

# Xenon in mercury–manganese stars

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## ABSTRACT

Previous studies of elemental abundances in mercury–manganese (HgMn) stars have occasionally reported the presence of lines of the ionized rare noble gas Xe II, especially in a few of the hottest stars with  $T_{\text{eff}} \sim 13\,000\text{--}15\,000\text{ K}$ . A new study of this element has been undertaken using observations from Lick Observatory’s Hamilton Échelle Spectrograph. In this work, the spectrum synthesis program UCLSYN has been used to undertake abundance analysis assuming local thermodynamic equilibrium. We find that in the Smith & Dworetsky sample of HgMn stars, Xe is vastly overabundant in 21 of 22 HgMn stars studied, by factors of 3.1–4.8 dex. There does not appear to be a significant correlation of Xe abundance with  $T_{\text{eff}}$ . A comparison sample of normal late B stars shows no sign of Xe II lines that could be detected, consistent with the expected weakness of lines at normal abundance. The main reason for the previous lack of widespread detection in HgMn stars is probably due to the strongest lines being at longer wavelengths than the photographic blue. The lines used in this work were  $\lambda 4603.03$ ,  $\lambda 4844.33$  and  $\lambda 5292.22$ .

**Key words:** stars: abundances – stars: atmospheres – stars: chemically peculiar.

## 1 INTRODUCTION

Among the chemically peculiar (CP) stars of the upper main sequence, the mercury–manganese (HgMn) stars ( $10\,500 \leq T_{\text{eff}} \leq 14\,500\text{ K}$ ) constitute some of the objects most intensively studied with a wide range of optical and ultraviolet spectra (summarized by Wahlgren 2004). The reasons for this include that: many of these stars are extremely slow rotators, making details of their line profiles easily studied for isotopic anomalies, for example; they are not affected by strong magnetic fields, which simplifies theoretical considerations and there are many of these stars bright enough to study with the highest spectral resolutions available. Most often these stars have been studied individually, but a few studies have considered single elements among a set of stars to determine the overall behaviour of abundances and isotope distributions as a function of physical variables such as  $T_{\text{eff}}$  (e.g. Smith 1993; Smith & Dworetsky 1993; Smith 1994, 1996, 1997; Woolf & Lambert 1999; Dworetsky & Budaj 2000). Here, we report an analysis of strong unblended lines of the rare noble gas xenon [atomic number 54; cosmic  $\log A(\text{Xe}) = 2.27$  on the scale where  $\log A(\text{H}) = 12.00$ ] with a view to determine its abundance in a sample of HgMn stars. As will be shown, Xe is found in nearly all HgMn stars and exhibits abundance excesses of 3 dex or more.

Previous observations of Xe II in the spectra of HgMn stars are scanty, although it was originally reported as a possible identification in 3 Cen A by Bidelman (1962) and a probable identification was

reported by Andersen, Jaschek & Cowley (1984) in the He-weak Bp star HR 6000 which seems to be closely related to the HgMn stars. More recently, Xe II was identified in HR 7361 by Adelman (1992); 46 Aql by Sadakane et al. (2001);  $\kappa$  Cnc by Ryabchikova & Smirnov (1988); 33 Gem by Adelman, Philip & Adelman (1996) and 112 Her by Ryabchikova, Zakharova & Adelman (1996). This sparseness may be attributable to the past tendency to observe these stars mainly in the blue photographic region, where Xe II lines are relatively weak. For example, Guthrie (1985) explored Cowley’s Dominion Astrophysical Observatory  $2.4\text{ \AA mm}^{-1}$  spectrograms of several HgMn stars but did not report Xe II. In this work, the strong lines of Xe II used were  $\lambda 5292.22$  and  $\lambda 4844.33$ , supplemented by the weaker  $\lambda 4603.03$  visible in most of the programme stars.

## 2 OBSERVATIONS

The list of stars analysed for this study is from the paper of Smith & Dworetsky (1993) who originally listed 26 stars. In Table 1, two stars are omitted that are not HgMn stars, 36 Lyn (a magnetic Ap star) and HR 6000, a hot analogue of the HgMn stars. Two other stars were also omitted,  $\varphi$  Phe and  $\nu$  Cnc, due to the absence of good spectra. This left a sample of 22 HgMn stars.

Apart from  $\beta$  Scl, the observations for this study were obtained with the Hamilton Échelle Spectrograph (HES; Vogt 1987; Misch 2003) at Lick Observatory, fed by the 0.6-m Coudé Auxilliary Telescope, during four observing runs in 1994–1997. Prior to our 1994 observations, improvements were made in the resolution and instrumental profile of the HES by the replacement of some of the optical components, which also made it possible to use the full field of the

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**Table 1.** Programme HgMn stars.

