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Neon abundances in normal late-B and mercury–manganese stars

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ABSTRACT

We make new non-local thermodynamic equilibrium calculations to deduce the abundances of neon from visible-region echelle spectra of selected Ne I lines in seven normal stars and 20 HgMn stars. We find that the best strong blend-free Ne line that can be used at the lower end of the effective temperature T_{eff} range is λ6402, although several other potentially useful Ne I lines are found in the red region of the spectra of these stars. The mean neon abundance in the normal stars ($\log A = 8.10$) is in excellent agreement with the standard abundance of neon (8.08). However, in HgMn stars neon is almost universally underabundant, ranging from marginal deficits of 0.1–0.3 dex to underabundances of an order of magnitude or more. In many cases, the lines are so weak that only upper limits can be established. The most extreme example found is υ Her with an underabundance of at least 1.5 dex. These underabundances are qualitatively expected from radiative acceleration calculations, which show that Ne has a very small radiative acceleration in the photosphere, and that it is expected to undergo gravitational settling if the mixing processes are sufficiently weak and there is no strong stellar wind. According to theoretical predictions, the low Ne abundances place an important constraint on the intensity of such stellar winds, which must be less than $10^{-14}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ if they are non-turbulent.

Key words: line: profiles – stars: abundances – stars: chemically peculiar.

1 INTRODUCTION

HgMn stars are a subclass of chemically peculiar star occupying the spectral region corresponding approximately to MK types B9–B6 (10 500–16 000 K). Owing to low helium abundances, their spectral classes are generally placed by observers in the A0–B8 range. Observationally, they are characterized by extremely low rotational velocities, weak or non-detectable magnetic fields and photometric variability, and atmospheric deficiencies of light elements (e.g. He, Al and N) coupled with enhancements of the heavy elements (e.g. Hg, Mn, Pt, Sr and Ga). In addition, the heavy elements also have non-terrestrial isotopic abundances (Smith 1997; Bohlender, Dworetsky & Jomaron 1998). The currently favoured mechanism for explaining these anomalies is the radiative diffusion hypothesis (Michaud 1970). This work has been advanced in the form of a parameter-free model (Michaud 1986).

The quiescent atmospheres of these stars makes them one of the best natural laboratories for studying the competing processes of gravitational settling and radiative levitation (Vauclair & Vauclair 1982). In the absence of disrupting mechanisms such as convection, rotationally-induced meridional currents, high micro-turbulence and magnetic fields, certain rare elements can reach a factor of 10^5 enhancement over their standard abundances. Because of the strength and sharpness of normally exotic spectroscopic lines, HgMn stars are also useful for constraining fundamental atomic data (Lanz 1995).

Although there have been many studies of individual HgMn stars and of the abundances of many elements across a sample of HgMn stars, we have been unable to find any papers mentioning the abundance of Ne in HgMn stars, with the recent exception of a paper by Adelman & Pintado (2000) in which local thermodynamic equilibrium (LTE) calculations established that Ne I line strengths in κ Cnc implied an overabundance of 0.64 dex, while an underabundance was found in HR 7245. The He-weak star 3 Cen A also seemed to be overabundant in Ne relative to the Sun (we will look again at these results in Section 5). However, according to the original investigations by Auer & Mihalas (1973), who showed that non-LTE (NLTE) methods yield Ne I lines that are nearly double the strength expected from LTE calculations at an effective temperature $T_{\mathrm{eff}} = 15\,000$ K, Ne is known to exhibit strong non-LTE effects in B stars. Thus the overabundances reported may well be a result of neglecting NLTE considerations.

The lack of Ne observations in late-B stars is slightly surprising, because Ne is an important and interesting element. The standard abundance of Ne (Anders & Grevesse 1989; Grevesse, Noels & Sauval 1996), which was deduced from the solar wind, nebular

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spectroscopy, stellar observations and analyses such as those of Auer & Mihalas, is comparable with that of C, N and O. It is also interesting because its atomic structure resembles that of He, with a very high first ionization potential (of about 22 eV). Consequently, all of its resonance lines and the ground state photoionization continuum are in the Lyman continuum where the stellar energy flux in the photosphere of late-B stars is low. One would then expect that the radiative acceleration of Ne may not be enough to balance gravity and that Ne should sink. Indeed, theoretical calculations by Landstreet, Dolez & Vauclair (1998), who considered a non-turbulent mass loss or stellar wind in the stellar envelopes, predict that there will be: (1) neon underabundances if the mass-loss rate is less than $10^{-14}\,M_{\odot}\,yr^{-1}$; (2) neon overabundances for mass loss in the range 10^{-14}–$10^{-12}\,M_{\odot}\,yr^{-1}$; or (3) normal neon abundances for mass loss over $10^{-12}\,M_{\odot}\,yr^{-1}$. Also, our own calculations of radiative accelerations in the atmospheres (Budaj & Dworetsky, in preparation) predict a pattern of general photospheric underabundances for Ne.

In this paper, we present an abundance analysis of visible Ne I lines based on a full NLTE treatment of the strength of λ6402. It is the strongest unblended line of Ne I in the visible spectrum. We also demonstrate that, to a close order of magnitude, several other Ne I lines tend to have similar NLTE enhancements and can be used if spectra showing λ6402 are not available. We find that for most HgMn stars, neon turns out to be underabundant, which suggests that the first scenario described by Landstreet et al. (1998) is the most likely one.

2 OBSERVATIONS

Our stellar sample is based upon that of Smith & Dworetsky (1993), who analysed data from the *International Ultraviolet*

Table 1. Programme stars: basic data and adopted atmospheric parameters.

