

Elemental abundances in normal late-B and HgMn stars from co-added IUE spectra^{*}

I. Iron-peak elements

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Abstract. The abundances of five iron-peak elements (chromium through nickel) in a sample of forty normal, superficially normal, and HgMn-type late-B stars are derived by spectrum-synthesis analysis of co-added high-resolution *International Ultraviolet Explorer* (IUE) spectra. Approximately solar abundances of these elements are obtained for the normal stars, with the notable exception of α Lyr which is shown to be mildly metal-deficient in accordance with published analyses of its visual-region spectrum. The superficially normal stars are generally indistinguishable from the normal stars in terms of their iron-peak elemental abundances. The HgMn stars exhibit a large diversity in chromium and iron abundances, a striking effective-temperature-dependent manganese enhancement, and substantially sub-solar abundances of cobalt and nickel. Even for Mn, Co, and Ni there are some HgMn stars which depart from the more general behaviour of the group as a whole, and thus these results tend to confirm the rather heterogeneous nature of this peculiarity class suspected in previous surveys of their visual-region spectra. By making schematic corrections for the effects on our analysis of atmospheric chemical stratification, we show that the predictions of radiative diffusion theory for manganese are in excellent accord with the observed upper envelope of abundances in the HgMn stars.

Key words: stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: early-type – ultraviolet: stars

1. Introduction

The HgMn stars are a sub-class of the B-type chemically peculiar stars characterised by, *inter alia*, a distinct pattern of abundance anomalies (in particular enhanced mercury and/or manganese), low rotational velocities, an absence of photometric or

spectroscopic variability, a near-normal incidence of spectroscopic binarity, and weak or non-existent magnetic fields (see, e.g., Preston 1974; Jaschek & Jaschek 1974; Sadakane 1984a; Dworetsky 1986; Takada-Hidai 1991; Dworetsky 1993). Interest in HgMn stars over the last two decades has been motivated primarily by a desire to test the radiative diffusion hypothesis first advanced as an explanation of chemically peculiar stars by Michaud (1970). Consensus of opinion and weight of evidence currently favour the diffusion hypothesis over rival explanations of peculiar stars such as accretion of supernova ejecta (Guthrie 1967) and selective magnetic accretion from the interstellar medium (Havnes & Conti 1971). Since Michaud's original paper, diffusion theory has been elaborated and refined to the extent that a parameter-free model for non-magnetic peculiar A and B stars has now been advanced (Michaud 1981, 1986). The HgMn stars are of special interest in this respect because their observed properties suggest that they probably exemplify the operation of diffusion processes in their purest form (Vauclair & Vauclair 1982).

However, despite a sizable body of observational work, it has yet to be conclusively demonstrated that diffusion processes are solely responsible for the anomalies seen in peculiar A and B stars. Principal among a number of outstanding problems is the question as to whether the parameter-free model can account for the *diversity* of chemical compositions seen in the atmospheres of HgMn stars (cf. Wolff 1983, pp. 146–147). Such stars with essentially identical effective temperatures, surface gravities, and apparent rotational velocities, but quite different abundance anomalies, are frequently cited in the literature. Heacox (1979) drew attention to ϕ Her and ν Her, which have very similar stellar parameters but differ radically in their Be, Sc, Y, and Zr abundances. This anomalous pattern of behaviour is seen even in the grossly overabundant elements which characterise the class—mercury and manganese. Well-known examples of such behaviour are 53 Tau, which exhibits strong Mn but no observable trace of Hg (Adelman 1987), and χ Lup, which exhibits strong Hg but no enhancement of Mn (Dworetsky 1971).

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^{*} Based on IUE observations procured from the World Data Centre archive at the UK Rutherford Appleton Laboratory

While specific examples of such anomalous behaviour in HgMn stars are readily cited, it is not clear whether they are characteristic of the class in general rather than indicative of a few conspicuously 'pathological' objects. In this respect, many previous investigations of these stars have foundered for lack of either satisfactory sample size, coverage of the periodic table, or both. The surveys of Heacox (1979) and Guthrie (1984) counter these criticisms to some extent in that both were directed at establishing a broad picture of the compositions of HgMn stars rather than a detailed view of any single star or element. However, both of these studies were based on visual-region photographic spectra and therefore constituted only a partial exploration of the HgMn phenomenon. The strong lines of many elements of interest (in particular the resonance lines) are located in the satellite ultraviolet (UV), inaccessible to ground-based observation. For some elements, visual-region studies have established abundance patterns only where gross enhancements are in evidence such as in the cases of, for example, gallium, manganese, and mercury—the behaviour of these elements in normal B-type stars is virtually unknown. For other elements which are cosmically rare or apparently underabundant in the HgMn stars, such as aluminium and cobalt, our knowledge is even less complete.

Numerous investigations of the UV spectra of HgMn stars have been carried out, notably by K. Sadakane and colleagues in Japan, and D.S. Leckrone of NASA's Goddard Space Flight Center. These two groups have taken a pragmatic approach in the analysis of the ultraviolet spectra of these stars by limiting their studies to a single element at a time. The Japanese group has generally investigated moderately large samples of stars, often making use of the technique of equivalent-width measurement (e.g., Sadakane et al. 1983; Sadakane et al. 1985; Takada-Hidai et al. 1986). Unfortunately, the line density in the UV spectra of late B-type stars is usually too high to admit the reliable measurement of equivalent widths—all observed features are effectively blends of varying degrees of complexity. Only synthetic reconstruction of a spectrum can satisfactorily disentangle the contribution of blending lines from a line of interest. This difficult problem has been addressed for a limited sample of stars by Leckrone (1981, 1984) who has examined a few elements in detail by spectrum synthesis of the features of interest. More recently, Leckrone and collaborators have acquired and analysed in detail *Goddard High Resolution Spectrograph* observations of the cool HgMn star χ Lup (Leckrone et al. 1991). Although these new data are offering extraordinary insights into the compositional anomalies of HgMn stars, they are, as yet, limited in both quantity and wavelength coverage.

Ultraviolet spectra afford a unique and important perspective on the nature and origins of HgMn stars. There is, therefore, a clear need for a detailed and wide-coverage abundance survey of these stars in this wavelength region. Such a survey should sample a sufficiently large number of stars and elements as to be representative of the HgMn class as a whole, and yet not be so extensive as to prejudice the use of the same detailed methods of analysis seen in the study of individual objects. With this motivation in mind, we have carried out such a study mak-

ing use of data accumulated over the last decade in the public-domain *International Ultraviolet Explorer* (IUE) archives. The specific objective of our survey is to establish as accurately as possible, and in an internally consistent manner, the chemical compositions of a significant sample of HgMn stars through spectrum-synthesis analysis of their UV spectral lines. Since a secure understanding of HgMn stars is only possible by direct comparison with spectroscopically normal late-B type stars, a sample of such objects is included in our programme.

In this first paper in a series on abundances in normal late-B and HgMn stars, attention is focussed on five iron-peak elements (Cr through Ni). Although some of these elements have been investigated in the 'photographic domain' (e.g., Heacox 1979; Guthrie 1984), IUE spectra offer the advantage of access to their strong UV lines (resonance lines in particular); these can be highly effective probes of atmospheric abundance even in cases of extreme abundance deficiency. The UV spectra of late-B stars are dominated by lines of the iron-peak elements, particularly those of the second spectra of iron and (for HgMn stars) manganese. Therefore, besides being of intrinsic interest, reliable abundances for these elements are an important prerequisite to studies of other more exotic species, which will be presented in subsequent papers of this series.

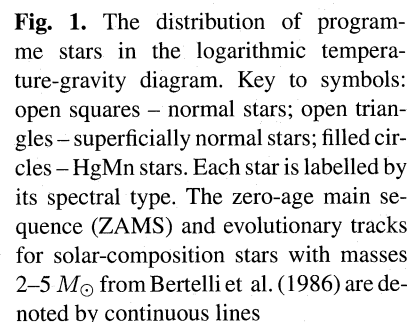
2. Programme stars

The programme stars fall into three spectroscopically defined groups: normal stars, superficially normal stars, and HgMn stars. They were selected primarily from analyses in the literature, subject to the constraint of the availability of high-resolution IUE spectra in the World Data Centre archive at the UK Rutherford Appleton Laboratory (RAL). Within this constraint, only stars with projected equatorial rotational velocities ($v \sin i$) less than $\sim 50 \text{ km s}^{-1}$ were admitted in order to alleviate blending difficulties in the crowded UV spectral region.

Most of the normal stars were selected from published analyses of visual-region spectra by Adelman (e.g., Adelman 1984; Adelman 1986). These were supplemented by a few sharp-lined normal stars identified in high-dispersion surveys of late-B and early-A stars in the Northern and Southern hemispheres by M.M. Dworetsky (cf. Dworetsky 1976; Dworetsky et al. 1980; Dworetsky et al. 1982).

The superficially normal stars were taken from the list of objects examined by Cowley (1980) based in turn on the results of Dworetsky's (1976) search for peculiar stars in the spectral range B8–A0 III. These are very sharp-lined stars which possess normal MK classifications, but nonetheless exhibit mild peculiarities when observed at the highest spectral resolution.

The HgMn stars were selected primarily from the published analyses of IUE spectra of Sadakane and colleagues (e.g., Sadakane et al. 1983). All of the HgMn stars in the programme appear in Schneider's (1981) catalogue of known or suspected HgMn stars except ν Cnc, HR 6000, and HR 7775. The cool star ν Cnc is apparently one of the mildest members of the HgMn class and may constitute a link with the slightly cooler hot Am stars (Adelman et al. 1984; Adelman 1989). The He-weak



served in the class as a whole (Aikman 1976; Gerbaldi et al. 1985; Schneider 1986). Among the normal and superficially normal stars, the binary frequency is only $\sim 15\%$ which is somewhat lower than that observed for normal main-sequence stars in general (Jaschek & Gómez 1970). This is clearly a selection effect since low- $v \sin i$ stars in binary systems are predominantly HgMn (or other peculiar) types (cf. Wolff & Preston 1978). The distribution of apparent rotational velocities is strongly biased towards low values for both normal and HgMn samples in accordance with the requirement that the programme stars be sufficiently sharp-lined to be amenable to analysis in the ultraviolet. While it would have been desirable to include some HgMn stars of higher $v \sin i$ in the sample in order to discriminate better abundance systematics with rotational velocity, the analysis of all but the strongest lines in the ultraviolet spectra of such objects is beyond the analytical tools currently available and is probably not warranted by the quality of observational material which exists.

