6)</b>	–	z <sup>5</sup> P <sub>3</sub>	6,12
3d <sup>4</sup> ( <sup>5</sup> D)4s4p( <sup>3</sup> P <sup>o</sup> )	w <sup>5</sup> P <sub>3</sub>	86897.831	<b>-7.6 (6)</b>	–	e <sup>7</sup> S <sub>3</sub>	12,13
	w <sup>5</sup> P <sub>2</sub>	86936.981	<b>-10.9 (6)</b>	–	e <sup>7</sup> S <sub>3</sub>	12,13
3d <sup>5</sup> ( <sup>4</sup> P)4p	w <sup>5</sup> P <sub>1</sub>	86961.122	<b>-21.0 (7)</b>	–	e <sup>7</sup> S <sub>3</sub>	12,13
	y <sup>7</sup> P <sub>4</sub>	83529.52	<b>26.02 (13)</b>	–	e <sup>7</sup> S <sub>3</sub>	12
	y <sup>7</sup> P <sub>3</sub>	83375.80	<b>27.1 (3)</b>	–	e <sup>7</sup> S <sub>3</sub>	12
	y <sup>7</sup> P <sub>2</sub>	83255.99	<b>-38.4 (4)</b>	–	e <sup>7</sup> S <sub>3</sub>	12
3d <sup>5</sup> ( <sup>6</sup> S)5p	x <sup>7</sup> P <sub>2</sub>	85895.477	<b>-7.18 (9)</b>	–	e <sup>7</sup> S <sub>3</sub>	2,4,8

<sup>a</sup>Energy levels were taken from Kramida & Sansonetti (2013). <sup>b</sup>Magnetic dipole constants are reported in 10<sup>-3</sup> cm<sup>-1</sup> and the one standard uncertainty of each level is in parentheses. <sup>c</sup>All previous values are taken from Holt et al. (1999) unless otherwise stated. \* denotes values taken from Blackwell-Whitehead et al. (2005b). \*\* denotes values taken from Villemoes et al. (1991). Recommended values are in bold font. <sup>d</sup>Lines used to determine A constant are symmetric. The value was determined by varying FWHM as described in Section 3.

### 3.2 Magnetic dipole constant of the ground level

The ground level, a<sup>7</sup>S<sub>3</sub>, has strong transitions to the z<sup>7</sup>P<sub>j</sub><sup>o</sup> levels and weaker ones to the z<sup>5</sup>P<sub>2,3</sub><sup>o</sup> levels. The z<sup>7</sup>P<sub>j</sub><sup>o</sup> levels were used by Blackwell-Whitehead et al. (2005b) to derive the HFS constants for the ground level. The z<sup>5</sup>P<sub>2,3</sub><sup>o</sup> and z<sup>7</sup>P<sub>2</sub> HFS constants have been measured by Holt et al. (1999) and can be used to derive the A constant of the a<sup>7</sup>S<sub>3</sub> level that is independent from the measurements of Blackwell-Whitehead et al. (2005b). We fixed the value of the B constant for the a<sup>7</sup>S<sub>3</sub> level to zero and the A and B constants for the upper levels to the values determined by Holt et al. (1999). The damping parameter is allowed to vary.

The derivation of the A constant for the ground level, a<sup>7</sup>S<sub>3</sub>, using the process in Section 3.1 is given in Table 2. The first and second columns give the upper level and its A constant, respectively, with the wavelength of the transition given in the third column. Each transition is observed in up to 4 spectra, and the reference number of the spectrum in column 4 corresponds to the reference number in column 1 of Table 1. Column 5 of Table 2 gives the A constant and uncertainty derived from the corresponding lines in these spectra. The weighted mean and uncertainty are derived using equations (1), (2) and (3) and added in quadrature to the uncertainty of the upper level, giving the values in column 6. Finally, the weighted average and uncertainty of the three transitions is taken, giving the final result and uncertainty in column 7.