Star	HD	Spectral type	V_r (km s^{-1})	T_{eff} (K)	log g (dex cm s^{-2})	ξ (km s^{-1})	Ref.	$v \sin i$ (km s^{-1})	Ref.
				Normal and superficially normal stars					
π Cet	17081	B7 V	+15 SB	13 250	3.80	0.0	(1)	25	(3)
134 Tau	38899	B9 IV	+18 V	10 850	4.10	1.6	(1)	30	(3)
τ Her	147394	B5 IV	−14 V?	15 000	3.95	0.0	(3)	32	(3)
ζ Dra	155763	B6 III	−17 V?	12 900	3.90	2.5:		34	(3)
α Lyr	172167	A0 Va	−14 V	9450	4.00	2.0	(4)	24	(3)
HR 7098	174567	A0 Vs	−3	10 200	3.55	1.0	(3)	11	(3)
21 Aql	179761	B8 II–III	−5 V	13 000	3.50	0.2	(1)	17	(3)
HR 7338	181470	A0 III	−14 SBO	10 250	3.75	0.5	(3)	3	(3)
ν Cap	193432	B9.5 V	−2 V?	10 300	3.90	1.6	(1)	27	(3)
HR 7878	196426	B8 IIIp	−23	13 050	3.85	1.0:		6	(9)
21 Peg	209459	B9.5 V	−0	10 450	3.50	0.5	(3)	4	(3)
				HgMn stars					
87 Psc	7374	B8 III	−16 V	13 150	4.00	1.5	(3)	21.0	(5)
53 Tau	27295	B9 IV	+12 SBO	12 000	4.25	0.0	(2)	6.5	(5)
μ Lep	33904	B9 IIIpHgMn	+28	12 800	3.85	0.0	(2)	15.5	(5)
HR 1800	35548	B9 pHgSi	−9 V?	11 050	3.80	0.5	(3)	3.0	(5)
33 Gem	49606	B7 III	+13	14 400	3.85	0.5:		22.0	(5)
HR 2676	53929	B9.5 III	+6 V?	14 050	3.60	1.0:		25.0	(5)
HR 2844	58661	B9 pHgMn	+21 V	13 460	3.80	0.5:		27.0	(5)
ν Cnc	77350	A0 pSi	−15 SBO	10 400	3.60	0.1	(6)	13	(6)
κ Cnc	78316	B8 IIIpMn	+24 SB1O	13 500	3.80	0.0	(2)	7	(5)
HR 4072	89822	A0 pSiSr:Hg:	−0 SB2O	10 500	3.95	1.0	(7)	3.2	(7)
χ Lup	141556	B9 IV	+5 SB2O	10 750	4.00	0.0	(11)	2.0	(7)
ι CrB	143807	A0 p:Hg:	−19 SB	11 000	4.00	0.2	(6)	1.0	(7)
υ Her	144206	B9 III	+3	12 000	3.80	0.6	(1)	9.0	(5)
ϕ Her	145389	B9 p:Mn:	−16 SB1O	11 650	4.00	0.4	(8)	10.1	(5)
HR 6997	172044	B8 II–IIIpHg	−26 SBO	14 500	3.90	1.5	(3)	36.0	(5)
112 Her	174933	B9 II–IIIpHg	−20 SB2O	13 100	4.10	0.0:		5.5	(12)
HR 7143	175640	B9 III	−26 V?	12 100	4.00	1.0	(3)	2.0	(5)
HR 7361	182308	B9 IVpHgMn	−20 V?	13 650	3.55	0.0	(3)	8.2	(5)
46 Aql	186122	B9 IIIpHgMn	−32	13 000	3.65	0.0	(3)	3.0	(5)
HR 7664	190229	B9 pHgMn	−22 SB1	13 200	3.60	0.8	(8)	8.0	(5)
HR 7775	193452	A0 III	−18[a]	10 800	3.95	0.0	(3)	0.8	(10)

[a] Hoffleit & Warren (1991) cite HR 7775 as SB1O although this is a confusion with β Cap (HR 7776).

Notes: Spectral types and radial velocity data are from Hoffleit & Warren (1991). Values of T_{eff} and log g are from Smith & Dworetsky (1993), or (12) in the case of 112 Her. Values of V and V?, respectively, indicate known or suspected radial velocity variables; SB indicates a spectroscopic binary (SB1 and SB2, respectively, denote single- and double-lined systems); O indicates a published orbit (see Batten, Fletcher & MacCarthy 1989). Microturbulence parameters ξ appended by a colon (:) are approximate and were derived solely from ultraviolet Fe II lines by Smith & Dworetsky (1993).

References: (1) Adelman & Fuhr (1985); (2) Adelman (1988a); (3) Smith (1992); (4) Gigas (1986); (5) Dworetsky, Jomaron & Smith (1998); (6) Adelman (1989); (7) Harman (1997); (8) Adelman (1988b); (9) Cowley (1980); (10) Bohlender, Dworetsky & Jomaron (1998); (11) Wahlgren, Adelman & Robinson (1994); (12) Ryabchikova, Zakhorova & Adelman (1996).

Explorer (*IUE*) on the ultraviolet resonance lines of iron-peak elements in 26 HgMn, four superficially normal and 10 normal stars. We observed definite detections or determined upper limits for Ne I in 21 of the HgMn stars in the Smith & Dworetsky (1993) sample, and in 11 of the normal and superficially normal group. Some of the other stars in the two samples were lacking data in the red region, or were cooler than 10 000 K, and we did not expect to observe any Ne I lines. Physical parameters of the stars in this study are given in Table 1.

All observations were obtained with the Hamilton Echelle Spectrograph (HES; Vogt 1987) at the Lick Observatory, fed by the 0.6-m Coudé Auxilliary Telescope (CAT), during four runs in 1994–1997. Further details of the instrument can be found in Misch (1997). Shortly before our observations in 1994, some of the HES optical components were replaced, improving the resolution and instrumental profile, and making it possible to use the full field of the 2048 × 2048 CCDs to maximum advantage. We used both the unthinned phosphor-coated Orbit CCD (Dewar 13) and, from July 1995, the thinned Ford CCD (Dewar 6), depending on availability as the latter was shared with the multi-object spectrograph on the 3-m telescope. The spectral range for the observations was 3800–9000 Å. The typical signal-to-noise ratio (S/N) per pixel in the centres of orders ranged from 75 to 250. The Orbit CCD is cosmetically very clean, with very few bad pixels or columns, whereas the thinned Ford CCD contains several column defects but offers a much higher detector quantum efficiency in the blue. We used the Ford CCD whenever it was available. With the slit settings used, the combination of spectrographs and CCDs gave resolutions $R \approx 46\,500$. Flat fields were made using the polar axis quartz lamp and wavelength calibrations were obtained with a Th–Ar comparison.