Figure 1 reveals an unfortunate deficit of normal and superficially normal programme stars in the effective-temperature interval 11 000–13 000 K ($\log T_{\text{eff}} \approx 4.05\text{--}4.10$ dex K), although this could not have been predicted from the spectral types. A preliminary—although far from exhaustive—search of the literature did not reveal any suitably sharp-lined spectroscopically

The frequency of known spectroscopic binaries in the HgMn sample is approximately 50 % which is consistent with that ob-

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

Star	HD	Spectral type	V_r (km s ⁻¹)	N_{IUE}	T_{eff} (K)	$\log g$ (dex cm s ⁻²)	ξ (km s ⁻¹)	Ref.	$v \sin i$ (km s ⁻¹)	Ref.
<i>Normal stars</i>										
π Cet	17081	B7 V	+15 SB	8	13 250	3.80	0.0	[1]	25	[3]
134 Tau	38899	B9 IV	+18 V	9	10 850	4.10	1.6	[1]	30	[3]
θ Leo	97633	A2 V	+ 8 V	12	9 350	3.65	1.8	[2]	24	[3]
τ Her	147394	B5 IV	-14 V?	2	15 000	3.95	0.0	[2]	32	[3]
ζ Dra	155763	B6 III	-17 V	4	12 900	3.90	2.5:	[3]	34	[3]
α Lyr	172167	A0 Va	-14 V	11	9 450	4.00	2.0	[4]	24	[3]
HR 7098	174567	A0 Vs	- 3	2	10 200	3.55	1.0	[3]	11	[3]
21 Aql	179761	B8 II-III	- 5 V	9	13 000	3.50	0.2	[1]	17	[3]
ν Cap	193432	B9.5 V	- 2 V?	8	10 300	3.90	1.6	[1]	27	[3]
ξ Oct	215573	B6 IV	+16 V?	11	14 050	3.85	0.5:	[3]	5	[3]
<i>Superficially normal stars</i>										
HR 7338	181470	A0 III	-15 SB2O	2	10 250	3.75	0.5	[3]	3	[3]
κ Cep	192907	B9 III	-23 V	2	10 350	3.65	0.5	[3]	23	[3]
HR 7878	196426	B8 IIIp	-23	2	13 050	3.85	1.0:	[3]	6	[9]
21 Peg	209459	B9.5 V	- 0	4	10 450	3.50	0.5	[3]	4	[3]
<i>HgMn stars</i>										
87 Psc	7374	B8 III	-15 SBO	2	13 150	4.00	1.5	[3]	21	[3]
ϕ Phe	11753	B9 pHgMn ^a	+12 SB	3	10 700	3.80	0.5:	[3]	13	[10]
53 Tau	27295	B9 IV	+12 SBO	4	12 000	4.25	0.0	[2]	5	[11]
μ Lep	33904	B9 pHgMn	+26	2	12 800	3.85	0.0	[2]	18	[11]
HR 1800	35548	B9 pHgSi	-12	3	11 050	3.80	0.5	[3]	1	[3]
33 Gem	49606	B7 III	+11	2	14 400	3.85	0.5:	[3]	22	[3]
HR 2676	53929	B9.5 III	+ 6 V?	2	14 050	3.60	1.0:	[3]	30	[3]
HR 2844	58661	B9 pHgMn	+21 SBO	2	13 460	3.80	0.5:	[3]	30	[3]
ν Cnc	77350	A0 pSi	-14 SBO	2	10 400	3.60	0.1	[6]	13	[6]
κ Cnc	78316	B8 IIIpMn	+24 SB1O	23	13 500	3.80	0.0	[2]	6	[11]
36 Lyn	79158	B8 IIIpMn	+21 V	4	13 700	3.65	2.0:	[3]	49	[3]
HR 4072	89822	A0 pSiSr:Hg:	- 3 SB2O	3	10 500	3.95	1.1	[7]	2	[12]
χ Lup	141556	B9 IV	-16 SB2O	2	10 750	4.00	1.0	[7]	2	[12]
ι CrB	143807	A0 p:Hg:	-20 SB2O	13	11 000	4.00	0.2	[6]	5	[6]
ν Her	144206	B9 III	+ 3	2	12 000	3.80	0.6	[1]	11	[10]
HR 6000	144667	A0-3 III	—	1	14 000	4.30	1.5:	[3]	15	[13]
ϕ Her	145389	B9 p:Mn:	-17 SB1O	4	11 650	4.00	0.4	[8]	10	[8]
28 Her	149121	B9.5 III	-27	2	11 000	3.80	0.0	[8]	8	[8]
HR 6997	172044	B8II-III pHg	-27 SBO	2	14 500	3.90	1.5	[3]	34	[3]
112 Her	174933	B9II-III pHg	-20 SB2O	3	13 450	4.15	0.0:	[3]	5	[10]
HR 7143	175640	B9 III	-26 V?	2	12 100	4.00	1.0	[3]	2	[3]
HR 7361	182308	B9 pHgMn	-22	4	13 650	3.55	0.0	[3]	9	[3]
46 Aql	186122	B9 III	-32	2	13 000	3.65	0.0	[3]	1	[3]
HR 7664	190229	B9 pHgMn	-23 SB1O	2	13 200	3.60	0.8	[8]	8	[8]
HR 7775	193452	A0 III	-18 ^b	3	10 800	3.95	0.0	[3]	1	[3]
β Scl	221507	B9.5 IVpHgMnEu	+ 2	2	12 400	3.90	0.0:	[3]	27	[3]

^aBuscombe (1984).^bHoffleit & Jaschek (1982) cite HR 7775 as SB1O although this is a confusion with β Cap $\equiv$ HR 7776 (cf. Hoffleit 1984).

Notes: Spectral types and radial velocity data from Hoffleit & Jaschek (1982) with revisions according to Hoffleit (1984) and Stickland & Weatherby (1984). ‘V’ and ‘V?’: known and suspected radial velocity variables respectively; ‘SB’: spectroscopic binary (‘SB1’ and ‘SB2’ denote single- and double-lined systems respectively); ‘O’: published orbit (see Batten et al. 1989).

N_{IUE} is the number of co-added high-resolution long-wavelength *IUE* spectra.

Microturbulence parameters appended by a colon (‘:’) were derived from UV Fe II lines (see Sect. 4.2).

References: [1] Adelman & Fuhr (1985); [2] Adelman (1988a); [3] Smith (1992); [4] Gigas (1986); [6] Adelman (1989); [7] Dworetsky & Coates (personal communication); [8] Adelman (1988b); [9] Cowley (1980); [10] White et al. (1976); [11] Adelman (1987); [12] Dworetsky (1971); [13] Castelli et al. (1985).

normal stars in this narrow effective temperature interval for which *IUE* observations are available. The absence of such stars in the programme is in retrospect regrettable, but does not seriously compromise its objectives.

There are few stars close to the ZAMS, as might be expected for a sample drawn from the field rather than young clusters. The apparently youngest object in the programme is the He-weak Bp star HR 6000 (this has an anomalous spectral type of A0–3 III; cf. Andersen et al. 1984). This star forms a visual double with the probable pre-main-sequence star HR 5999 and by implication may be as young as 7×10^5 years (Thé & Tjin A Djie 1978, 1979). By reference to the evolutionary tracks, it appears that none of the stars has reached the terminal-age main sequence, in accordance with the view that HgMn stars are still in their core-hydrogen burning phase. Incidentally, it is noted that this conclusion could not be drawn on the basis of evolutionary calculations which do not include the strong convective core overshooting adopted by Bertelli et al. (1986) as has been suggested by recent work on the galactic cluster NGC 2301 (Napiwotzki et al. 1991). With these caveats entered, it is concluded that the programme satisfactorily samples the effective-temperature and surface-gravity régime of HgMn stars.

3. Observations and reductions

3.1. *Échelle* extraction

The observational dataset comprises all high-resolution long-wavelength (LW) *IUE* spectra of the programme stars available as of summer 1988 in the RAL archive. These data were de-archived in the form of geometrically and/or photometrically corrected échelle images, and subsequently reduced at the UCL *Starlink* node by using the IUEDR software package (Giddings & Rees 1989). Particular attention was exercised in the pre-extraction editing of image pixels rendered photometrically corrupted by the presence of microphonic modulation, cosmic ray events, or camera hotspots. Saturated pixels and fiducial marks ('reseaux') are automatically flagged by the IUEDR software and do not contribute to the extracted spectra. The échelle order extraction was carried out with a numerical sampling slit of width $\sqrt{2}$ geometric pixels in the dispersion direction (the slit height is automatically optimised by IUEDR on an order-by-order basis). The extracted échelle orders were finally mapped onto a single regular wavelength array with 0.05-Å point spacing.

3.2. *Spectrum co-addition*

Since the signal-to-noise ratio (S/N) of single well-exposed high-resolution *IUE* spectra is rather limited for the purposes of quantitative analysis (typically $S/N \sim 10$ –15), we have sought to improve their quality by co-addition. West & Shuttleworth (1981) have shown that the S/N increases approximately with the square-root of the number of co-added spectra up to a limit imposed by the presence of fixed pattern noise. However, improvements beyond this limit can be obtained by co-adding spectra exposed through different locations in the large aperture of the *IUE* spectrograph since these are variously displaced with

respect to the camera faceplate (and hence the fixed pattern) by a maximum of $\sim \pm 4$ pixels (Leckrone & Adelman 1989). Furthermore, the time-variability of the fixed pattern spatial distribution allows additional gains in the S/N to be achieved by co-adding spectra secured at different epochs in the *IUE* operational life-time. Listed in Table 1 under the heading N_{IUE} are the number of *IUE* spectra de-archived and co-added for each star in the programme. For many of the programme stars, only 2–4 spectra were available in the archives, and the improvement in S/N afforded by co-addition is correspondingly modest (i.e., less than a factor of 2). There are, however, some programme stars which have been rather extensively observed and for which it has been possible to produce spectra with remarkably high S/N by normal standards for *IUE* data, the HgMn star κ Cnc being a case in point.

In order to minimise the potential degradation in spectral resolution associated with the co-addition process, individual spectra for each programme star were first cross-correlated to determine their relative displacements by using the program IUEXCOR written by P.C.T. Rees. The cross-correlation displacements were found to be a function of wavelength and were satisfactorily represented by second-order polynomials, the coefficients of which were used to transform the individual spectra onto a common wavelength scale by using the *Starlink* software DIPSO (Howarth & Murray 1991). The individual spectra were co-added adopting wavelength-dependent weights determined by using a code which evaluates the root-mean-square random noise in *IUE* data from its amplitude in the Fourier domain (Smith 1992). These 'merged' spectra were then transformed to the laboratory wavelength frame by cross-correlation against a 'template' synthetic spectrum computed in high-resolution for the entire wavelength range of the *IUE* LW cameras.

3.3. *Continuum normalisation*

The final stage in the reduction chain involved normalising the observed spectra to the 'line-free' continuum. This is notoriously difficult for the *IUE* spectra of late-B stars because of their high line-density and problems associated with residual échelle ripple. Our adopted continuum normalisation procedure is illustrated for the normal star α Lyr in Fig. 2. The upper panel in this figure shows a 50-Å segment of synthetic spectrum computed by adopting the atmospheric parameters listed for this star in Table 1, and by using best estimates of its metal abundances from the literature. This synthetic spectrum has been convolved with appropriate rotation and instrumental profiles as described in Sect. 5. Line-free continuum windows were identified in the synthetic spectrum by searching for regions where the normalised flux approaches unity to within a few (typically $\lesssim 5$) percent (these continuum windows are indicated by arrows in Fig. 2). The co-added *IUE* spectrum of α Lyr was next examined for corresponding flux peaks in these continuum windows, and those which yielded a good match with the synthetic spectrum were retained for normalisation (examples of continuum windows which do *not* exhibit a satisfactory match are indicated by asterisks in Fig. 2). The line-free continuum was then