Star	HD	$T_{\text{eff}}$ (K)	$\log g$ (cgs)	Reference	$\xi$ ( $\text{km s}^{-1}$ )	Reference	$v \sin i$ ( $\text{km s}^{-1}$ )	Reference
87 Psc	7374	13150	4.00	(1)	1.5	(1)	21	(4)
53 Tau	27295	12000	4.25	(1)	0.0	(2)	5	(3, 5)
$\mu$ Lep	33904	12800	3.85	(1)	0.0	(2)	15.5	(4)
HR 1800 <sup>a</sup>	35548	11050	3.80	(1)	0.5	(1)	3	(4)
33 Gem	49606	14400	3.85	(1)	0.5:	(1)	19.5	(5)
HR 2676	53929	14050	3.60	(1)	1.0:	(1)	21	(5)
HR 2844	58661	13460	3.80	(1)	0.5:	(1)	27	(4)
$\kappa$ Cnc <sup>a</sup>	78316	13200	3.7	(6)	0.0	(2)	6	(3)
HR 4072 <sup>a</sup>	89822	10650	3.8	(7)	1.0	(7)	3.2	(7)
$\chi$ Lup <sup>a</sup>	141556	10650	3.90	(8)	0.0	(8)	2	(7)
$\iota$ CrB <sup>a</sup>	143807	11000	4.00	(1)	0.2	(9)	1	(7)
$\nu$ Her	144206	12000	3.80	(1)	0.6	(10)	9	(4)
$\phi$ Her <sup>a</sup>	145389	11525	4.05	(11)	0.4	(11)	8.0	(11)
28 Her	149121	11000	3.80	(1)	0.0	(12)	8	(12)
HR 6997	172044	14500	3.90	(1)	1.5	(1)	34	(1)
112 Her <sup>a</sup>	174933	13100	4.10	(13)	0.0	(13)	6	(13)
HR 7143	175640	12100	4.00	(1)	1.0	(1)	2	(4)
HR 7361	182308	13650	3.55	(1)	0.0	(1)	9	(1)
46 Aql	186122	13000	3.65	(1)	0.0	(1)	1	(1)
HR 7664	190229	13200	3.60	(1)	0.8	(12)	8	(4)
HR 7775	193452	10800	3.95	(1)	0.0	(1)	1	(1)
$\beta$ Scl	221507	12400	3.90	(1)	0.0:	(1)	25	(4)

<sup>a</sup>Binaries with two spectra. Values given for  $T_{\text{eff}}$ ,  $\log g$ ,  $v \sin i$  and microturbulent velocity,  $\xi$ , are for the primary star.

Values of  $\xi$  followed by a colon (:) are approximate and were derived solely from ultraviolet Fe II lines by (1).

References: (1) Smith & Dworetsky (1993); (2) Adelman (1988a); (3) Adelman (1987); (4) Dworetsky, Jomaron & Smith (1998); (5) Determined from this work; (6) Ryabchikova et al. (1998); (7) Harman (1997); (8) Wahlgren, Adelman & Robinson (1994); (9) Adelman (1989); (10) Adelman & Fuhr (1985); (11) Zavala et al. (2007); (12) Adelman (1988b); (13) Ryabchikova et al. (1996).

2048  $\times$  2048 CCDs to maximum advantage. For our observations, both the unthinned phosphor-coated Orbit CCD (Dewar 13) and, from July 1995, the thinned Ford CCD (Dewar 6) were used, depending on availability as the latter was shared with the multi-object spectrograph on the 3-m telescope. The Orbit CCD has very few bad pixels or columns. The Ford CCD has several column defects but it has a much higher quantum efficiency in the blue and so we used the Ford CCD whenever it was available. The spectral range for the observations was 3800–9000 Å and the typical signal-to-noise ratio (S/N) per pixel in the centres of orders ranged from 75 to 250 depending on wavelength. With the slit settings used, the combination of spectrograph and CCDs gave resolutions  $R \approx 46\,500$ . We used the polar axis quartz lamp for flat-fields and a Th–Ar comparison for wavelength calibration.

The observations of  $\beta$  Scl are from the UVES Paranal Observatory Project (ESO DDT Program ID 266.D-5655) which is an ongoing program to observe, reduce and provide a public library of good quality spectra of bright southern stars obtained with the Ultraviolet and Visual Échelle Spectrograph (UVES) mounted on the Very Large Telescope (VLT) unit Keuyen (VLT UT2). The UVES Paranal Observatory Project is described by Bagnulo et al. (2003). The project provides almost complete wavelength coverage from 3000–10 000 Å for all stars observed. The spectral resolution is about 80 000 and the typical S/N is 300–500 in the V band.