The echelle spectra were extracted and calibrated using standard IRAF extraction packages (Valdes 1990; 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; we have therefore made no corrections for it. Allen's method is based on a direct comparison of the solar spectrum (as reflected from the roof of the CAT coelostat) observed using the HES with the Kitt Peak Solar Flux Atlas (Kurucz et al. 1984). As the latter was obtained using a Fourier transform spectrometer, it has no measurable parasitic light. The Kitt Peak spectrum is convolved with a suitable instrumental profile to match the HES data; both spectra must be normalized at the same points for a valid comparison. The ratio of summed equivalent widths of various features with good adjacent continuum points, in many different spectral orders, provides the measure of the amount of parasitic light.

3 ABUNDANCE DETERMINATION

3.1 Stellar parameters and stellar atmospheres

Effective temperatures and surface gravities of programme stars are summarized in Table 1. In general, the parameters adopted follow our previous work (Smith & Dworetsky 1993; Dworetsky, Jomaron & Smith 1998; Jomaron, Dworetsky & Allen 1999). Seven stars are noted as double-lined spectroscopic binaries in Table 2; one of these (HR 1800) is better described as a close visual binary in which we can see evidence of the secondary spectrum as rotationally-broadened features. The parameters and light ratios quoted in all seven cases are those adopted for the primary star. Suitable light ratios for other wavelength regions were found by the use of Kurucz (1993) model atmosphere fluxes. The light ratio estimated in this way for λ6402 is given in Table 3, where it is representative of the values throughout the range $\lambda\lambda$5800–6700. The adopted light ratio for the visual binary HR 1800 ($\rho = 0.243$ arcsec) is 2.45, based on $\Delta H_p = 0.96$ mag from The Hipparcos Catalogue (ESA 1997). Another star, 33 Gem, is suspected of being double lined but there is not yet any information on the orbit or light ratio (Hubrig & Launhardt 1993); we treat it as a single star or 'average component.' We note that Adelman, Philip & Adelman (1996) also treated 33 Gem as a single star, noting that the question of binarity could not be conclusively resolved with their data.

3.2 Atomic data for the LTE approximation

As all the Ne lines in the stars observed are either weak or, except for the hottest stars such as τ Her, not strongly saturated, the main atomic parameter of critical importance for LTE calculations is the oscillator strength, given as $\log gf$ in Table 2. We take our oscillator strengths from the calculations of Seaton (1998), who showed that his calculations were in excellent agreement (within 10 per cent) with other recent theoretical and laboratory data such as that of Hartmetz & Schmoranzer (1984) for the 3s–3p transitions of interest in this work, and also in excellent agreement with the critically evaluated *gf* values as given by Auer & Mihalas (1973).

For the radiative damping, we assumed the classical damping constant $\Gamma_R = 2.223 \times 10^7/\lambda^2\,\mathrm{s}^{-1}$ (λ in μm). This is a good approximation (within a factor of 2) for these lines as the typical lifetime of the upper levels is about 20 ns, and the abundances are not sensitive to the adopted values in any event. Van der Waals contributions to line broadening are also expected to be very small; a suitable approximation by Warner (1967) was used. For Stark broadening we adopted the recent experimental results of del Val, Aparicio & Mar (1999), and used an estimate of the temperature scaling factor proportional to $T^{0.4}$ to convert their w_m at 18 000 K to values for 12 000 K by multiplying by an average factor of 0.85 (Griem 1974). One line, λ5852, was not included in their list and we adopted the simple approximation given in CD23 data (Kurucz 1990). In general, the measured values that we used are about 3 times the values in CD23 for lines in common. We carried out worst-case sensitivity tests by varying the Val et al. Stark broadening by a factor of 2 for the strongest lines in τ Her; the largest effect on derived abundances was less than 0.01 dex.

3.3 Equivalent widths and LTE results

Estimated abundances for several identified Ne I lines were determined using the exact curve-of-growth technique in the LTE approximation. We measured the equivalent widths, W_λ, of Ne absorption lines in the programme spectra by numerical integration in the DIPSO V3.5 package (Howarth et al. 1998) and compared them with the calculated values for each line, which were generated by our spectrum-synthesis code UCLSYN (Smith & Dworetsky 1988; Smith 1992). The necessary atmospheric parameters given in Table 1 – T_{eff}, $\log g$ and microturbulence (ξ) – were taken from Smith & Dworetsky (1993), except for

Table 2. Ne I equivalent widths (mÅ) and LTE abundances for normal and HgMn programme stars on the scale $\log N(\mathrm{H}) = 12$.