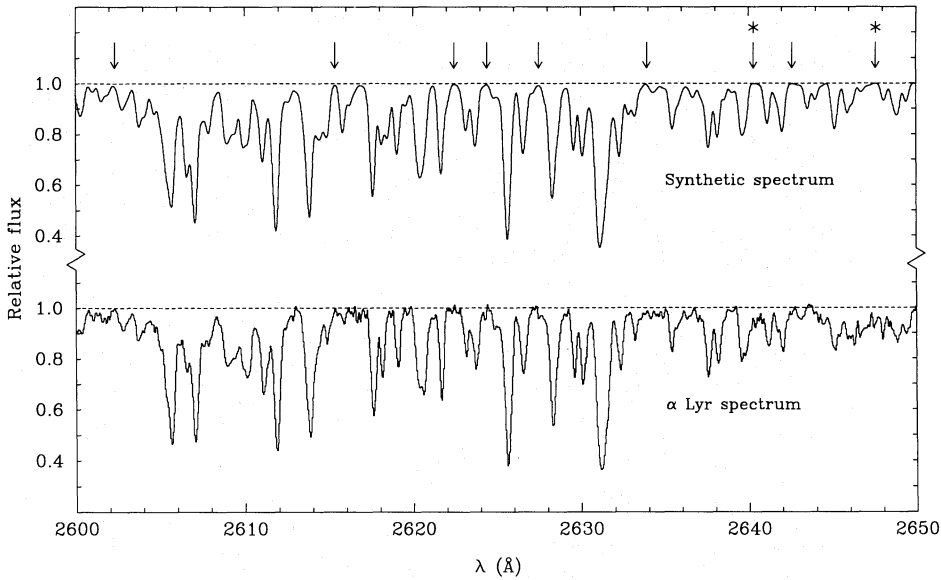


Fig. 2. Illustration of the adopted procedure for continuum location in observed spectra. The upper panel shows a 50-Å segment of synthetic spectrum in which line-free continuum windows have been identified and are indicated by arrows. The lower panel is the corresponding 50-Å segment of co-added *IUE* spectrum of α Lyr which has been normalised by fitting a Hermite spline to these continuum windows. Asterisks (*) denote synthetic continuum windows which are apparently *not* line-free in the observed spectrum

modelled by fitting Hermite splines (Hill 1982) to the continuum window regions in *both* the synthetic and observed spectra, making judicious allowance for the presence of random noise in the latter. Finally, the observed spectrum was rectified in two steps: first, by division by the observed continuum model; and second, by multiplication by the synthetic continuum model. The second step corrects the observed spectrum for non-zero residual flux in the apparently ‘line-free’ synthetic continuum windows. The lower panel in Fig. 2 shows the corresponding 50-Å segment of the co-added *IUE* spectrum of α Lyr normalised according to this procedure.

We find that approximate starting abundances are generally adequate to identify potentially line-free continuum windows in the synthetic spectra, and thereby perform the initial rectification to the *observed* continuum. However, accurate abundances (especially for iron and manganese) are important for the second corrective rectification to the *synthetic* continuum, as are the assumed values of $v \sin i$ and instrumental response function width. Accordingly, our initial continuum normalisation for the observed spectra of the programme stars was refined in step with the iterative determination of iron and manganese abundances described in Sect. 5. This procedure ensured ‘first-order’ consistency in the final abundances for these two spectroscopically dominant elements.

In the illustrative example of Fig. 2, there is evidently good agreement between synthetic and observed spectra, and the continuum location is accordingly relatively secure. For other spectral regions in which our adopted line list (see Sect. 5) is less complete, and for other programme stars in which the UV line density is considerably higher (e.g., the HgMn stars), identification of continuum windows becomes significantly more difficult. We estimate the uncertainty in continuum location to be $\pm 10\%$ in some line-dense spectral regions (especially the far UV), and thus this step in the reduction chain represents one of the single largest sources of error in UV spectrum-synthesis analysis.

4. Atmospheric parameters

4.1. Effective temperatures and surface gravities

The HgMn stars appear to be photometrically indistinguishable from normal stars of similar spectral type in the Strömgren and Geneva photometric systems (Cameron 1966; Eggen 1983, 1984; Hauck 1976; North & Kroll 1989). We have therefore derived effective temperatures and surface gravities from calibrations of these photometric systems based on spectroscopically normal stars and solar-metallicity model atmospheres. Strömgren photometric data were taken from the homogenised catalogue of Hauck & Mermilliod (1980), dereddened with the program UVBYBETA of Moon (1985), and used to derive T_{eff} and $\log g$ values according to the (c_0, β) grid of Moon & Dworetzky (1985) as implemented in Moon’s (1985) program TEFFLOGG. Geneva photometric data were obtained from the catalogue of Rufener (1981) and used to derive T_{eff} and $\log g$ values according to North & Nicolet’s (1990) calibration of the reddening-free parameters X and Y (Smith 1992).

Further constraints on the effective temperatures and surface gravities of the programme stars were obtained by fitting the predictions of Kurucz (1979) solar-metallicity model atmospheres to de-reddened spectrophotometric scans and $H\gamma$ profiles of the programme stars taken primarily from the literature. These calculations were carried out by using software which constructs a $T_{\text{eff}}\text{-}\log g$ diagram for each programme star (Smith 1992). Contours of constant $\Delta\chi^2 = \chi^2 - \chi_{\text{min}}^2$ are drawn in these $T_{\text{eff}}\text{-}\log g$ diagrams to indicate solution regions for the spectrophotometric and spectroscopic data (cf. Press et al. 1986, Chapter 14). Superposition of photometric data points on these diagrams then allows a direct comparison of the photometrically and spectroscopically derived parameters. An example of this procedure is illustrated in Fig. 3 which is a diagnostic $T_{\text{eff}}\text{-}\log g$ diagram for the superficially normal programme star 21 Peg. The adopted atmospheric parameters for the programme stars are mean values from the photometric and ‘best-fit’ spectroscopic analyses.

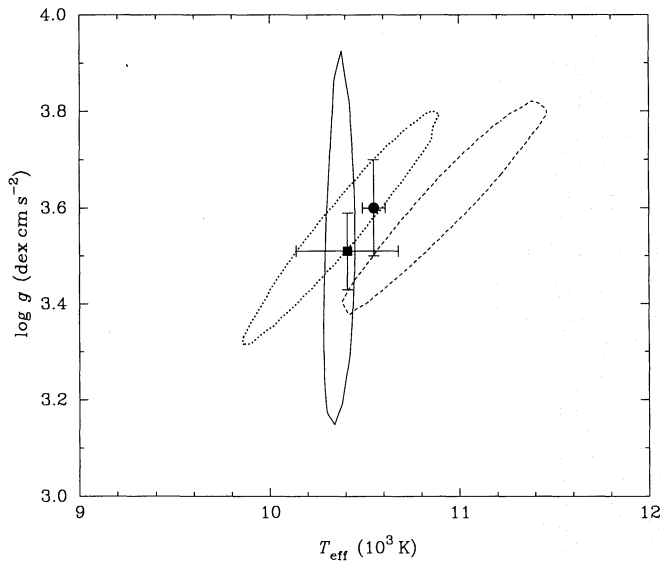


Fig. 3. Example of a diagnostic temperature-gravity diagram for one of the programme stars (21 Peg). Contours of constant $\Delta\chi^2 = 4.0$ correspond to 95 % confidence regions for the best-fit model energy distributions and Balmer line profiles (Kurucz 1979). Key: continuous line – spectrophotometric scan (Adelman & Pyper 1983); dashed line – photographic H γ profile (Smith 1992); dotted line – CCD H γ profile (Smalley 1992); filled square – Strömgren photometry; filled circle – Geneva photometry

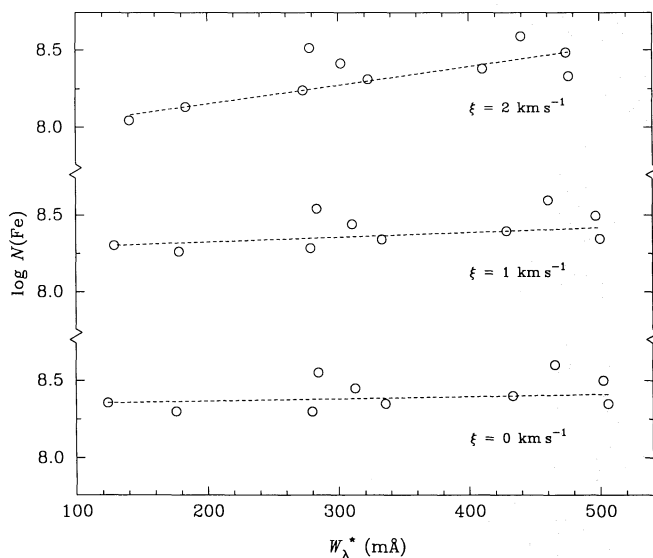


Fig. 4. Example of the application of Magain's (1984) null-correlation method in the determination of microturbulence. The abundances derived from UV Fe II lines in 112 Her ($\log N(\text{Fe})$) are plotted as a function of *synthetic* equivalent width (W_λ^*) for three values of microturbulence (ξ) as indicated. A *minimum* correlation between abundance and synthetic equivalent width is obtained for $\xi = 0 \text{ km s}^{-1}$. Note that only the two weakest lines analysed ($W_\lambda^* < 200 \text{ mÅ}$) are sensitive to ξ

These results are presented in Table 1 and will be described in detail elsewhere.

It is important to note that the effects of He-deficiency and enhanced Mn abundance have been neglected in our determination of the atmospheric parameters for the HgMn stars. According to the analysis carried out by Auer et al. (1966), a He-deficiency with respect to the Sun of $\sim 0.7\text{--}0.8$ dex will induce a systematic *underestimate* in $\log g$ by ~ 0.1 dex for stars analysed under the assumption of a solar composition (cf. Norris 1971). We have confirmed this result explicitly by computing a small grid of He-deficient model atmospheres by using Kurucz's (1970) code ATLAS6 (cf. North & Kroll 1989). We find that at these systematically lower values of $\log g$, the normal-helium models are essentially identical to the low-helium models. The effects of enhanced Mn abundance on the inferred atmospheric parameters of HgMn stars are somewhat more difficult to evaluate in the absence of model atmospheres computed for a specific HgMn-like mixture of abundances. The increased UV line blanketing associated with an overabundance of Mn could have important effects on the atmospheric structure, and in particular on the temperature distribution in superficial layers. These considerations would suggest that the T_{eff} values obtained here may be systematically overestimated, although detailed calculations will need to be carried out in order to confirm this and to evaluate the magnitude of any associated error.

4.2. Microturbulence parameters

The microturbulence parameters (ξ) adopted for most of the programme stars were taken from fine analyses of visual-region spectra in the literature. These data were augmented by values derived in an analysis of co-added Dominion Astrophysical Observatory (DAO) 2.4 Å mm^{-1} spectra of a small selection of the programme stars (Smith 1992). However, for some of the programme stars it was necessary to make recourse to approximate ξ -values derived by analysis of the UV Fe II lines studied in this paper. These data were obtained by application of the null-correlation method as modified by Magain (1984). The essence of Magain's modification is that *synthetic* equivalent widths (computed for an assumed abundance and microturbulence parameter) are used in preference to observed values. This method avoids the systematic errors associated with the invalid assumption that line abundances and equivalent widths are *intrinsically* uncorrelated in the presence of observational errors. In contrast to the situation encountered in the derivation of microturbulence from visual-region spectra, the *weakest* lines in this UV analysis were strong enough to be on the saturated portion of the curve of growth and therefore sensitive to ξ ; these were used to determine the microturbulence parameter by reference to strong lines in the damping region of the curve of growth for which the ξ -dependence was negligible.

An example of the application of this technique is illustrated in Fig. 4 where iron abundances derived from UV Fe II lines in the HgMn programme star 112 Her are plotted as a function of synthetic equivalent width for three values of ξ . Regression lines for these data have been superposed on this figure to aid

visualisation of the underlying correlations. In this example, a minimum correlation between line abundances and synthetic equivalent widths is observed for $\xi = 0 \text{ km s}^{-1}$.