The Lick Observatory Échelle spectra were extracted and calibrated using standard IRAF extraction packages (Valdes 1992; Churchill 1995), running on the Starlink node of University College London (UCL). Previous measurements (Allen 1998) showed that there were no measurable effects of parasitic light (residual scattered light) in the line profiles provided that general scattered

light in the adjacent interorder spaces was taken as the subtracted background. In practice, the residual scattered light was less than approximately 1 per cent and so we have made no corrections for it (see Dworetsky & Budaj 2000, for further details).

### 3 ABUNDANCE DETERMINATION

#### 3.1 Stellar parameters and stellar atmospheres

The effective temperatures and surface gravities of the HgMn programme stars are given in Table 1. Seven of the stars are listed as being binaries with two spectra; of these, six are noted as double-lined spectroscopic binaries but HR 1800 is more accurately described as a close visual binary where the secondary spectrum is evident as rotationally broadened features. The adopted stellar data and light ratios for the binary stars are shown in Table 2. With the exception of  $\phi$  Her, the light ratios follow those used in our previous work (Dworetsky & Budaj 2000). We obtained the light ratio for  $\phi$  Her by using the magnitude difference of 2.57 mag at 5500 Å as determined by Zavala et al. (2007). Light ratios were interpolated to the relevant wavelengths for the Xe II lines in this study using the Kurucz (1993) model atmosphere fluxes. Although HR 7775 is known to have a faint visual secondary contributing  $\sim 2$ –4 per cent of the flux (Bohlender, Dworetsky & Jomaron 1998) in this analysis, we have treated it as a single star and ignored the presence of the secondary.

In Table 1, when  $v \sin i$  is listed as being determined from this work it was calculated using the spectrum synthesis program UCLSYN (Smith & Dworetsky 1988; Smith 1992) which calculates a rotational profile from the limb darkening and then performs a  $\chi^2$  minimization to get a best fit, holding other parameters constant. This

**Table 2.** Binary stars: adopted stellar data and light ratios.

Star	$\lambda$	$L_A/L_B$	$T_{\text{eff}A}/\log g_A$ (K)/(cgs)	$T_{\text{eff}B}/\log g_B$ (K)/(cgs)	$L_A/L_B$ 4603 Å	$L_A/L_B$ 4844 Å	$L_A/L_B$ 5292 Å	Ref.
HR 1800	$H_p$	2.45	11050/3.8	9500/4.0	2.44	2.63	2.39	(1)
$\kappa$ Cnc	5480	11.5	13200/3.7	8500/4.0	12.7	14.3	11.8	(2)
HR 4072	4520	5.45	10650/3.8	8800/4.2	5.39	5.77	5.17	(3)
$\chi$ Lup	4520	3.65	10650/3.9	9200/4.2	3.64	3.87	3.56	(4)
$\iota$ CrB	4520	2.70	11000/4.0	9000/4.3	2.67	3.05	2.56	(3)
$\phi$ Her	5500	10.67	11525/4.05	8000/4.30	12.45	12.70	11.05	(5)
112 Her	4520	6.20	13100/4.1	8500/4.2	6.14	6.94	5.70	(6)

Note: The entry for HR 1800 is the ratio quoted for the broadband  $H_p$  filter, which we assume to be the light ratio at  $H\beta$ .

References: (1) ESA (1997); (2) Ryabchikova et al. (1998); (3) Harman (1997) and Jomaron, Dworetzky & Allen (1999); (4) Harman (1997), Jomaron et al. (1999) and Wahlgren et al. (1994); (5) Zavala et al. (2007); (6) Ryabchikova et al. (1996).

**Table 3.** Atomic data for Xe II lines.

LS designation	Wavelength (Å)	lower e.p. (eV)	$\log gf^a$	$10^6 \gamma_s/n_e$ ( $\text{cm}^3\text{s}^{-1}$ )
$6s^2 P_{3/2}-6p^2 P_{3/2}$	4603.03	11.79	-0.02	6.58
$6s^4 P_{5/2}-6p^4 D_{7/2}$	4844.33	11.54	0.51	7.23
$6s^4 P_{5/2}-6p^4 P_{5/2}$	5292.22	11.54	0.38	6.46

<sup>a</sup>Values of  $\log gf$  were calculated from the transition probabilities given by Zielińska et al. (2002) for  $\lambda 4844.33$  and  $\lambda 5292.22$  and Gigosos et al. (1994) for  $\lambda 4603.03$ .

was done for several lines in the spectrum and then the average  $v \sin i$  was adopted.