	λ5852.49		λ6096.16		λ6266.50		λ6382.99		λ6402.25		λ6598.95		λ6717.04	
Star	W_λ	$\log A$	W_λ	$\log A$	W_λ	$\log A$	W_λ	$\log A$	W_λ	$\log A$	W_λ	$\log A$	W_λ	$\log A$
							Normal and superficially normal stars							
π Cet	8	8.13	10	8.06	15	8.43	18	8.44	39	8.54	–	–	11	8.37
134 Tau	–	–	–	–	–	–	–	–	≤15	≤8.78	–	–	–	–
τ Her	22	8.52	20	8.25	–	–	26	8.41	59	8.67	–	–	30	8.76
ζ Dra	13:	8.49:	20:	8.59:	–	–	24:	8.73:	30	8.32	–	–	–	–
α Lyr	–	–	–	–	–	–	–	–	<10	<9.18	–	–	–	
HR 7098	–	–	–	–	–	–	–	–	1.8:	7.55:	–	–	–	–
21 Aql	10	8.21	12	8.12	9	8.07	12	8.12	35	8.38	–	–	13	8.43
HR 7338[a]	–	–	–	–	–	–	–	–	4.0	8.05	–	–	–	–
ν Cap	–	–	–	–	–	–	–	–	≤10	≤8.69	–	–	–	–
HR 7878	8	8.18	14	8.33	8	8.10	16	8.42	30	8.34	4	7.90	10	8.38
21 Peg	5	8.65	4	8.37	≤4	≤8.52	≤2	≤8.03	9	8.36	≤2	≤8.40	≤2	≤8.35
							HgMn stars							
87 Psc	–	–	–	–	–	–	–	–	≤8	≤7.41	–	–	–	–
53 Tau	–	–	–	–	–	–	–	–	≤5	≤7.63	–	–	–	–
μ Lep	–	–	–	–	–	–	–	–	≤10	≤7.60	–	–	–	–
HR 1800[a]	–	–	–	–	–	–	–	–	≤7	≤8.02	–	–	–	–
33 Gem	19	8.47	27	8.52	12	8.08	14	8.04	38	8.22	15	8.34	17	8.41
HR 2676	–	–	–	–	–	–	–	–	25	7.83	–	–	–	–
HR 2844	–	–	–	–	–	–	–	–	≤16	≤7.71	–	–	–	–
ν Cnc	–	–	–	–	–	–	–	–	≤5	≤8.05	–	–	–	–
κ Cnc[a]	21	8.69	22	8.53	22	8.65	21	8.49	38	8.44	12	8.38	20	8.71
HR 4072[a]	–	–	–	–	–	–	–	–	4.1	8.04	–	–	–	–
χ Lup[a]	–	–	–	–	–	–	–	–	4.1	7.95	–	–	–	–
ι CrB[a]	–	–	–	–	–	–	–	–	3.7	7.76	–	–	–	–
υ Her	–	–	–	–	–	–	–	–	≤1.0	≤6.63	–	–	–	–
ϕ Her	–	–	–	–	–	–	–	–	2.0	7.17	–	–	–	–
HR 6997	15	8.30	19	8.24	20:	8.38:	20	8.25	37	8.15	–	–	–	–
112 Her[a]	2.4	7.64	–	–	1.8	7.43	–	–	7.1	7.42	≤1.2	≤7.43	≤3.6	≤7.91
HR 7143	–	–	≤1:	≤7.3:	≤1:	≤7.4:	≤2:	≤7.6:	≤3.0	≤7.21	≤1:	≤7.6:	–	–
HR 7361	18	8.47	23	8.44	18	8.38	20	8.33	40	8.35	13	8.30	–	–
46 Aql	≤2	≤7.4	2:	7.2:	3:	7.4:	3:	7.4:	9	7.41	2:	7.5:	≤2	≤7.4
HR 7664	8	8.07	13	8.16	11	8.17	12	8.10	29	8.16	8	8.13	10	8.24
HR 7775	≤3	≤8.42	≤2	≤8.05	≤2	≤8.22	6	8.72	–	–	≤1	≤8.16	≤4	≤8.79
$\overline{\log(A/A_{\star})}$		−0.02		−0.05		−0.05		−0.04		−0.02		−0.13		+0.10
$\log gf$		−0.49		−0.31		−0.37		−0.24		+0.33		−0.35		−0.35

[a] Binaries with two spectra. The W_λ values are corrected for dilution effects as described in the text. Colons (:) indicate uncertain values.

Table 3. Binary stars: adopted stellar data and light ratios.

Star	λ (Å)	L_A/L_B	$T_{effA}/\log g_A$ (K)/(cgs)	$T_{effB}/\log g_B$ (K)/(cgs)	L_A/L_B 6402 Å	Ref.
HR 7338	4481	3.16	10 250/3.8	8500/4.0	2.72	(1)
HR 1800	H_p	2.45	11 050/3.8	9500/4.0	2.34	(2)
κ Cnc	5480	11.5	13 200/3.7	8500/4.0	10.70	(3)
HR 4072	4520	5.45	10 650/3.8	8800/4.2	5.01	(4)
χ Lup	4520	3.65	10 650/3.9	9200/4.2	3.35	(4)
ι CrB	4520	2.70	11 000/4.0	9000/4.3	2.46	(4)
112 Her	4520	6.20	13 100/4.1	8500/4.2	5.20	(5)

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 Hβ. References: (1) Petrie (1950); (2) ESA (1997); (3) Ryabchikova et al. (1998); (4) Harman (1997) and Jomaron, Dworetsky & Allen (1999); (5) Ryabchikova et al. (1996).

112 Her where we used the values given by Ryabchikova, Zakhorova & Adelman (1996). In the cases of the seven binaries with double spectra, we adopted the light ratios cited in Section 3.1 in order to correct for dilution effects. The equivalent widths (corrected for binarity where necessary) and LTE abundances for several lines are given in Table 2. We used the 2 km s^{-1} grid of the Kurucz (1993) models and interpolated to produce a model at the chosen T_{eff} and $\log g$ of each star.

We searched a list of Ne I lines from Wiese, Smith & Glennon (1966) in the range $\lambda\lambda$5800–6800 and narrowed the list to include only the lines that were fairly strong, without evident blending problems and not situated at the ends of echelle orders where the spectra are noisiest. In a few cases the quality of the spectra justify quoting equivalent widths to the nearest 0.1 mÅ. For each star a mean LTE abundance, weighted by equivalent width, was calculated on the scale $\log N(\mathrm{H}) = 12.00$. To investigate the consistency of the results from the selected lines, the deviations of each line from the mean of all the lines, $\log(A/A_{\star})$, were calculated for each star where a meaningful average could be computed. These are summarized in Table 2 where the values of $\overline{\log(A/A_{\star})}$ represent the mean deviations from the overall LTE abundance for each line. The small mean deviations imply that the results for each line are broadly consistent with one another and the relative *gf* values of Seaton (1998). However, one line (λ6402) is considerably stronger than all the others, and is well suited for abundance determinations in the largest number of stars, especially for the stars at the low-T_{eff} end of the sequence and with abundances apparently below the standard value. In the remainder of this paper, we shall consider only this line, although future investigators may wish to consider some of the other lines further.