The paucity of *measurable* UV lines which are sensitive to the microturbulence parameter, and uncertainties in the damping constants for strong lines, limit the accuracy of the ξ -values derived in this way. It nevertheless seems preferable to adopt these coarse estimates rather than to assume arbitrary values for the microturbulence in the few programme stars which have not been subject to fine analysis in the visual region. Extending this UV analysis to those programme stars for which reliable microturbulence parameters have been derived from optical spectra indicates satisfactory agreement between the two wavelength regions, and suggests that the errors associated with the UV results are $\sim \pm 0.5 \text{ km s}^{-1}$. The adopted ξ -values for the programme stars are listed in Table 1 with citation to sources in the literature where appropriate.

4.3. Rotational velocities

The accuracy of a spectrum-synthesis analysis is very largely dependent on the quality of the adopted values of rotational velocity for the stars analysed. We have therefore sought to acquire as accurate values of these parameters as possible for the purposes of this investigation. The adopted rotational velocities for the programme stars are listed (with literature sources where appropriate) in Table 1. Most of these values were derived by an application of the Fourier analysis method described by Gray (1976, 1992) to the co-added *IUE* and (in some cases) DAO spectra of the programme stars (Smith 1992), details of which will be published elsewhere. These data were supplemented where necessary by values obtained from recent high-dispersion analyses in the literature.

5. Abundance analysis

As a preliminary to the abundance analysis, solar-metallicity model atmospheres were computed under the assumption of local thermodynamic equilibrium (LTE) for the adopted values of T_{eff} and $\log g$ by using Kurucz's code ATLAS6 (Kurucz 1970; Kurucz 1979). Elemental abundances were then determined by interactively fitting the observations for each programme star with LTE synthetic spectra computed using the aforementioned models and the spectrum-synthesis code UCLSYN (Smith & Dworetsky 1988; Smith 1992). Rotational broadening of the synthetic spectra was treated by convolution with a rotation profile calculated under the assumption of a quadratic limb-darkening law. Instrumental broadening was handled by convolution with a Gaussian response function, the full-width-half-maximum (FWHM) of which was specified as the following explicit function of wavelength:

$$\text{FWHM} = (0.156 \pm 0.004) + (2.2 \pm 0.1) \times 10^{-5} \lambda \quad \text{\AA}. \quad (1)$$

This expression was determined by fitting a least-squares straight line to results from a detailed Fourier analysis of the co-added LW *IUE* spectra of the sharpest-lined programme stars,

and is typically 5–10 % greater than that appropriate for single spectra (Smith 1992).

The lines analysed for each element were generally selected according to the availability of accurate atomic data in recent critical compilations of oscillator strengths (e.g., Martin et al. 1988; Fuhr et al. 1988; Morton 1991). In order to mitigate the deleterious effects of line blending, only the strongest and 'cleanest' (i.e., least blended) lines of the dominant singly-ionised stages of the iron-peak elements have been investigated here.

Atomic data for blending lines were drawn from the extensive tabulations of semi-empirical transition probabilities for iron-peak elements by Kurucz (1990) and for all other elements by Kurucz & Peytremann (1975), with substitutions, as appropriate and where available, for more accurate data from the literature (primarily the NBS critical compilations). Lines which connect to predicted upper levels (i.e., those not classified by laboratory term analysis) in the Kurucz datasets have *not* been used here.

The Kurucz (1990) dataset was also adopted as the primary source for radiative and collisional damping parameters for the iron-peak elements. For all other elements contributing to blends, radiative damping constants were usually obtained by summing the Einstein *A*-values for the lower and upper levels in the transitions of interest. Although these radiative *A*-sums were frequently incomplete for lack of the requisite atomic data, this approximation was often found to be better than the assumption of *classical* damping. Stark damping parameters were treated according to the approximate formulations given by Freudenstein & Cooper (1978) and Griem (1968) for neutral and ionised species respectively (cf. Cugier & Hardorp 1988).

For the analysis, abundances for blending species were initially adopted from published visual-region studies (see, e.g., references for ξ -values in Table 1). However, to ensure internal consistency, the analyses of the spectroscopically dominant species Fe II and Mn II were carried out first, and iterated through an extra cycle—this was found to be a particularly important measure for the extreme HgMn stars in which line blending causes the inferred abundances of these elements to be tightly coupled. Then, as the investigation proceeded, the abundances derived for successive elements were adopted as the default values for subsequent calculations.

6. Results

The derived mean abundances and associated standard errors for Cr through Ni in the programme stars are presented in Table 2. Examples of best-fit synthetic spectra are illustrated in Figs. 5–7. The mean abundances for each element are plotted versus effective temperature in Fig. 8.

6.1. Chromium

Chromium abundances were derived by fitting synthetic spectra to the Cr II resonance lines $\lambda\lambda 2055, 2061$ (multiplet UV1)

Table 2. Programme stars: mean abundances for iron-peak elements

Star	HD	Chromium	Manganese	Iron	Cobalt	Nickel
<i>Normal stars</i>						
π Cet	17081	6.0 ± 0.2	5.60 ± 0.05	7.50 ± 0.05	5.7 ± 0.2	6.2 ± 0.1
134 Tau	38899	5.7 ± 0.1	5.35 ± 0.10	7.45 ± 0.05	4.8 ± 0.4	5.8 ± 0.2
θ Leo	97633	6.1 ± 0.2	5.50 ± 0.10	7.55 ± 0.05	5.7 ± 0.2	6.7 ± 0.1
τ Her	147394	5.7 ± 0.3	5.85 ± 0.15	7.65 ± 0.15	5.7 ± 0.4	5.9 ± 0.4
ζ Dra	155763	5.3 ± 0.2	5.50 ± 0.20	6.65 ± 0.10	4.8 ± 0.1	5.5 ± 0.2
α Lyr	172167	5.5 ± 0.1	5.05 ± 0.10	6.95 ± 0.05	4.7 ± 0.4	5.9 ± 0.1
HR 7098	174567	6.4 ± 0.1	5.70 ± 0.10	7.65 ± 0.05	6.1 ± 0.1	6.6 ± 0.1
21 Aql	179761	5.7 ± 0.2	6.20 ± 0.15	7.45 ± 0.05	5.9 ± 0.3	6.0 ± 0.1
ν Cap	193432	5.6 ± 0.2	5.20 ± 0.05	7.40 ± 0.05	5.3 ± 0.3	6.2 ± 0.2
ξ Oct	215573	5.5 ± 0.2	5.00 ± 0.10	7.40 ± 0.05	5.4 ± 0.4	5.9 ± 0.1
<i>Superficially normal stars</i>						
HR 7338	181470	5.7 ± 0.1	5.55 ± 0.05	7.40 ± 0.05	5.8 ± 0.1	6.6 ± 0.1
κ Cep	192907	6.2 ± 0.3	5.45 ± 0.10	7.45 ± 0.10	5.8 ± 0.2	6.4 ± 0.2
HR 7878	196426	5.4 ± 0.3	5.65 ± 0.10	7.55 ± 0.05	5.7 ± 0.3	6.1 ± 0.1
21 Peg	209459	5.7 ± 0.1	5.65 ± 0.10	7.45 ± 0.05	5.9 ± 0.1	6.3 ± 0.2
<i>HgMn stars</i>						
87 Psc	7374	5.9 ± 0.3	7.40 ± 0.05	6.40 ± 0.20	5.7 ± 0.4	5.2 ± 0.5
ϕ Phe	11753	6.2 ± 0.1	6.20 ± 0.10	7.65 ± 0.05	$\leq 2.5 \pm 0.5$	5.1 ± 0.2
53 Tau	27295	6.1 ± 0.1	7.25 ± 0.05	6.75 ± 0.10	3.8 ± 0.5	5.6 ± 0.1
μ Lep	33904	6.3 ± 0.2	7.50 ± 0.05	7.45 ± 0.05	3.8 ± 0.5	5.6 ± 0.3
HR 1800	35548	5.8 ± 0.2	6.05 ± 0.15	7.30 ± 0.05	$\leq 2.5 \pm 0.5$	5.1 ± 0.3
33 Gem	49606	5.8 ± 0.3	7.50 ± 0.10	7.60 ± 0.10	$\leq 2.5 \pm 0.5$	6.1 ± 0.4
HR 2676	53929	4.4 ± 0.1	6.15 ± 0.20	7.70 ± 0.05	$\leq 2.5 \pm 0.5$	5.6 ± 0.2
HR 2844	58661	6.3 ± 0.4	7.90 ± 0.10	7.20 ± 0.20	$\leq 4.0 \pm 0.5$	5.9 ± 0.5
ν Cnc	77350	6.5 ± 0.2	6.00 ± 0.05	7.65 ± 0.05	6.4 ± 0.2	6.4 ± 0.1
κ Cnc	78316	5.9 ± 0.2	7.80 ± 0.10	7.75 ± 0.05	3.3 ± 0.5	5.7 ± 0.2
36 Lyn	79158	6.7 ± 0.4	5.20 ± 0.15	8.10 ± 0.10	5.8 ± 0.2	6.3 ± 0.1
HR 4072	89822	6.1 ± 0.1	5.90 ± 0.10	7.65 ± 0.05	$\leq 2.5 \pm 0.5$	5.6 ± 0.3
χ Lup	141556	5.7 ± 0.2	4.85 ± 0.05	7.55 ± 0.10	4.4 ± 0.2	5.8 ± 0.1
ι CrB	143807	6.4 ± 0.1	6.55 ± 0.15	7.85 ± 0.05	$\leq 2.5 \pm 0.5$	6.0 ± 0.1
ν Her	144206	6.1 ± 0.3	7.10 ± 0.05	7.20 ± 0.05	$\leq 2.5 \pm 0.5$	5.5 ± 0.3
HR 6000	144667	5.6 ± 0.4	6.70 ± 0.10	8.30 ± 0.05	$\leq 3.0 \pm 0.5$	5.7 ± 0.2
ϕ Her	145389	6.7 ± 0.1	6.95 ± 0.10	7.65 ± 0.05	6.1 ± 0.2	5.8 ± 0.2
28 Her	149121	5.9 ± 0.1	6.35 ± 0.10	7.75 ± 0.05	$\leq 2.5 \pm 0.5$	5.6 ± 0.5
HR 6997	172044	—	8.15 ± 0.05	7.25 ± 0.15	$\leq 3.0 \pm 0.5$	5.5 ± 0.8
112 Her	174933	5.1 ± 0.3	6.75 ± 0.10	8.40 ± 0.05	$\leq 2.5 \pm 0.5$	5.5 ± 0.0
HR 7143	175640	6.5 ± 0.1	7.65 ± 0.05	6.95 ± 0.05	$\leq 3.0 \pm 0.5$	5.8 ± 0.3
HR 7361	182308	5.3 ± 0.2	7.90 ± 0.05	7.85 ± 0.05	$\leq 2.5 \pm 0.5$	5.8 ± 0.4
46 Aql	186122	4.2 ± 0.2	6.30 ± 0.05	8.00 ± 0.05	$\leq 2.5 \pm 0.5$	5.2 ± 0.1
HR 7664	190229	5.1 ± 0.2	6.30 ± 0.15	8.10 ± 0.05	$\leq 2.5 \pm 0.5$	5.5 ± 0.3
HR 7775	193452	6.3 ± 0.2	6.15 ± 0.05	7.95 ± 0.05	4.5 ± 0.5	5.4 ± 0.2
β Scl	221507	6.7 ± 0.3	7.40 ± 0.05	7.65 ± 0.10	$\leq 2.5 \pm 0.5$	6.0 ± 0.2

Notes: Abundances are given on a scale where $\log N(\text{H}) \equiv 12$. Quoted uncertainties are formal standard errors.

and to the subordinate lines $\lambda\lambda 2653, 2666, 2971, 2989$ (multiplets UV7, UV8 and UV80). The resonance line $\lambda 2065$ and the subordinate line $\lambda 2835$ were also considered for analysis, but proved to be unsuitable because of severe contamination by blends. Oscillator strengths for the resonance lines were taken from Aashamar & Luke (1990) following the recommendations of Morton (1991). For the subordinate lines analysed here, the

Martin et al. (1988) oscillator strengths were adopted; these are cited with uncertainties of less than 50 %.