### 3.2 Atomic data

The oscillator strengths used in this analysis are given as  $\log gf$  in Table 3. For the  $\lambda 4844.33$  and  $\lambda 5292.22$  lines, we obtained the oscillator strengths by using the transition probabilities given by Zielińska, Bratasz & Dzierżega (2002). These authors carried out a critical evaluation of experimental lifetimes in the literature and measured their own branching ratios which they used to calculate transition probabilities. They claimed uncertainties of <5 per cent for some lines. Zielińska et al. (2002) did not include the  $\lambda 4603.03$  line in their analysis, and we obtained the oscillator strength for this line by using the transition probability given by Gigosos et al. (1994) who used a pulsed arc as a plasma source and used a method which enabled them to determine the plasma temperature and transition probabilities simultaneously from relative intensities of spectral lines. The lower level excitation potentials, also listed in Table 3, are from Ryabchikova & Smirnov (1988). The LS designations are from Di Rocco, Iriarte & Pomarico (2000).

We assumed the classical radiative damping constant  $\Gamma_R = 0.2223 \times 10^{16}/\lambda^2 \text{ s}^{-1}$  (where  $\lambda$  is in Å). This is a good approximation for these lines as the typical lifetime of the upper level is about 10 ns. For the Van der Waals damping, we have followed the formulation by Warner (1967). At the effective temperatures found in the HgMn stars, Van der Waals damping is expected to make only a small contribution to the line broadening because hydrogen is mostly ionized except at the coolest end of the temperature range. For Stark broadening, we used the results of Popović & Dimitrijević (1996) who calculated theoretical values for the Stark widths of Xe II lines and compared them with measured values in the literature. Examination of their paper shows that their theoretical widths are reasonably representative of the measured widths for a wide range of experi-

mental temperatures. The variation with temperature was so small that we assumed the average theoretical value for the Stark width (which we obtained from the listed ratios of measured to theoretical values in Popović & Dimitrijević 1996) at a temperature of  $T_{\text{eff}} \sim 12000$  K for all the HgMn programme stars. We present the Stark widths in the form of  $\gamma_s/n_e$  as given in Table 3. We found that the most significant source of damping in our sample of HgMn stars is  $\gamma_s$  which dominates by an order of magnitude over radiative and Van der Waals damping.

### 3.3 Abundances and equivalent widths

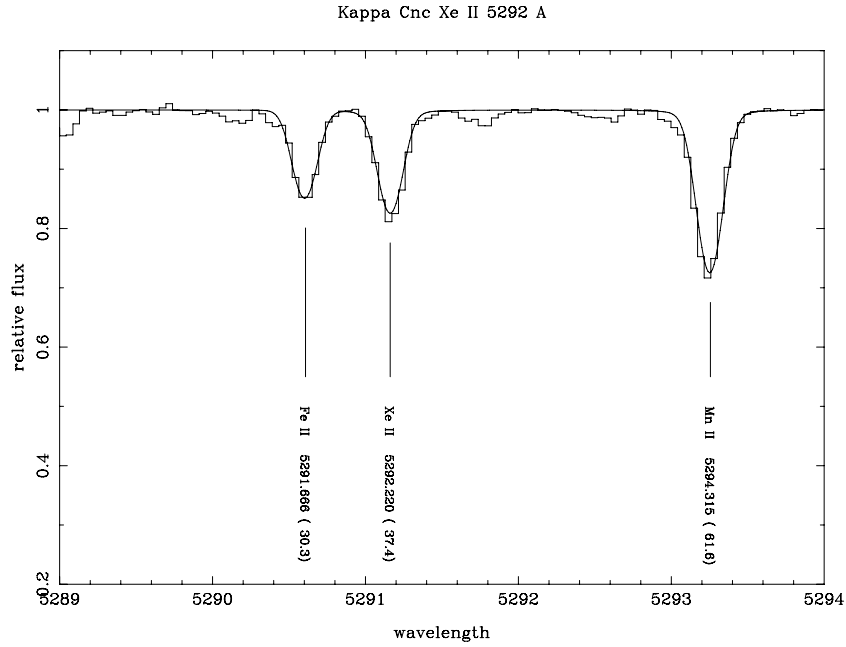
Determination of abundances and equivalent widths was carried out using the spectrum synthesis program UCLSYN in the local thermodynamic equilibrium (LTE) approximation. When the Xe II lines were sharp and unblended, equivalent widths were measured interactively in UCLSYN and used in the program's exact curve of growth analysis to obtain the abundance for that line. In cases where rotational blending necessitated modelling of the spectra, we determined abundances from minimized  $\chi^2$  synthetic fits of the blended line profile holding all parameters constant except the abundance of Xe. In those cases, the equivalent width we give is that modelled from these least-squares fits for the Xe lines. In most of the binaries, the lines were sufficiently unblended to allow an equivalent width to be measured and an exact curve of growth analysis to be used. Some examples are presented in Figs 1 and 2.