3.4 A weak blending line?

Although we have chosen our list of Ne lines to be as blend-free as possible, there is a predicted weak blending feature in the CD23 list (Kurucz 1990) adjacent to the important line Ne I λ6402.246: Fe II at λ6402.397. In programme stars (Table 1) with approximately standard or lower Fe abundances, this line would have a typical strength of about 0.5 mÅ, too small to affect our results in any significant way. However, in the few stars with enhanced Fe abundances such as 112 Her (Smith & Dworetsky 1993, $\log A(\mathrm{Fe}) = 8.40$), the strongest iron-rich case, the possible blending effect would have raised the apparent abundance of Ne by 0.3 dex. It should be noted that for sharp-lined stars, the displacement of the blend is enough to make its existence apparent. The existence of this line with the *gf* value listed remains to be confirmed; future work directed at refining the neon analysis should address the question of its actual strength with better observations.

4 NLTE CALCULATIONS AND ABUNDANCES

4.1 Calculations and the Ne I model atom

The first full NLTE calculations of neon line strengths for Ne I were made by Auer & Mihalas (1973) using NLTE model atmospheres. Unfortunately for our purposes, their analysis was restricted to the hotter stars with $T_{\mathrm{eff}} > 15\,000$ K. Recently, their calculations were revisited and extended to cooler temperatures by Sigut (1999). Sigut used the T–τ relations, particle densities and electron number densities from Kurucz LTE line-blanketed models and solved the restricted NLTE problem, i.e. only the equations of radiative transfer and statistical equilibrium for Ne. His grid of equivalent widths also has rather large steps for our purposes: 2000 K, 0.5 dex and 0.5 dex in temperature, gravity and Ne abundance, respectively.

In this section we examine in detail the temperature, gravity and Ne-abundance region where all our HgMn stars are found, solve the full NLTE problem using NLTE model atmospheres, and find a convenient way to represent the NLTE effects in the Ne I λ6402 line so that straightforward interpolation via LTE models can be performed. For the calculation of NLTE atmosphere models and level populations we used the TLUSTY195 code described in more detail in Hubeny (1988), and in Hubeny & Lanz (1992, 1995). Here H I and Ne I were treated as explicit ions, which means that their level populations were calculated in NLTE and their opacity was considered. Other elements like He, C, N and O were allowed to contribute to the particle and electron number density in LTE. Synthetic spectra and equivalent widths were then calculated with the SYNSPEC42 code (Hubeny, Lanz & Jeffery 1995). In the following, if not stated otherwise, ‘in LTE’ means ‘in LTE considering the NLTE model of the atmosphere’.

It is not possible to list here all of the input parameters entering the NLTE calculations and above mentioned codes. We will only mention the parameters that are most crucial for this particular problem or are different from those that could be generated interactively, e.g. by the very useful interface tool MODION (Varosi et al. 1995), part of the TLUSTY package for creating the model of the atom from the TOPbase data. We provide a copy of our input model for TLUSTY, which can be downloaded by anyone who wishes to repeat the calculations (Dworetsky & Budaj 2000).

Table 4. Ne I energy levels considered. Column 1: the Paschen level designation. Column 2: the *nlpqr* notation of Seaton (1998). Column 3: the ionization energy in cm^{-1}. Column 4: statistical weight of the level.

Paschen	Seaton	Energy	g
2p6 1S	2p	174 192.4	1.
1s5	3s332	40 148.6	5.
1s4	3s331	39 731.2	3.
1s3	3s110	39 371.8	1.
1s2	3s111	38 301.7	3.
2p10	3p311	25 932.7	3.
2p9	3p353	24 533.4	7.
2p8	3p352	24 366.2	5.
2p7	3p331	24 068.8	3.
2p6	3p332	23 874.6	5.
2p5	3p131	23 418.3	3.
2p4	3p132	23 331.9	5.
2p3	3p310	23 273.0	1.
2p2	3p111	23 152.0	3.
2p1	3p110	21 219.7	1.
2s5	4s332	15 589.3	5.
2s4	4s331	15 394.4	3.
2s3	4s110	14 810.5	1.
2s2	4s111	14 655.8	3.
3d6	3d310	12 680.8	1.
3d5	3d311	12 666.3	3.
3d4′	3d374	12 600.1	9.
3d4	3d373	12 598.3	7.
3d3	3d332	12 583.2	5.
3d2	3d331	12 553.8	3.
3d1″	3d352	12 490.8	5.
3d1′	3d353	12 489.0	7.
3s1″ ″	3d152	11 781.8	5.
3s1″ ′	3d153	11 780.3	7.
3s1″	3d132	11 770.5	5.
3s1′	3d131	11 754.8	3.

The spectrum of Ne I is that of an inert gas where the *LS* coupling breaks down and terms and multiplets do not provide an appropriate description of the atom, so that at least the lower terms and multiplets must be split into individual levels and transitions. We considered explicitly the first 31 levels of Ne I as Auer & Mihalas (1973), plus continuum, with each of the levels treated separately (Table 4). Paschen designations and experimental energies for the levels were taken from Moore (1949). Photoionization cross-sections for the terms were taken from the TOPbase data base (Cunto et al. 1993), as calculated by Hibbert & Scott (1994). We fit individual photoionization cross-sections to about 10–15 points using the MODION code. It was assumed that the photoionization cross-section was the same for the term as it was for the level but it was scaled to the particular level threshold. We used the calculated oscillator strengths of Seaton (1998) as before. For collisional excitation rates we used the van Regemorter formula as in Auer & Mihalas (1973). For collisional ionization we used equation (5.79) of Mihalas (1978) with $\bar{g}_i = 0.1$. With this input data we calculated the Ne I λ6402 equivalent width for the same abundance (10^{-4}), the f value (0.431), the microturbulence ξ ($4\,\mathrm{km\,s^{-1}}$) and the similar H–He NLTE models ($T_{\mathrm{eff}} = 15\,000$, $20\,000$ and $\log g = 4$) as Auer & Mihalas to check and compare our calculations. (For the hotter model, two terms of Ne II plus continuum were also considered

Table 5. Equivalent widths of Ne I λ6402 (mÅ) for two models, comparing this work (D+B) with Auer & Mihalas (1973).