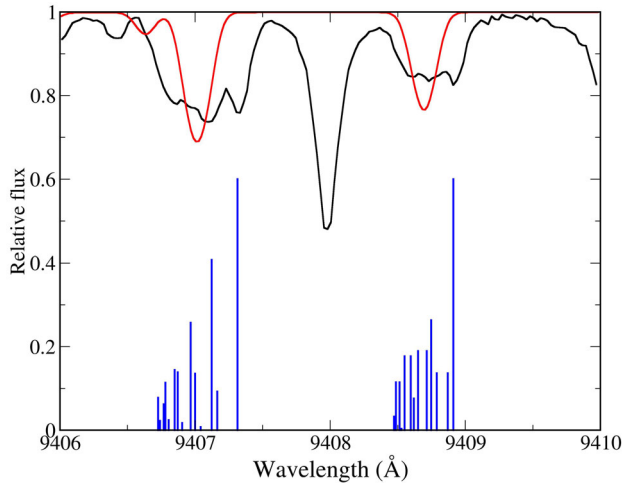
Our value for the A constant of the a<sup>7</sup>S<sub>3</sub> level is within 1.6 standard uncertainties of the value of 26.6 ± 0.3 × 10<sup>-3</sup> cm<sup>-1</sup> measured by Blackwell-Whitehead et al. (2005b). Our uncertainty is over a factor of 7 lower, despite our use of some of the same spectra used in Blackwell-Whitehead et al. (2005b). As mentioned earlier, Doppler broadening in our spectra does not allow for fully resolved spectra and consequently the fit is most sensitive to the difference in the A constants and not the magnitude of them. Blackwell-Whitehead

et al. (2005b) fitted both the A and B constants of both levels simultaneously and thus required four independent parameters to determine the separation of the unresolved HFS components. By using the HFS constants of Holt et al. (1999) for the upper level, and by fixing the value of the B constant of the a<sup>7</sup>S<sub>3</sub> level at zero, in our fitting only the A constant of the a<sup>7</sup>S<sub>3</sub> level determines the separation of the HFS components.

## 4 RESULTS AND DISCUSSION

We summarize our results of the analysis in Table 3. We compared our results with the A constants for 20 levels measured by Holt et al. (1999) using laser spectroscopy and our values are consistent within the joint uncertainties. We obtain a lower uncertainty for the ground level, a<sup>7</sup>S<sub>3</sub>, the septets z<sup>7</sup>P<sub>j</sub><sup>o</sup>, and a<sup>5</sup>S<sub>2</sub> than the previous measurements of Villemoes et al. (1991) and Blackwell-Whitehead et al. (2005b). From analysis of FT spectra in XGREMLIN, we can rapidly obtain HFS constants as long as HFS constants for one of the energy levels are known. Our recommended values are given in bold in Table 3. Where available, the values of Holt et al. (1999) are usually consistent with our values but have a lower uncertainty. The exception is our A constant for the z<sup>5</sup>P<sub>1</sub> level, which differs from the value of Holt et al. (1999) by 1.6 times the joint uncertainty, but agrees with the value of Villemoes et al. (1991) within the joint uncertainty.

Many of the lines of astrophysical interest occur in stars with a high abundance of Mn, but these lines may be very weak in our laboratory spectra. Although we cannot obtain HFS constants directly from these lines, we can derive the constants of the levels involved in the transition from strong lines elsewhere in our spectra. For example the lines around 9408 Å described in Castelli & Hubrig (2004) that we mentioned in our Introduction did not appear in our



**Figure 3.** A comparison of the observed spectrum of HD 175640 with the synthetic spectrum of (Castelli & Hubrig 2004) (red) in the region of the  $b^5D_3 - z^5P_2$  (9407.014 Å) and  $b^5D_2 - z^5P_2$  (9408.606 Å) transitions. The new positions of the HFS components are shown in blue.

spectra. Two of these lines shown in the HgMn star HD 175640 are shown in Fig. 3. The synthetic spectrum shown in red is taken from Castelli & Hubrig (2004) and does not include the HFS constants of the lower levels,  $b^5D_j$ . Our new values for the A constants of the lower levels can be used to obtain the positions of the HFS components shown in Fig. 3 and explain the discrepancy between the observed and synthetic spectra.

## 5 CONCLUSIONS

We have measured HFS A constants for 71 levels of singly ionized manganese using archival FT spectra of hollow cathode lamps taken at a variety of conditions. Of the 71 levels, 47 had no previous laboratory HFS constants. Previous measurements of HFS constants for eight levels were used as reference levels. A constants for almost all of the septet and quintet levels below  $87\,000\text{ cm}^{-1}$  have now been measured. HFS constants for 27 triplet and singlet levels are given in Holt et al. (1999), so constants for 106 of the 533 levels of Mn II are known. Roughly 120 of the remaining levels belong to triplet

and singlet levels below  $87\,000\text{ cm}^{-1}$  for which additional work is needed. Levels above  $87\,000\text{ cm}^{-1}$  are mainly from higher angular momentum levels that have small HFS. The new A constants for the  $b^5D$  levels account for the discrepancy between the synthetic and observed spectrum of HD 175640 in two lines at 9407 Å and 9408 Å reported by Castelli & Hubrig (2004).

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