Most of the lines analysed here are quite strong, but are situated in complex blends. In contrast, although the lines longward of $2900 \text{ \AA}$ are much weaker they nevertheless show relatively clean profiles. Some examples of best-fit synthetic spectra for $\lambda 2055$ are illustrated in Fig. 5a. In these spectra, only the chromium abundance has been adjusted to optimise the fit

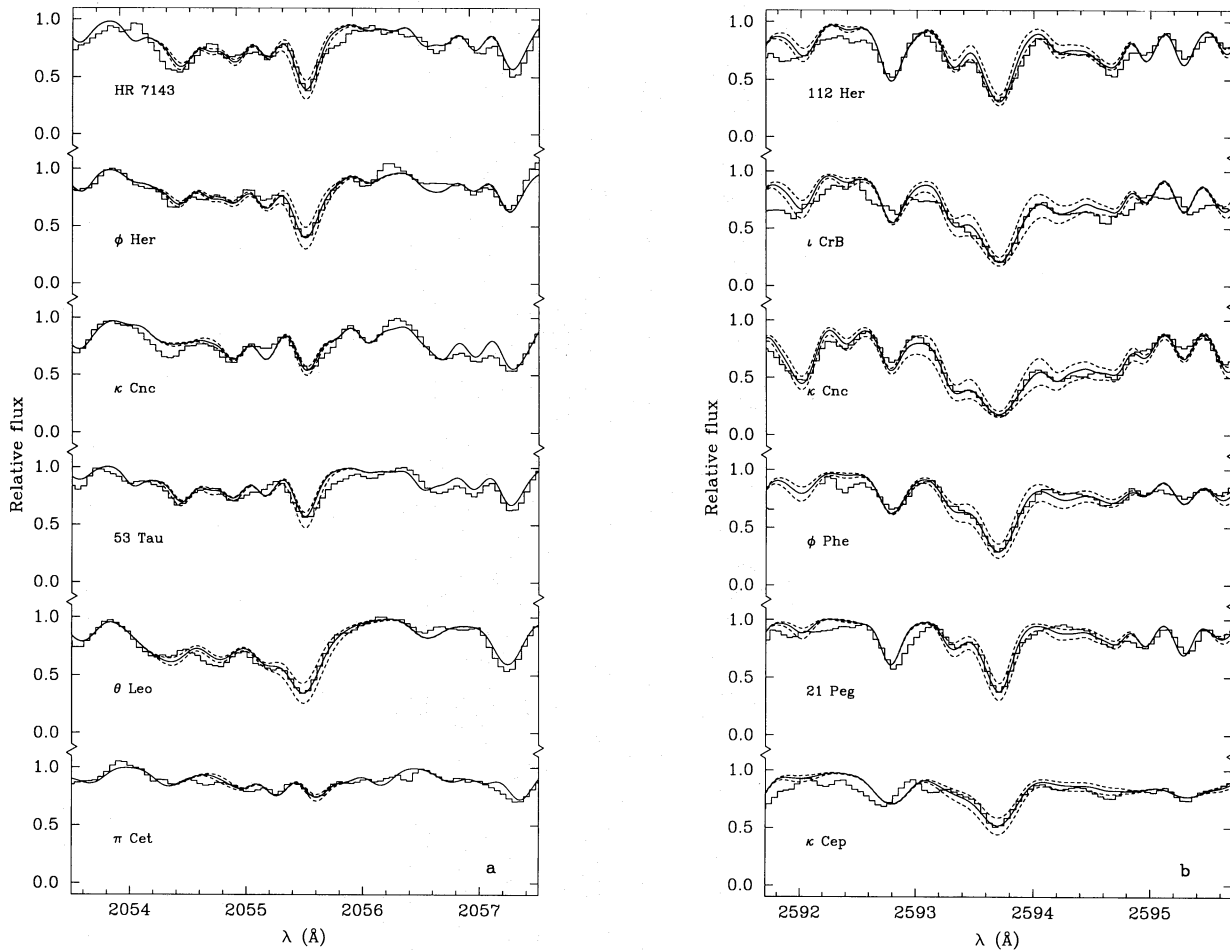


Fig. 5. a and b. Examples of best-fit synthetic spectra (continuous lines) for **a** Cr II $\lambda 2055$ and **b** Mn II $\lambda 2593$ compared with the co-added IUE spectra of selected programme stars (histogram lines). Synthetic spectra computed assuming abundances of ± 0.3 dex relative to the best-fit values are superposed to give a visual indication of the uncertainties in the derived abundances (dashed lines)

to the resonance line at 2055.60 Å. Spectra computed assuming chromium abundances of ± 0.3 dex relative to the best-fit values are also illustrated in order to give a visual impression of the uncertainties in the fits due to noise in the data. This line is evidently quite sensitive to abundance in the cooler programme stars (e.g., θ Leo and ϕ Her) for which the fitting error is ~ 0.1 dex, but becomes less sensitive in the hotter examples (e.g., π Cet and κ Cnc) for which a fitting error of 0.3 dex (or more in some extreme cases) seems appropriate. This behaviour is reflected in the other resonance and (to a lesser degree) subordinate lines analysed here, and is attributable to a shift with increasing T_{eff} (at constant abundance) from the damped to saturated regions of their curves-of-growth.

The line-to-line scatter in derived abundances was found to be quite large for some of the programme stars, particularly the hotter examples in which the Cr II lines are intrinsically weak. The abundance derived for the HgMn star HR 6997 was considered to be too uncertain to present here; the analysis of this star was severely hindered by the combination of relatively high $v \sin i$ and high T_{eff} (the latter resulting in weak Cr II lines).

For most stars analysed, the agreement between the UV and published visual-region abundances is satisfactory.

Mean chromium abundances are plotted as a function of effective temperature in Fig. 8a where they are compared with the solar value of 5.67 dex (Anders & Grevesse 1989). Chromium abundances for the normal and superficially normal stars appear to be rather widely distributed about the solar value. The HgMn stars are broadly scattered around the solar abundance with only two stars, 46 Aql and HR 2676, exhibiting significant chromium deficiencies.

6.2. Manganese

Manganese abundances were derived by fitting synthetic spectra to the resonance lines Mn II $\lambda\lambda 2576, 2593, 2605$ (multiplet UV1). These are sufficiently strong to be detected even in the hottest normal stars in the programme and it is therefore possible to provide 'control' data for the HgMn stars across their entire range in T_{eff} . Oscillator strengths were taken from Kurucz (1990) for the 'raie ultime' $\lambda 2576$ and from Martin et al. (1988) for $\lambda\lambda 2593, 2605$.

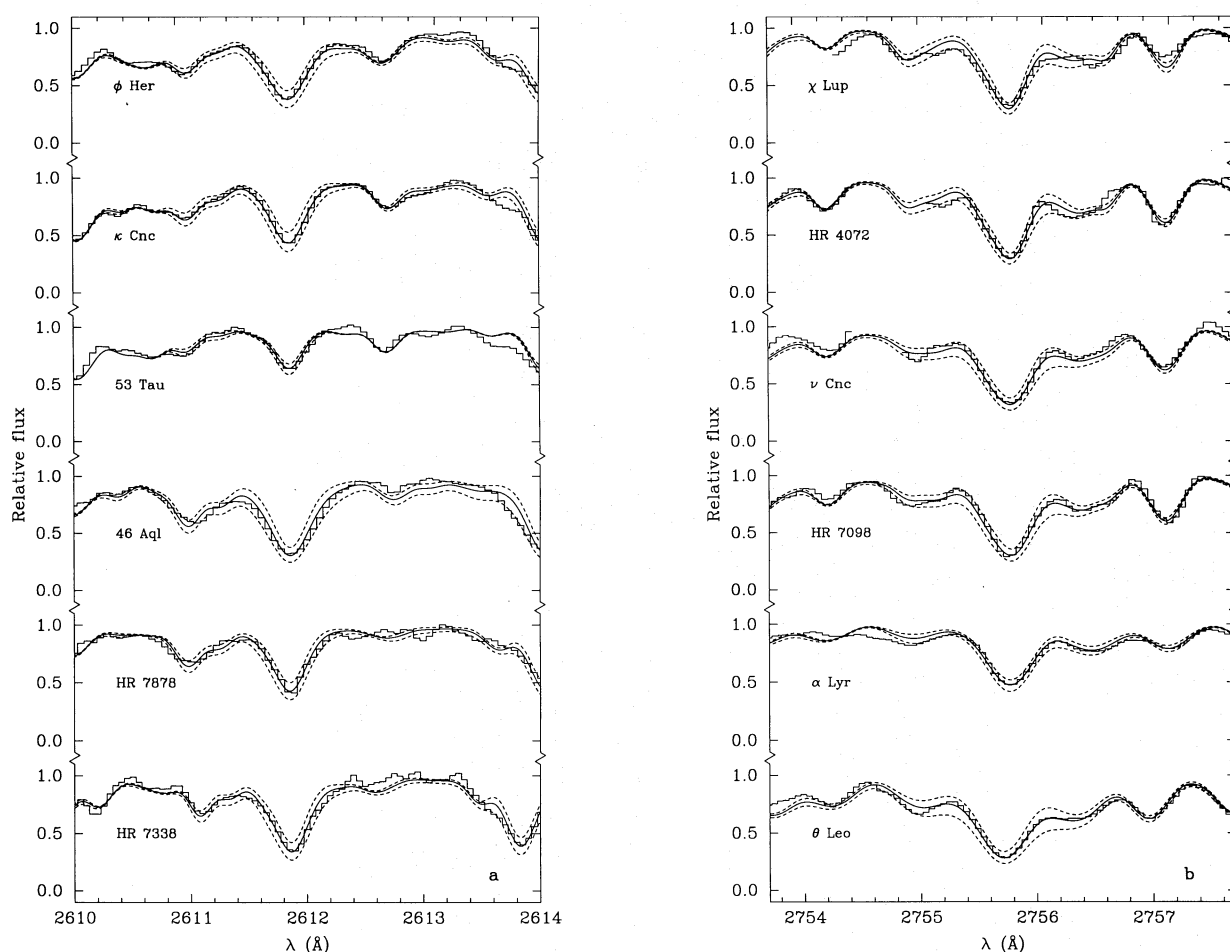


Fig. 6. a and b. Examples of best-fit synthetic spectra (continuous lines) for **a** Fe II $\lambda 2611$ and **b** Fe II $\lambda 2755$ compared with the co-added *IUE* spectra of selected programme stars (histogram lines). Synthetic spectra computed assuming abundances of ± 0.3 dex relative to the best-fit values are superposed to give a visual indication of the uncertainties in the derived abundances (dashed lines)

The least blended of the lines analysed is $\lambda 2576$ for which an excellent match was obtained between synthetic and observed spectra for most stars. The other two lines are more heavily blended, especially $\lambda 2605$ which is contaminated by a strong Fe II line. Some examples of best-fit synthetic spectra for $\lambda 2593$ are illustrated in Fig. 5b. In these spectra, only the manganese abundance has been adjusted to optimise the fit to the resonance line at 2593.72 Å. The uncertainties in the fits due to noise in the data are again indicated by synthetic spectra computed assuming manganese abundances of ± 0.3 dex relative to the best-fit values. The $\lambda 2593$ resonance line is clearly sensitive to abundance for all the stars illustrated in Fig. 5b, which are in turn broadly representative of the programme stars in general. The behaviour of the other manganese resonance lines examined here is similar to that of $\lambda 2593$, and thus the uncertainty in the individual fits due to noise in the data is estimated to be ~ 0.1 dex.