	LTE	NLTE	LTE	NLTE
D+B	30	46	39	74
A+M	28	45	40	79

Table 6. Equivalent widths of Ne I λ6402 (mÅ) for two Kurucz models with $T_{\rm eff} = 12\,000$ and 17 000 K, $\log g = 4$, $\xi = 5\,{\rm km\,s^{-1}}$, comparing this work (D+B) with Sigut (1999).

$T_{\rm eff}$	12 000 K		17 000 K	
	NLTE	NLTE/LTE	NLTE	NLTE/LTE
D+B	19	1.31	89	1.81
Sigut	18	–	86	1.80

explicitly.) The results are listed in Table 5 and are in very close agreement. To compare our results with the results of Sigut (1999), and to check the calculations for lower temperatures, we solved the similar *restricted* NLTE problem using Kurucz (1993) CD13 LTE line-blanketed models (computed with $\xi = 2\,{\rm km\,s^{-1}}$) with our Ne I atom model plus Hubeny's H I atom model (nine explicit levels plus continuum) and the same Ne abundance (1.12×10^{-4}), f value (0.428) and ξ ($5\,{\rm km\,s^{-1}}$) as Sigut. The results are compared in Table 6 and are also in very good agreement.

We found that although microturbulence can affect the equivalent widths resulting from desaturation effects, for the observed stars ($0 \le \xi \le 2.5$) it has negligible effect on the atmosphere model, Ne I level populations and LTE/NLTE equivalent-width ratio, $R = W_{\lambda({\rm LTE})}/W_{\lambda({\rm NLTE})}$. For this reason, our task can be considerably simplified as one can calculate a grid of models and LTE/NLTE ratios for only one $\xi = 0$. Also, the NLTE effect of varying the Ne abundance is quite small. While decreasing the Ne abundance from the standard value (8.08) by 1.0 dex reduces the equivalent width considerably, it raises the corresponding LTE/NLTE ratio R by only 0.03 ± 0.01. Consequently, the main results can be gathered into Table 7 listing $R(T_{\rm eff}, \log g)$ for standard Ne abundance and zero microturbulence. The ratio R ranges from around 0.6–0.7, at the high-$T_{\rm eff}$ end of the HgMn domain, to nearly 1.0 at the cool end of the sequence (where the lines of neon disappear and can no longer be studied). Dworetsky & Budaj (2000) provide a short FORTRAN77 code to interpolate in the grid (including the small effects of abundance) for anyone who wishes to undertake their own interpolations for R.

Hubeny (1981) pointed out that apart from hydrogen, C I and Si I are the other most important ions to be included explicitly in the NLTE calculations in early A stars. We have checked that for this particular problem, including these elements along with He may again slightly affect the equivalent width, but that it does not affect R significantly. The line strength results were somewhat sensitive to the collisional excitation. A more detailed analysis of the current precision of neon NLTE calculations can be found in Sigut (1999).

4.2 Neon abundances from non-LTE calculations

One may obtain a 'corrected' LTE equivalent width from

Table 7. LTE/NLTE equivalent-width ratio R (Ne I λ6402).

$T_{\rm eff}$	$\log g = 3.50$	3.75	4.00	4.25
11 000	0.78	0.81	0.84	0.87
12 000	0.72	0.75	0.79	0.82
13 000	0.67	0.70	0.74	0.77
14 000	0.63	0.66	0.69	0.73
15 000	0.59	0.62	0.65	0.69

Table 8. Non-LTE abundances from Ne I λ6402 for normal and HgMn programme stars on the scale $\log A({\rm H}) = 12.00$. Programme stars with high abundance upper limits or highly uncertain measurements have been omitted.

Star	$T_{\rm eff}$	$\log g$	W_λ	$W_{\rm LTE}/W_{\rm NLTE}$	$\log A$
		Normal and superficially normal stars			
π Cet	13 250	3.80	39	0.69	8.18
τ Her	15 000	3.95	59	0.64	8.15
ζ Dra	12 900	3.90	30	0.73	8.07
21 Aql	13 000	3.50	35	0.67	8.01
HR 7338	10 250	3.75	4.0	0.86	8.04
HR 7878	13 050	3.85	30	0.71	8.04
21 Peg	10 450	3.50	9	0.82	8.22
		HgMn stars			
87 Psc	13 150	4.00	≤8	0.76	≤7.27
53 Tau	12 000	4.25	≤5	0.83	≤7.53
μ Lep	12 800	3.85	≤10	0.75	≤7.43
HR 1800	11 050	3.80	≤7	0.83	≤7.90
33 Gem	14 400	3.85	38	0.67	7.87
HR 2676	14 050	3.60	25	0.66	7.54
HR 2844	13 460	3.80	≤16	0.72	≤7.50
ν Cnc	10 400	3.60	≤5	0.84	≤7.94
κ Cnc	13 500	3.80	38	0.69	8.08
HR 4072	10 500	3.95	4.1	0.87	7.96
χ Lup	10 750	4.00	4.1	0.87	7.87
ι CrB	11 000	4.00	3.7	0.85	7.67
υ Her	12 000	3.80	≤1.0	0.80	≤6.53
φ Her	11 650	4.00	2.0	0.83	7.08
HR 6997	14 500	3.90	37	0.67	7.82
112 Her	13 100	4.10	7.1	0.77	7.28
HR 7143	12 100	4.00	≤3	0.81	≤7.10
HR 7361	13 650	3.55	40	0.65	7.94
46 Aql	13 000	3.65	9	0.72	7.23
HR 7664	13 200	3.60	29	0.68	7.85

RW_λ(obs) and analyse the corrected width by using a standard LTE approach including the appropriate microturbulence in a fully line-blanketed case. We used UCLSYN to calculate the abundance of Ne from equivalent widths given in Table 2 after scaling by R from Table 7. The microturbulence parameters ξ were taken from Table 1. The results are shown in Table 8 and plotted as a function of $T_{\rm eff}$ in Fig. 1.