Of the three Xe II lines used,  $\lambda 4603.03$  was the weakest, but it was generally detectable without any difficulty. Fig. 3 illustrates this line in the spectrum of HR 7664, where the nearest line is of very overabundant P II.

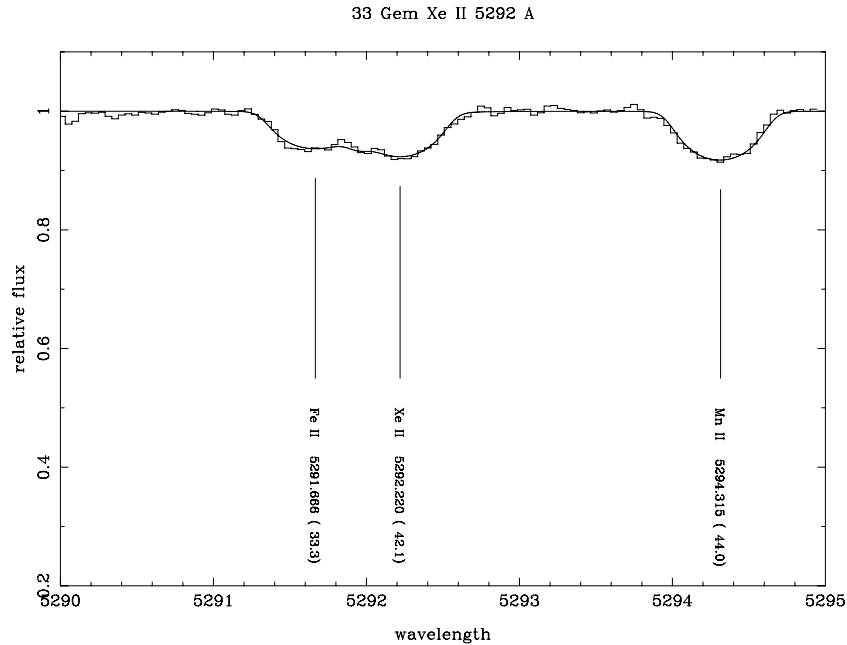
## RESULTS

The Xe II equivalent widths and abundances for the HgMn stars are given in Table 4. Xenon was detected in 21 out of 22 HgMn stars in the sample ( $\phi$  Her being the only exception). This is a somewhat surprising result given the paucity of previous detections in the literature. The cosmic abundance of xenon from Asplund, Grevesse & Sauval (2005) is 2.27 on the scale where  $\log A(\text{H}) = 12.00$ . The lower limit for detection in our sample is of the order of  $\log A(\text{Xe}) = 5.2$  depending on effective temperature and  $v \sin i$ . In all the HgMn stars where xenon was detected in this work, the mean Xe II abundance (Table 4) is much greater than the cosmic abundance of xenon.

In Fig. 4, the mean xenon abundances are plotted as a function of  $T_{\text{eff}}$ . There is a weak correlation but it is not significant



**Figure 1.** Xe II  $\lambda 5292.22$  in  $\kappa$  Cnc. The histogram represents the observed spectrum. Solid line is synthesis from UCLSYN. The wavelength shift is due to the synthesis including Doppler shifts in both components of the binary. Figures in brackets following line identifications are the observed equivalent widths in mÅ. Note that we did not attempt to identify all the weak lines in this spectrum.



**Figure 2.** Xe II  $\lambda 5292.22$  in 33 Gem. The higher rotational velocity ( $v \sin i = 19.5 \text{ km s}^{-1}$ ) creates some problems with blends and therefore synthesis of the spectrum is used to fit the blends.

( $r = 0.35 \pm 0.24$ ). We found no significant correlation with surface gravity or  $v \sin i$ .