We note that in the hottest Mn-rich stars (e.g., HR 6997), the resonance lines have extended wings which are difficult to fit simultaneously with the line cores, the latter being deeper than expected for LTE line formation. In this spectral region, the atmosphere becomes optically thin to line-centre radiation

only in the most superficial layers where the LTE assumption is unlikely to be valid. Therefore, in practice the fits were weighted in favour of the wings although some degree of compromise was exercised in deriving the final abundances. In some cases, possible interstellar contamination of the resonance lines was indicated by the presence of a wavelength-shifted absorption component. This is not expected to introduce significant error in the inferred abundances of most of the programme stars due to the combination of the great strength of the photospheric lines and the low reddening implied by photometry.

The derived abundances for the resonance lines exhibited a high degree of internal consistency. Agreement with published abundances is usually satisfactory with the notable exception of HR 1800 for which the visual-region abundance (Smith 1992) exceeds the UV value by approximately 0.8 dex.

Mean manganese abundances are plotted as a function of effective temperature in Fig. 8b where they are compared with the solar value of 5.39 dex from Anders & Grevesse (1989). The mean abundance for the normal and superficially normal stars is 5.5 ± 0.3 dex (s.d.), in good agreement with the solar abundance. The HgMn stars exhibit an exceptionally strong and

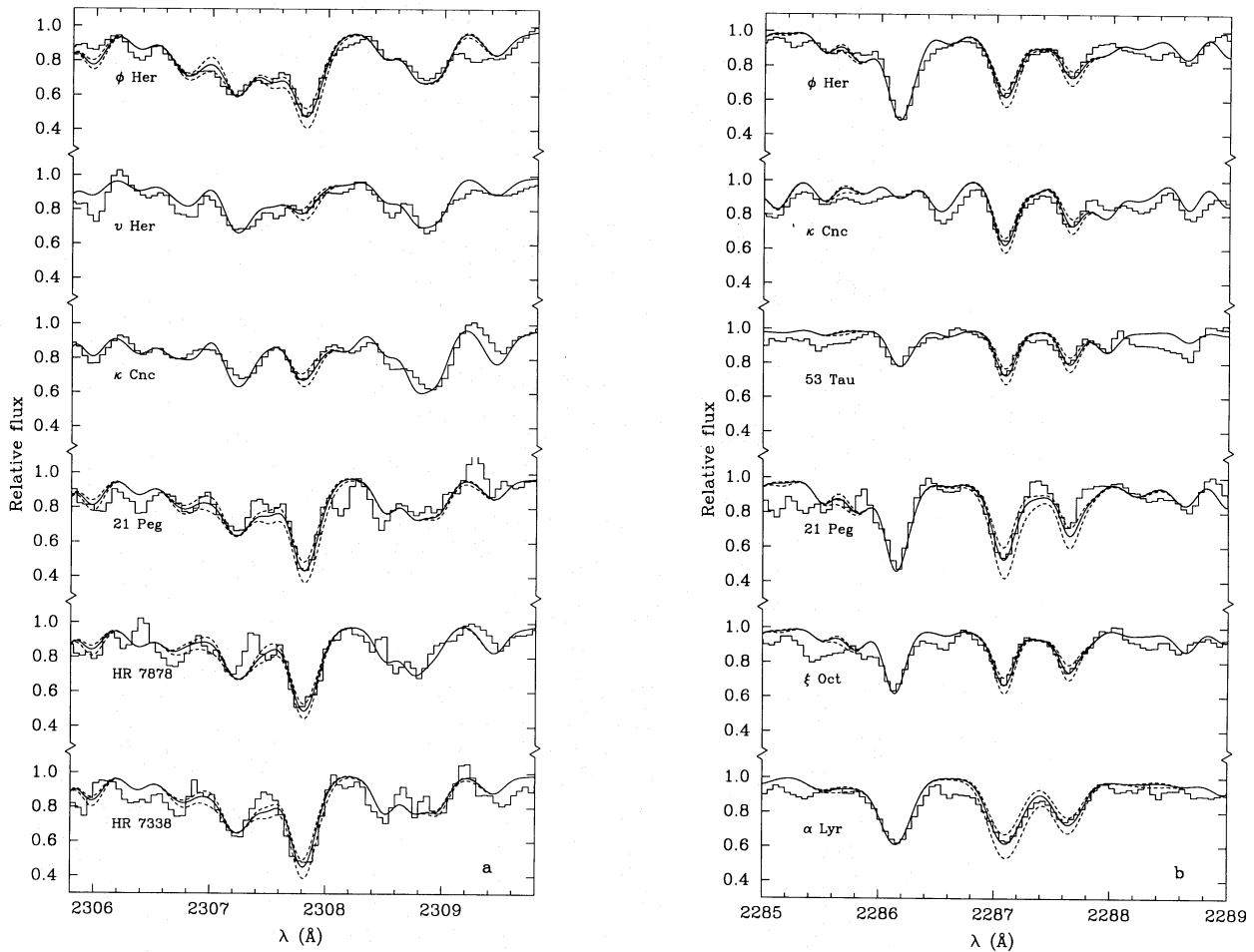


Fig. 7. a and b. Examples of best-fit synthetic spectra (continuous lines) for **a** Co II $\lambda 2307$ and **b** Ni II $\lambda 2287$ compared with the co-added *IUE* spectra of selected programme stars (histogram lines). Synthetic spectra computed assuming abundances of ± 0.5 dex relative to the best-fit values are superposed to give a visual indication of the uncertainties in the derived abundances (dashed lines). Note the presence of Co II $\lambda 2286$ left of centre in panel **b**

well-defined correlation with effective temperature. There is, however, a small group of HgMn stars in the T_{eff} -range 13 000–15 000 K which are only mildly Mn-rich; these include 46 Aql, HR 2676, HR 6000, 112 Her, and HR 7664. Two stars in the HgMn group, χ Lup and 36 Lyn, have manganese abundances of solar proportions or less. These results tend to support Cowley's (1980) suggestion that there exists a distinct group of *hot, mild* Mn stars which are difficult to identify using classical techniques.

6.3. Iron

There is an enormous selection of Fe II lines available for analysis in the LW wavelength range of the *IUE* cameras. However, in order to obtain accurate abundances, only lines with B-grade (or better) oscillator strengths in the Fuhr et al. (1988) compilation (i.e., error < 10 %) were analysed. Seven lines were selected from multiplet UV1 of the ground term: these were Fe II $\lambda\lambda 2598, 2607, 2611, 2613, 2617, 2621, 2628$. Three lines were selected from multiplet UV62: these were Fe II $\lambda\lambda 2730,$

2743, 2755. None of these lines originates from a 0 eV level and therefore interstellar contamination is not expected to be significant. Oscillator strengths were taken from the aforementioned compilation.

The UV1 lines are generally quite strong in the programme stars, but many are embedded in complex blends (notably $\lambda\lambda 2598, 2607, 2613, 2628$). The UV62 lines, however, all show relatively 'clean' profiles. Some examples of best-fit synthetic spectra for $\lambda 2611$ and $\lambda 2755$ are illustrated in Figs. 6a and b. As before, only the iron abundances have been adjusted to fit the lines in these spectra at 2611.87 and 2755.73 Å respectively. Superposed on these figures are synthetic spectra computed assuming iron abundances of ± 0.3 dex relative to the best fit values; these illustrate the sensitivity of the lines to abundance and suggest fitting errors of typically 0.1 dex (perhaps slightly more in a few Fe-deficient programme stars such as 53 Tau).

The internal consistency in derived abundances was found to be excellent, with the stars of higher $v \sin i$ (e.g., τ Her, 87 Psc, HR 2844, and HR 6997) presenting the largest line-to-line scatter. The external agreement is also generally good for all but the

highest- $v \sin i$ stars if a ‘realistic’ uncertainty of ± 0.3 dex is assumed for the abundances (cf. Baschek 1991). The formal standard errors of the analysis probably underestimate the true absolute errors in the abundances which will be dominated by propagated errors in the adopted atmospheric parameters and atomic data (see Sect. 7).

Mean iron abundances are plotted as a function of effective temperature in Fig. 8c where they are compared with the solar value, a recent determination of which is 7.54 dex (Biémont et al. 1991). These UV data show that the normal and superficially normal stars are quite tightly clustered about the solar abundance whereas the HgMn stars show a broad diversity in iron abundance which apparently increases with T_{eff} . There are two normal stars, however, which show significant deficiencies of iron: these are α Lyr and ζ Dra. According to these UV abundances, 87 Psc is the most Fe-deficient HgMn star in the programme, with an underabundance of approximately 1.1 dex with respect to the solar value. However, this abundance is somewhat more extreme than that implied from the analysis of its visual-region spectrum (Smith 1992). The classic manganese star 53 Tau has a well-defined Fe deficiency of 0.8 dex, in excellent agreement with its published visual-region abundance (Adelman 1987). These iron deficiencies are comparable to that of 0.9 dex reported by Ptitsyn & Ryabchikova (1986) for the hot ($T_{\text{eff}} \approx 14\,000$ K) manganese star HR 562. In contrast to these objects is a small group of mildly Fe-rich HgMn stars, the most extreme example of which is 112 Her with an overabundance of approximately 0.8 dex with respect to the Sun. It is interesting that this sub-group comprises nearly all of those objects identified as hot, mild manganese stars (see Sec. 6.2). Finally, it is worthwhile to note that the total range in iron abundance observed in the HgMn sample analysed here is 1.6 dex, or more if the result for 87 Psc is accepted at face value; this is greater than that observed for any other group of chemically peculiar stars (cf. Ptitsyn & Ryabchikova 1986).

6.4. Cobalt

Very few determinations of cobalt abundances in HgMn stars (or indeed normal stars) have been published. This is partly due to the fact that this element has few strong lines in the photographic spectral region. Fortunately, *IUE* spectra make accessible several relatively strong UV lines of cobalt. Abundances were determined by fitting synthetic spectra to the low-excitation lines Co II $\lambda\lambda 2286$, 2307 and 2580 (multiplets UV9 and UV14). We have also examined Co II $\lambda 2324$ (multiplet UV8), but found it to be too heavily blended for quantitative analysis. For $\lambda 2286$ and $\lambda 2307$, oscillator strengths were taken from Fuhr et al. (1988) who give estimated uncertainties of better than 10 %. The only source of data located for $\lambda 2580$ was Kurucz (1990).