Our results yield, for normal and superficially-normal stars, a mean abundance $\log A({\rm Ne}) = 8.10 \pm 0.03$ relative to 12.00 for H. This is in excellent agreement with the standard abundance of 8.08 for Ne given by Grevesse et al. (1996), which is essentially identical to the value of 8.09 given in the earlier compilation of Anders & Grevesse (1989). The standard abundance is partly based on local Galactic values (stars and nebulae), and on the application of a well-determined correction to the solar wind and solar energetic particle values, as well as the spectroscopy of solar prominences. We take this agreement as confirmation that our ratio method for LTE/NLTE equivalent-width scaling works well in the $T_{\rm eff}$ range of HgMn stars.

The HgMn stars are, with only one exception (κ Cnc), deficient

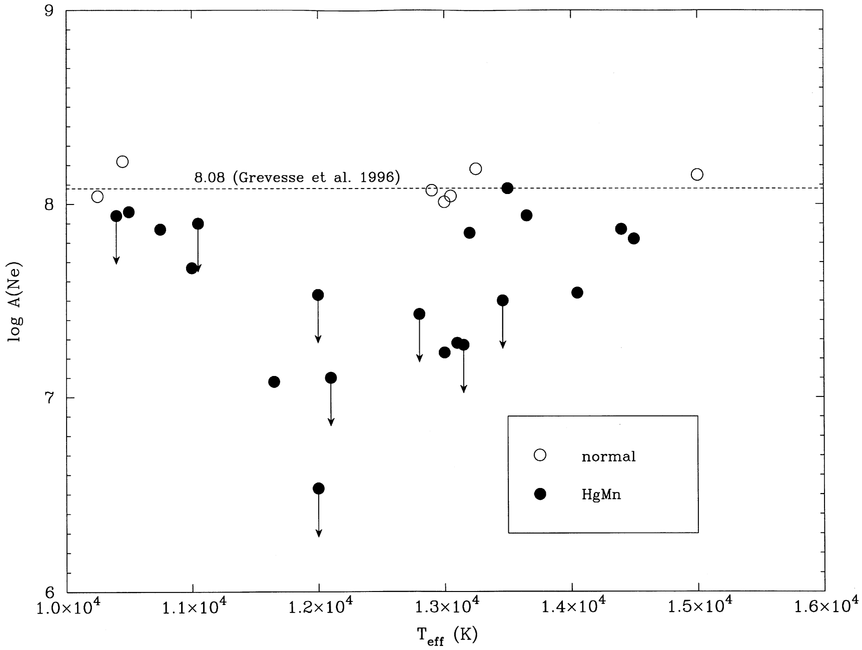

Figure 1. Abundances of Ne in normal stars (open circles) and HgMn stars (filled circles). Upper limits for the abundances are indicated by arrows. The standard abundance for Ne on the scale $\log A(\mathrm{H}) = 12.00$ is from Grevesse et al. (1996).

in Ne, although the deficits in a few cases are only marginal (0.1–0.2 dex). In many cases we are only able to establish upper limits for Ne abundances. The most extreme case is υ Her, for which we have particularly good spectra and were able to establish an upper limit 1.5 dex below the solar abundance. There is no case in our sample where Ne has an abundance greater than the standard value. The results of Adelman & Pintado (2000) can also be analysed using our method.

5 DISCUSSION

The error found for the average abundance for the normal stars is based on the scatter in the results. For comparison, following procedures adopted in previous papers in this series on HgMn stars (e.g. Smith & Dworetsky 1993; Jomaron et al. 1999) we propagate uncertainties in adopted estimates of the errors on each parameter as follows: ± 0.25 dex in $\log g$, ± 250 K in T_{eff}, $\pm 0.5\,\mathrm{km\,s^{-1}}$ in the microturbulence (ξ) and ± 5 per cent in W_λ. Propagating these errors through the 'corrected' LTE analysis used above for the Ne I $\lambda 6402$ line, using a model atmosphere at $T_{\mathrm{eff}} = 13\,000$ K with $\log g = 4.0$ and $\xi = 1$, leads to the following representative errors in the derived Ne abundances: ± 0.10 dex ($\log g$), ± 0.08 dex (T_{eff}), ± 0.01 dex (ξ) and ± 0.04 dex (W_λ) at standard abundance ($W_\lambda = 27$ mÅ); ± 0.10 dex ($\log g$), ± 0.07 dex (T_{eff}), ± 0.01 dex (ξ), ± 0.03 dex (W_λ) with neon underabundant by 0.5 dex ($W_\lambda = 13$ mÅ). These are very similar ranges; the combined expected error for one measurement is ± 0.13 dex. The standard deviation (s.d.) for the normal stars is ± 0.08 dex. This difference may reflect overestimates in some of the above factors (especially $\Delta \log g$) that comprise the estimated errors, but the two estimates are not in serious disagreement.

We have implicitly conducted all our analyses under the assumption of a homogeneous depth distribution of neon in the photospheres of the HgMn stars. It now seems well founded to conclude that in many HgMn stars the neon atoms may not be distributed with a constant fraction versus optical depth, because of gravitational settling, but our results offer no method of distinguishing clearly between a uniform depletion in the line-forming region and an inhomogeneous distribution in which the total number of absorbers is about the same. Given the scatter in abundance from star to star, linestrengths alone will be inadequate to prove the point one way or the other.