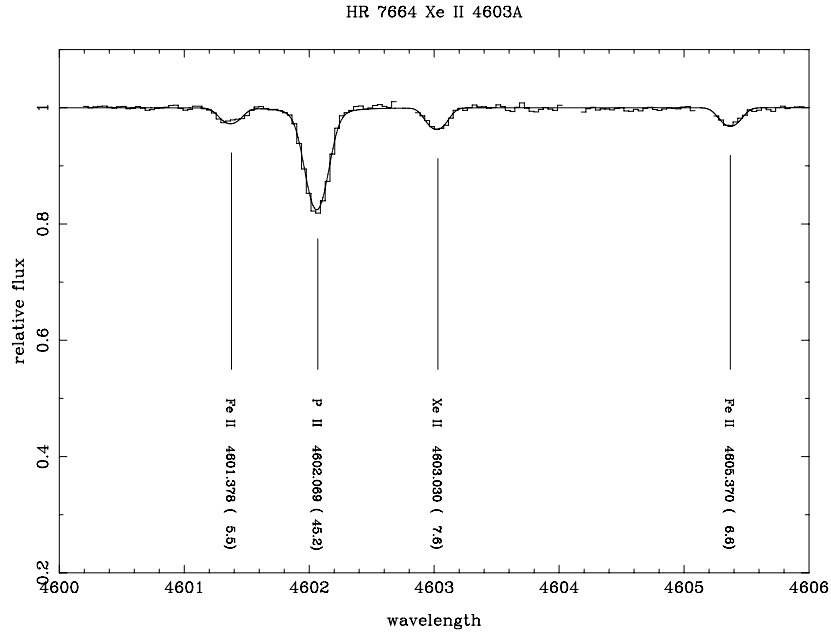
We examined available spectra of normal late B stars in the Smith & Dworetsky (1993) list and searched for any lines at positions of the Xe II lines. As expected, we found no sign of any absorption features corresponding to Xe II in the normal late B stars.

At this stage, no calculations of the NLTE effects for Xe II have been attempted, and it is quite possible that this may modify the

results presented here. However, a vast overabundance of xenon in nearly all HgMn stars seems an inescapable conclusion from this work.

## 5 ERROR ANALYSIS

The errors quoted on the mean abundances in Table 4 are formal standard errors on the mean, weighted where appropriate. As the



**Figure 3.** Xe II  $\lambda 4603.03$  in HR 7664. Gaps in the observed spectrum indicate where cosmic rays or bad columns have been removed.

**Table 4.** Xe II equivalent widths (mÅ) and abundances for HgMn programme stars, where  $\log A(\text{H}) = 12.00$ .

Xe II Line Star	$\lambda 4603.03$		$\lambda 4844.33$		$\lambda 5292.22$		Mean log A
	$W_\lambda$	log A	$W_\lambda$	log A	$W_\lambda$	log A	
87 Psc	$\leq 2.6$	$\leq 5.44$	4.5:	5.32:	4.8:	5.38:	$5.35 \pm 0.03$
53 Tau	$\leq 2.0$	$\leq 5.59$	3.1:	5.60:	3.3:	5.57:	$5.59 \pm 0.02$
$\mu$ Lep	10.1	6.26	25.3	6.78	26.2	6.85	$6.63 \pm 0.19$
HR 1800 <sup>a</sup>	4.3	6.25	5.4	6.14	3.3	5.82	$6.07 \pm 0.13$
33 Gem	$34.2:^\dagger$	$7.24:^\dagger$	38.5	6.98	$42.1^\dagger$	$7.16^\dagger$	$7.10 \pm 0.07^{**}$
HR 2676	$\leq 1.7$	$\leq 5.04$	11.2	5.53	$\leq 7.5:^\dagger$	$\leq 5.39:^\dagger$	5.53:
HR 2844	7.7:	5.94:	29.9	6.76	$20.4:^\dagger$	$6.36:^\dagger$	$6.46 \pm 0.20^{**}$
$\kappa$ Cnc <sup>a</sup>	20.8	6.88	36.1	7.19	37.4	7.32	$7.13 \pm 0.13$
HR 4072 <sup>a</sup>	3.9	6.17	6.6	6.29	4.9	6.06	$6.17 \pm 0.07$
$\chi$ Lup <sup>d</sup>	3.6	6.25	5.7	6.38	4.5	6.15	$6.26 \pm 0.07$
$\iota$ CrB <sup>a</sup>	*	*	4.5	6.18	5.3	6.24	$6.21 \pm 0.03$
$\nu$ Her	2.9:*	5.60:*	8.9	5.94	7.5	5.85	$5.84 \pm 0.07^{**}$
$\phi$ Her <sup>d</sup>	$\leq 1.2$	$\leq 5.39$	$\leq 1.2$	$\leq 5.16$	$\leq 1.2$	$\leq 5.11$	$\leq 5.22 \pm 0.09$
28 Her	$2.8:^\dagger$	$5.81:^\dagger$	6.8:	6.11:	5.9	6.00	$5.98 \pm 0.05^{**}$
HR 6997	24.6	6.62	41.8	6.78	45.2	6.93	$6.78 \pm 0.09$
112 Her <sup>d</sup>	10.0	6.40	22.1	6.84	20.9	6.78	$6.67 \pm 0.14$
HR 7143	4.0	5.82	10.8	6.15	9.1	6.01	$5.99 \pm 0.10$
HR 7361	21.6	6.71	35.4	6.93	41.1	7.24	$6.96 \pm 0.15$
46 Aql	6.6:*	5.86:*	15.5	6.08	17.7:	6.29:	$6.08 \pm 0.08^{**}$
HR 7664	7.6	5.88	18.8	6.11	17.2	6.12	$6.04 \pm 0.08$
HR 7775	$4.2:^\dagger$	$6.17:^\dagger$	5.7	6.19	6.5	6.20	$6.19 \pm 0.01^{**}$
$\beta$ Scl	9.0	6.26	16.1	6.42	$19.2^\dagger$	$6.61^\dagger$	$6.43 \pm 0.10$