The $\lambda 2286$ line is the strongest and least blended of the lines analysed. In the HgMn stars, all of the cobalt lines analysed tend to be either very weak or absent, and therefore only upper limits could be derived in most cases. Some examples of synthetic spectra for $\lambda 2307$ are presented in Fig. 7a (see also Fig. 7b for $\lambda 2286$). Only the cobalt abundance has been adjusted to

optimise the fit to the line at $2307.85 \text{ \AA}$. Here, synthetic spectra computed assuming cobalt abundances of ± 0.5 dex relative to the best-fit values have been superposed in order to give a visual impression of the uncertainties in the fits due to noise in the data. The sensitivity to abundance is evidently *very weak* for most stars illustrated in this figure; this is because $\lambda 2307$ lies predominantly on the ‘saturation’ region of its curve-of-growth. The other two lines analysed here exhibit essentially identical behaviour. This is, unfortunately, quite typical of those Co II lines which are sufficiently strong to be analysed using *IUE* data. The uncertainties in the best-fit cobalt abundances for individual lines are accordingly estimated to be of order 0.3–0.5 dex.

The internal consistency in derived abundances proved satisfactory for the normal stars considering the relative weakness of the lines analysed. For the HgMn stars, upper limits on the cobalt abundance were derived from the three lines, and the lowest value retained with an adopted uncertainty of ± 0.5 dex.

Mean cobalt abundances are plotted as a function of effective temperature in Fig. 8d where they are compared with the solar abundance of 4.92 dex from Anders & Grevesse (1989). The normal and superficially normal stars appear to have solar or slightly enhanced abundances of cobalt. The mean abundance for this group is 5.52 ± 0.45 dex (s.d.). Most of the HgMn stars are evidently grossly cobalt-deficient ($[\text{Co}/\text{H}] \lesssim -2$ dex), but there are, as before, notable exceptions which include the mildly cobalt-rich stars ν Cnc and ϕ Her, and cobalt-normal stars 87 Psc and 36 Lyn. The cobalt abundances in both the normal and HgMn groups do not appear to be correlated with T_{eff} , although it is possible that such a relationship is hidden within the upper limits obtained for most stars in the latter sample.

6.5. Nickel

Nickel abundances were derived by fitting synthetic spectra to the low-excitation lines Ni II $\lambda\lambda 2165$, 2184, 2270, 2287 (multiplets UV12, UV13 and UV38). The adopted oscillator strengths were taken from Fuhr et al. (1988) and have estimated uncertainties of between 10 and 25 %.

Some examples of best-fit synthetic spectra for $\lambda 2287$ are presented in Fig. 7b. For these spectra, the nickel abundance has been adjusted to optimise the fit to the line at $2287.09 \text{ \AA}$. Note that this figure coincidentally includes the Co II line at $2286.15 \text{ \AA}$ (see Sect. 6.4). Superposed on Fig. 7b are synthetic spectra computed assuming nickel abundances of ± 0.5 dex relative to the best-fit values; these indicate that the $\lambda 2287$ line is moderately sensitive to abundance in the cooler programme stars (e.g., α Lyr and 21 Peg), but only *very weakly* so in the hotter examples (e.g., ξ Oct and 53 Tau). Again, this is characteristic of the observable Ni II lines which tend to be saturated in stars which have $T_{\text{eff}} \gtrsim 12\,000$ K and/or mild nickel deficiencies (as appears to be the case for most of the HgMn sample). The estimated fitting error for each nickel line analysed here accordingly lies in the range 0.3–0.5 dex.

The internal consistency in the derived abundances is satisfactory for most stars, although less so for those with higher $v \sin i$ (e.g., 87 Psc, 36 Lyn, and HR 6997). The external agree-

ment is very good considering the rather large internal errors. The results for ν Her and HR 6000 are exceptions since the published abundances are respectively 0.9 and 0.7 dex less than those suggested by this analysis (Adelman & Fuhr 1985; Castelli et al. 1985).

Mean nickel abundances are plotted as a function of effective temperature in Fig. 8e where they are compared with the solar value of 6.25 dex from Anders & Grevesse (1989). The normal stars are scattered about the solar abundance with a dispersion of 0.35 dex. Apparent overabundances of nickel in this group are restricted to the coolest stars in the sample. The HgMn stars are generally Ni-deficient although there are some examples with abundances which are essentially solar to within the formal errors of the analysis including, in particular, ν Cnc and 36 Lyn. The HgMn star 46 Aql has one of the largest, and best-determined, nickel deficiencies of the stars analysed. An application of Student's t -test for distributions with equal variances demonstrates that the normal/superficially normal and HgMn groups have significantly different mean nickel abundances at a confidence level of better than 99.9 %. The nickel abundances are not significantly correlated with T_{eff} .

7. Error analysis

7.1. Spectroscopic binarity

A potentially important source of systematic error in the observations analysed in this study arises from the composite nature of the spectra of some of the programme stars since five (HR 7338, HR 4072, χ Lup, ι CrB, and 112 Her) are known double-lined spectroscopic binaries (e.g., Batten et al. 1989) and one (HR 1800) is a close visual binary (Baize & Petit 1989). No attempt has been made here to allow for dilution effects, or for superposition of primary and secondary spectral lines, although this can in principle be achieved given knowledge of the atmospheric parameters of both components, their light ratio, and the system's orbital elements (e.g., Leckrone et al. 1991). It is nonetheless worthwhile to consider the UV light ratios for the components of these systems in order to assess the likely errors on the inferred abundances.

Accordingly, continuum light ratios in the wavelength range 1900–3250 Å were derived for these binary systems from estimates of their visual-region light ratios and by reference to Kurucz (1979) model atmospheres of appropriate effective temperature and surface gravity. For the cool HgMn binaries HR 4072 and χ Lup, Dworetsky (1971) derived light ratios at $\lambda 4481$ of $L_A/L_B = 4.82$ and $L_A/L_B = 3.80$ respectively. Using his effective temperatures and surface gravities for the components of these systems yields light ratios in the ultraviolet of ~ 7 –9 for HR 4072 and ~ 5 –7 for χ Lup. A UV light ratio of similar magnitude is inferred for the ι CrB system which is, according to Dworetsky (1980), strikingly similar to those of HR 4072 and χ Lup. For HR 7338, the photographic magnitude difference between components of 1^m25 (Petrie 1950) coupled with estimated primary and secondary spectral types of B9 and A2–A3 respectively (Smith 1992) also implies a similar UV light

ratio to that of χ Lup. For 112 Her, Seligman & Aller (1970) obtained a light ratio at 4000 Å of 10.0 ± 0.5 . Adopting their estimates of the atmospheric parameters for the components of this system yields a UV light ratio of ~ 20 –30. Finally, the binary HR 1800 has a visual magnitude difference between components of 0^m6 (Baize & Petit 1989), and estimated primary and secondary spectral types of B9 and A0–A1 respectively (Smith 1992); these data indicate a (very approximate) UV light ratio of ~ 3 –4.

These UV light ratios suggest that errors in derived abundances due to the composite nature of the spectrum of 112 Her are entirely negligible. For the cooler spectroscopic binaries HR 4072, χ Lup, ι CrB, and HR 7338 there may be *small* systematic errors in the derived abundances, although these are unlikely to be important. However, the situation is rather less secure for the visual binary HR 1800 for which the contribution of the secondary component to the total UV spectrum is probably *not* negligible longward of approximately 2000 Å. It is difficult to evaluate the quantitative effect of binarity on the line profiles and associated equivalent widths in the UV spectra of these stars; simple dilution considerations would suggest maximum errors in W_λ of order 10–20 % might occur in unfavourable circumstances for the cool spectroscopic binaries (perhaps as large as 30–40 % for HR 1800), although if the spectral lines are coincident (which seems likely for a visual binary), the precise effects become difficult to predict.

In conclusion, the effects of spectroscopic binarity on the abundances derived for most of the programme stars probably do not exceed those due to other sources of observational and analytical error. The abundances derived for HR 1800 constitute a useful first reconnaissance of its chemical composition, but should nevertheless be considered provisional pending a more detailed treatment of its composite UV spectrum.

7.2. Atomic data

A second important source of error in this study lies in the atomic data used in the spectrum synthesis. The primary iron-peak lines examined in this work have oscillator strengths with estimated errors in the range 10–50 %; these propagate trivially into the inferred abundances ($\Delta \log N = -\log e \Delta f/f$) to yield uncertainties of 0.04–0.22 dex. These errors are essentially systematic and constant, and therefore do not affect the *differential* aspect of the abundances (i.e., between normal and HgMn stars). The influence of errors in the atomic data adopted for the blending lines, however, will tend to vary with the atmospheric parameters and composition of the programme stars. For example, errors in the blending-line list for Mn II will have a relatively strong bearing on the abundances derived for the HgMn stars, but less so for their normal congeners.

A critical evaluation of the Kurucz & Peytremann (1975) and Kurucz (1990) atomic datasets used here is beyond the scope of this paper, although an investigation has been carried out by Leckrone et al. (1990) to which the reader is referred for details. In summary, they find that errors in the transition probabilities of a few tenths up to 2 dex are not uncommon, particularly where

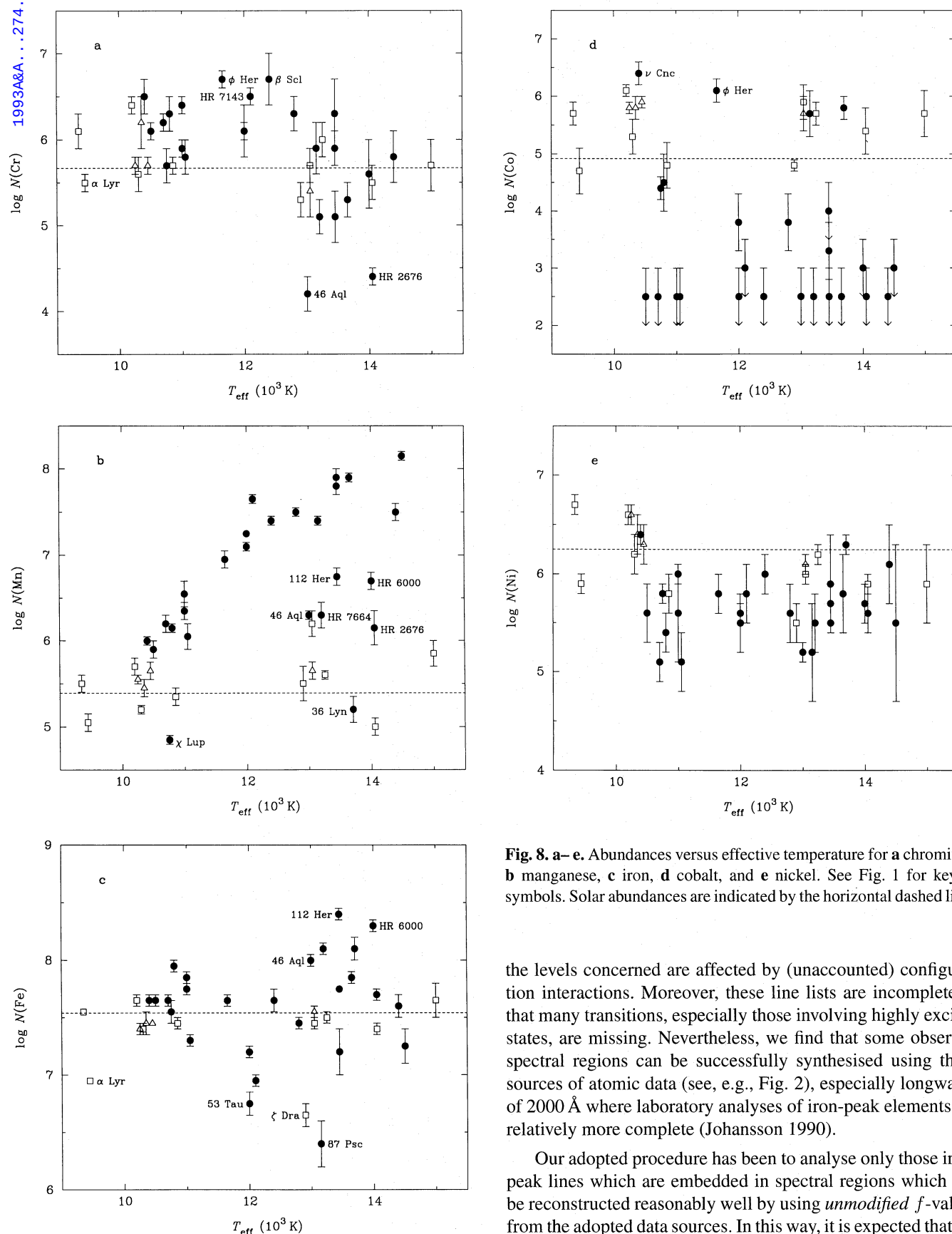


Fig. 8. a–e. Abundances versus effective temperature for **a** chromium, **b** manganese, **c** iron, **d** cobalt, and **e** nickel. See Fig. 1 for key to symbols. Solar abundances are indicated by the horizontal dashed lines

the levels concerned are affected by (unaccounted) configuration interactions. Moreover, these line lists are incomplete in that many transitions, especially those involving highly excited states, are missing. Nevertheless, we find that some observed spectral regions can be successfully synthesised using these sources of atomic data (see, e.g., Fig. 2), especially longwards of 2000 Å where laboratory analyses of iron-peak elements are relatively more complete (Johansson 1990).