One should consider the question of whether or not we may lump together the normal and superficially normal stars. The 'superficially normal' stars listed in Tables 1, 2 and 8 were originally described as such by Cowley (1980), owing to their relatively sharp lines, but subsequent investigations by Smith & Dworetsky (1990, 1993) and Smith (1993, 1994, 1996, 1997) have shown that HR 7338, HR 7878 and 21 Peg have abundances that are not distinguishable from the abundances of normal stars for C, N, Cr–Ni, Mg, Al, Si, Cu, Zn, Ga and Hg. Cowley thought that HR 7878 and HR 7338 were normal stars with no trace of peculiarity, although he suspected that 21 Peg might be related to early Am stars because of a weaker than expected Sc II line, and Sadakane (1980) found that both 21 Peg and HR 7338 may have 'hot Am' characteristics, such as mild Ba and Y enhancements. One of these, 21 Peg, is listed in the Hg peculiar class by Renson et al. (1991) without a reference cited, but Smith's (1997) study of Hg II lines showed that the Hg abundance is effectively indistinguishable from that found in normal stars. Landstreet (1998) also describes it as a normal star. In what follows we assume that 21 Peg is a normal B9.5 V star and that HR 7338 is also normal. In this work we therefore feel justified in including these three stars with the normal stars in Table 8 and Fig. 1.

The equivalent-width measures of Adelman & Pintado (2000) for 3 Cen A, κ Cnc and HR 7245 can be used with the results of Section 4 to derive approximate NLTE abundances for neon. For the first two of these stars, those authors give only the equivalent width of $\lambda 5852.49$ (although their table headings say 5842.49, which is evidently a misprint). We assume, based on the discussion of Section 3.3, that the correction factor R may be taken to be about the same as for $\lambda 6402$, and we further assume that we can extrapolate the correction factor to $T_{\rm eff} = 17\,500$ K for 3 Cen A, for which we assume $R = 0.59$. This well-known peculiar He-weak star has some characteristics similar to HgMn stars. We find a near-standard Ne abundance of 8.17, while κ Cnc has a slight overabundance (8.32) and the HgMn star HR 7245, which has a measured equivalent width of 8 mÅ, has a low abundance (7.32) similar to that of 112 Her. Given that our assumptions above could be subject to some uncertainty, at this stage we would not wish to conclude much more than that the abundance of neon seems consistent with the standard value in 3 Cen A and κ Cnc, but in the case of HR 7245 we are probably on firm ground in assigning a very low abundance of neon.

We explored briefly the question of whether the Ne abundances in HgMn stars depend on atmospheric parameters. It seems that the largest anomalies (underabundances) are generally observed in the middle of the temperature range of HgMn stars ($11\,500 < T_{\rm eff} < 13\,000$ K; see Fig. 1). No apparent correlation with the surface gravity can be seen in Table 8. It is not possible to draw any conclusions about the dependencies on rotational velocity as we have chosen to work with a selected sample of HgMn stars with fairly small $v \sin i$ in order to ensure accurate abundance determinations.

6 CONCLUSIONS

We have measured the equivalent widths (or upper limits) of several Ne I lines in the spectra of 11 normal late-B stars and 21 HgMn stars in the same $T_{\rm eff}$ range. These lines were selected after a search for lines that were well placed in echelle orders in the HES and that appeared not to have any significant blending features in the sample of stars studied. When analysed using LTE methods in fully line-blanketed atmospheres, there is a steady increase with $T_{\rm eff}$ in the apparent abundance above the standard value of $\log A(\mathrm{Ne}) = 8.08$. It is apparent from previous studies that this is a result of NLTE effects. We note that the strongest line of Ne in the red region, $\lambda 6402$, and the six other lines studied, generally give concordant LTE abundances, suggesting that they are affected by NLTE effects by roughly the same amount. These lines may be of use in future investigations, provided further observations and NLTE calculations are made.

We undertook a detailed NLTE analysis of $\lambda 6402$ by use of a full analysis including NLTE for H I and Ne I. We confirm earlier studies by obtaining very similar results when similar inputs are used, and find that the ratio of the NLTE and LTE equivalent widths calculated for a given NLTE model atmosphere is a slowly varying function of $T_{\rm eff}$ and surface gravity. This ratio only slightly depends on the actual abundance of Ne, and is also very insensitive to the microturbulence, so it becomes possible to interpolate, in a table of the ratio R, the ‘correction factor’ by which an observed equivalent width must be scaled in order to produce the NLTE abundance from a much easier LTE analysis.

The normal stars in our sample yield a mean logarithmic Ne abundance of 8.10, well within our formal mean error of ± 0.03 of the standard value, 8.08, given by Grevesse et al. (1996). This gives us additional confidence that our models, and the ratio method of using LTE calculations as an interpolation device, work satisfactorily for late-B stars. The smallness of the scatter (s.d. $\pm$ 0.08) for the individual stars suggests that the error budget in Section 5 is rather conservative.

It is clear from our results for the HgMn stars that the abundances of Ne range from standard abundance, or slightly below, to extreme deficiencies of an order of magnitude or more. In several cases we have only obtained upper limits, and additional observations of very high quality would be needed in order to attempt to detect the weak Ne lines in these stars. There is a tendency for the Ne abundance to be smallest in the middle of the HgMn effective temperature range, but there is no dependence on surface gravity. There is not a single confirmed case in which Ne has an enhanced abundance, which is strong evidence for the absence in HgMn stars of non-turbulent stellar winds (i.e. the hydrogen-mass-loss rate must be $<10^{-14}\,\mathrm{M_\odot\,yr^{-1}}$) that might compete with radiative atomic diffusion and produce accumulations of light elements in the photosphere, as suggested by Landstreet et al. (1998). That such winds might exist was studied by Babel & Michaud (1991), Babel (1992) and Krtička & Kubát (2000).

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