<sup>a</sup>Double-lined spectroscopic binary (visual binary in the case of HR 1800) with observed  $W_\lambda$ ; abundance takes secondary dilution into account.

Notation ‘\*’ means bad column or cosmic ray hit.

Notation ‘:’ means approximate.

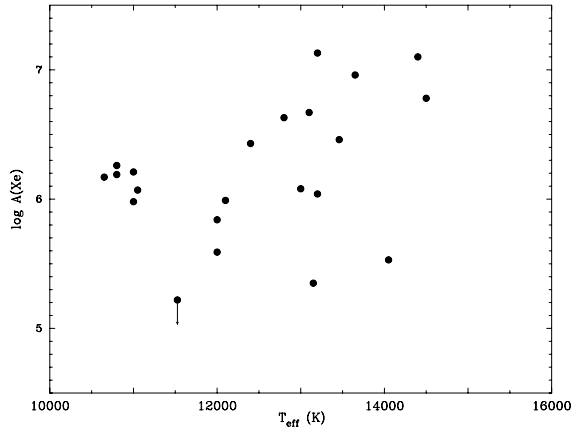
Notation ‘ $\dagger$ ’ means that the line was blended.

Notation ‘\*\*’ indicates that approximate values are given half-weight in the calculation of the mean log A. In such cases, the error quoted is the error on the weighted mean.

Note that, except for  $\phi$  Her, upper limits are not included when calculating the mean log A.

calculation of such errors involves small number statistics, these formal errors are not especially reliable. We also considered the errors due to uncertainties in the atmospheric parameters or observational data. To address this, we have examined the effect on the

abundances of uncertainties in  $T_{\text{eff}}$ ,  $\log g$ , microturbulent velocity, Stark broadening and equivalent width, by varying these parameters one at a time whilst holding all other parameters constant. This was done for HR 7143, one of the weaker-lined stars in our sample



**Figure 4.** Mean xenon abundances as a function of  $T_{\text{eff}}$  in the HgMn programme stars. Arrow indicates upper limit. Solar  $\log A(\text{Xe}) = 2.27$ .

and HR 7361 which is one of the strong-lined stars in our sample. The adopted uncertainties in the parameters were:  $\pm 250$  K for  $T_{\text{eff}}$ ;  $\pm 0.10$  dex for  $\log g$ ;  $\pm 0.5$  km s $^{-1}$  for microturbulent velocity and  $\pm 50$  per cent for  $\gamma_s/n_e$ . In a star that rotates more rapidly, the noise will affect more pixels than it would over a narrower line; therefore, we have adopted an error in equivalent width of  $\pm 2$  mÅ for HR 7361 and  $\pm 1$  mÅ for HR 7143. The results of this error analysis are shown in Table 5 where we list the absolute values of the errors in  $\log A$ . Some of the errors were slightly asymmetric and in such cases the mean absolute error in abundance is given. The errors were added in quadrature to derive the total error given in the last column of Table 5.

## 6 DISCUSSION

### 6.1 The xenon enhancement in HgMn stars

Xenon (Xe II) is yet another of the spectra originally omitted from the revised multiplet tables by Moore (1945) as ‘not of astrophysical interest’ yet subsequently found in the HgMn stars and other CP types (e.g. Ga II, Kr II, Pt II, Au II, Hg II, Ti II and Bi II have also been identified in stars).

The xenon enhancement in HgMn stars rivals that of other rare elements such as Hg (Smith 1997; Woolf & Lambert 1999) with many of the stars having Xe enhancement of the order of 40–50 000. Such a large enhancement of abundance implies a strong upwards radiative acceleration on Xe over a wide range of  $T_{\text{eff}}$  and  $\log g$ , and it will be interesting to see if this prediction is confirmed by future calculations, and to see whether Xe is expected to be stratified in a thin layer. Radiative diffusion processes must be dredging up xenon

from deep inside the stellar envelope to get an enhancement of this size. As can be seen in Fig. 4, the enhancements found in the cooler HgMn stars clustered around 11 000 K are all very similar at about 3.9 dex. At higher  $T_{\text{eff}}$ , the enhancements show much more scatter, which is not an artefact of the measurement uncertainties but must be a real effect. The one star with an upper limit only,  $\phi$  Her, could itself have a considerable enhancement of Xe but yet be below the limit of detectability in this work.

We looked at what we feel are the 10 best-observed stars in Table 4 to see if there were any systematic differences in results from the lines used. The mean difference between  $\log A$  derived from  $\lambda 4844$  and  $\lambda 5292$  is  $0.03 \pm 0.06$  dex, so these two lines give results that agree very well. The mean difference between abundances from  $\lambda 4603$  and the average of the other two lines is  $-0.22 \pm 0.08$  dex, which seems obviously significant. The most likely explanation is an error in one or more of the adopted oscillator strengths. However, this does not affect any of the essential conclusions in this work.

The rarity of Xe II identifications in previous work is explicable by the relative weakness of its lines in the photographic blue region, where many observations were done only below 4600 Å. It is easy to understand why the lines might be overlooked in some earlier work of this sort – and in at least one case, a strong line of another element masks the presence of a Xe II line, as discussed below.

### 6.2 A comment on strontium abundances

In the course of an investigation of strontium abundances in HgMn stars (Dworetzky, Dyer & Persaud 2008), it was noted that Sr II  $\lambda 4215.519$  apparently persisted even when Sr II  $\lambda 4077.714$  was completely undetectable. An example of this is seen in the Sr II results of Ryabchikova et al. (1996), where  $\lambda 4215.519$  has a measured equivalent width of 6.5 mÅ in 112 Her. We also found a similar strength for this line, but a wavelength slightly shifted. We were unable to detect Sr II  $\lambda 4077.714$  at all ( $\leq 0.6$  mÅ), nor did Ryabchikova et al. (1996) report seeing this line.

The solution to this anomaly is our identification of a blend of Sr II with Xe II  $\lambda 4215.60$  (Hansen & Persson 1987), which has an estimated strength of 4 mÅ in 112 Her from the abundance in Table 4 and an astrophysical  $\log gf$  of  $-1.06$ , based on the Lick observations of the ultrasharp-lined, Sr-deficient, ‘mild’ HgMn star 46 Aql (Cowley 1980; Smith & Dworetzky 1993). The remaining strength of this feature in 112 Her is probably due to weak lines of Mn II and Cr II. Strontium is at least 1.0 dex below solar abundance in both 46 Aql and 112 Her.

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**Table 5.** Typical absolute abundance errors resulting from uncertainties in parameters or observational data.

Xe II Line	Star	Error in log abundance for:					Total
		$\Delta T_{\text{eff}} = \pm 250$ K	$\Delta \log g = \pm 0.10$ dex	$\Delta \xi = \pm 0.5$ km s $^{-1}$	$\Delta \gamma_s/n_e = \pm 50$ per cent	$\Delta W_\lambda$	
$\lambda 4603.03$	HR 7143	0.04	0.04	0.02	0.00	0.14	0.15
	HR 7361	0.04	0.03	0.04	0.02	0.10	0.12
$\lambda 4844.33$	HR 7143	0.08	0.07	0.05	0.01	0.07	0.14
	HR 7361	0.04	0.04	0.07	0.07	0.08	0.14
$\lambda 5292.22$	HR 7143	0.06	0.04	0.04	0.01	0.08	0.12
	HR 7361	0.04	0.02	0.07	0.09	0.08	0.15

For HR 7143 ( $T_{\text{eff}} = 12\,100$  K), we adopted the estimate  $\Delta W_\lambda = \pm 1$  mÅ; for HR 7361 ( $T_{\text{eff}} = 13\,650$  K),  $\Delta W_\lambda = \pm 2$  mÅ.

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