Our adopted procedure has been to analyse only those iron-peak lines which are embedded in spectral regions which can be reconstructed reasonably well by using *unmodified* f -values from the adopted data sources. In this way, it is expected that the cumulative variation of blending-line opacity across of the spectral features of interest is satisfactorily reproduced. However, as

the referee of this paper points out, it should be recognised that at *IUE* spectral resolution, the effects of errors and omissions in the blending-line list can become quite indistinct. Thus, for weak lines in particular, errors in the blending lines will tend to introduce associated errors in the inferred iron-peak elemental abundances. We conclude that for elements which are of normal abundance or overabundant, the magnitude of errors due to missing lines is probably not more than 0.5 dex, and therefore the gross abundance variations reported here cannot be doubted. In the case of elements which are underabundant, the derived upper-limit abundances may be somewhat higher (i.e., less restrictive) than would otherwise be inferred from the same observations given essentially complete atomic data.

7.3. Atmospheric parameters and observations

The error estimates cited for the mean abundances in this paper are mostly standard errors calculated from the internal scatter from two or more lines of the same species. These errors do not directly convey the propagated errors in the abundances due to errors in the adopted atmospheric parameters or observational data. In order to redress this shortcoming, a schematic analysis of the possible errors in the derived abundances due to errors in these sources was carried out. Uncertainties in the following five quantities were considered: effective temperature, logarithmic surface gravity, microturbulence, Stark damping, and equivalent widths.

For effective temperature and surface gravity, uncertainties of ± 250 K and ± 0.25 dex respectively were adopted as suggested by the scatter in the values of T_{eff} and $\log g$ derived for the programme stars using photometric and spectrophotometric techniques (see Sect. 4.1; Smith 1992). For microturbulence, an uncertainty of $\Delta\xi = \pm 1 \text{ km s}^{-1}$ was adopted; this encompasses a large fraction of the observed values of this parameter in the programme stars and is probably generously representative of the true uncertainty. An uncertainty of $\Delta\Gamma_S = \pm 50\%$ was assumed for the Stark damping parameters. Finally, a nominal uncertainty in equivalent width of $\Delta W_\lambda = \pm 10\%$ was adopted in order to explore the effect of errors in the observations due to, for example, systematic misplacement of the continuum, flux zero-level errors, or the unaccounted contribution of a secondary spectrum (cf. Sect. 7.1).

Mean errors in abundance corresponding to the adopted uncertainties in these five parameters were computed for each of the iron-peak elements analysed in this paper. Errors were computed for abundances with respect to the Sun of 0 and ± 1 dex for all elements except Mn (for which abundances with respect to the Sun of 0, +1, and +2 dex were adopted). A ‘canonical’ microturbulence parameter of $\xi = 1 \text{ km s}^{-1}$ was assumed for these calculations which were carried out using $\log g = 4$ Kurucz (1979) model atmospheres with effective temperatures of 10 000, 12 500, and 15 000 K in order to examine the large-scale T_{eff} -sensitivity of the errors. A summary of the results from the error analysis is presented in Table 3 which gives, for each element and parameter considered, the mean value and range in derived absolute abundance errors.

Abundance errors due to errors in effective temperature and in surface gravity are typically less than ~ 0.1 dex. In view of this lack of sensitivity, it is reasonable to conclude that the pronounced correlation observed between abundance and effective temperature for manganese in the HgMn stars can *not* be attributed to systematic error in the adopted atmospheric parameters.

The importance of errors in microturbulence varies quite considerably amongst the lines analysed and the summary results presented in Table 3 must be interpreted with caution because the influence of this parameter is sensitively dependent on the individual strength of the lines under investigation. However, judging by this analysis, the lines of some species must lie predominantly on the saturation portion of their curves of growth. This is apparently the case at solar abundances and below for many of the Cr II, Co II, and Ni II lines for which the mean errors are typically ~ 0.2 – 0.3 dex. Therefore, some of the scatter observed in the Cr, Co, and Ni abundances in both the normal and HgMn samples may be attributable to errors in the adopted values of ξ .

The sensitivity of the derived abundances to the adopted Stark damping parameters appears to be very weak for all species analysed here except for Mn II in the HgMn stars where the typical error is ~ 0.05 dex. This should not, however, be taken as license to ignore the contribution of Γ_S in abundance determinations since for some of the stronger UV lines observed in peculiar stars it can become important (Smith 1992).

Finally, the effect of a nominal error of $\pm 10\%$ in the equivalent widths of the lines analysed is seen to be typically 0.1–0.3 dex; this is comparable with the ‘eye-estimates’ of the uncertainties in the best-fit synthetic spectra presented in Sect. 6. That these errors are considerably higher than the expected error of ~ 0.04 dex for lines on the linear portion of the curve-of-growth simply reflects the fact that nearly all of the lines amenable to analysis with *IUE* spectra are strong enough to lie on the saturation or damping regions.

8. Discussion

8.1. Abundances: systematics and anomalies

The results from the analysis of the normal programme stars tend to confirm the hypothesis that their atmospheric abundances of iron-peak elements are *broadly* similar to those of the sun. For only one star, α Lyr, are there significant and consistent departures from solar abundances in all the elements examined here. This star is metal-deficient by typically ~ 0.6 dex according to this study, in good quantitative agreement with previous work (e.g., Sadakane et al. 1986; Gigas 1986; Adelman & Gulliver 1990). The distribution of abundances about the solar values for the spectroscopically normal sample is somewhat greater than would be expected on the basis of observational and analytical error, and may in fact indicate true cosmic scatter (cf. Cowley et al. 1982; Holweger et al. 1986; Lemke 1989, 1990).

The superficially normal programme stars do not appear to be distinguishable from their normal counterparts in terms

Table 3. Error analysis for iron-peak elemental abundances

Species	Error in abundances for ...				
	$\Delta T_{\text{eff}} = \pm 250 \text{ K}$	$\Delta \log g = \pm 0.25 \text{ dex}$	$\Delta \xi = \pm 1 \text{ km s}^{-1}$	$\Delta \Gamma_s = \pm 50 \%$	$\Delta W_\lambda = \pm 10 \%$
Cr II	0.07	0.03	0.25	0.00	0.18
	0.04–0.11	0.00–0.06	0.00–0.48	0.00–0.01	0.05–0.28
Mn II	0.09	0.01	0.12	0.05	0.13
	0.08–0.11	0.00–0.05	0.00–0.36	0.02–0.07	0.09–0.25
Fe II	0.07	0.04	0.16	0.01	0.15
	0.03–0.10	0.00–0.09	0.00–0.48	0.00–0.01	0.09–0.27
Co II	0.06	0.05	0.32	0.00	0.20
	0.01–0.09	0.01–0.09	0.07–0.50	0.00–0.01	0.08–0.28
Ni II	0.04	0.06	0.23	0.01	0.17
	0.00–0.08	0.02–0.10	0.00–0.51	0.00–0.01	0.09–0.28

Notes: For each species, the mean absolute abundance error is given above the range in absolute abundance errors. The abundance errors were computed for $T_{\text{eff}} = 10\,000$, $12\,500$, and $15\,000 \text{ K}$, and for elemental abundances with respect to the Sun of 0 and $\pm 1 \text{ dex}$ (except Mn II for which abundances with respect to the Sun of 0, +1, and +2 dex were adopted).

of iron-peak abundances. This conclusion is largely supported by formal statistical tests (Student's t for equal and unequal variances; Press et al. 1986), but deserves confirmation based on a larger sample than that examined here.

Several systematics in the iron-peak elemental abundances of HgMn stars emerge from the results derived in this study. Chromium is on average normal but exhibits a broad spread in abundances with a few stars showing significant deficiencies when compared with spectroscopically normal stars of similar effective temperature. Manganese is overabundant in nearly all HgMn stars and exhibits a strong positive correlation with effective temperature. Cobalt is grossly underabundant (by $\gtrsim 2 \text{ dex}$) in most HgMn stars, but is overabundant in some. Finally, nickel is almost uniformly deficient in HgMn stars. The results for cobalt and nickel constitute the first quantification of characteristics of HgMn stars previously recognised in a qualitative manner by, for example, Jaschek & Jaschek (1974).

However, in addition to systematics, this study also provides support for the suggestion that HgMn stars are, to some extent, a chemically heterogeneous group (cf. Heacox 1979; Wolff 1983). Evidence for this is seen in the number of stars which depart from the more general behaviour of the majority, and moreover, in the fact that the *identification* of these anomalous HgMn stars varies from element to element. Particularly compelling examples of this are seen in chromium, where two stars (46 Aql and HR 2676) are anomalously underabundant; in cobalt, where at least four stars ($\nu \text{ Cnc}$, $\phi \text{ Her}$, 87 Psc, and 36 Lyn) are anomalously overabundant with respect to their HgMn congeners; and in manganese, where there are numerous stars which fall significantly below the envelope defined in the abundance versus T_{eff} diagram of Fig. 8b (discussed in more detail in Sect. 8.3). Indeed, the broad diversity of iron abundances observed in the HgMn stars (which reaches a maximum of $\sim \pm 0.8$ – 1.0 dex near $13\,000 \text{ K}$) is further indication of large star-to-star variation.

These anomalies lie well outside the range of estimated uncertainties discussed in Sect. 7, and given the internal consis-

tency of the analysis, are undoubtedly significant. Only in the case of 36 Lyn is it possible to attribute these anomalous abundances to questionable classification in the HgMn group (see Sect. 8.2). Thus, it is reasonable to conclude that the heterogeneity identified in the iron-peak elements of the HgMn stars studied here is in fact an intrinsic property of their atmospheric chemistry.

8.2. Comments on individual stars

A full account of the compositional profiles of the individual programme stars is postponed for a later paper in this series. It is, nevertheless, appropriate to discuss the impact of the abundances derived in this paper on the peculiarity-class assignments of some of the stars in the programme.

8.2.1. 33 Gem $\equiv$ HD 49606

The assignment of this star in the HgMn class has been doubted on the basis of a reported magnetic field and an unusually strong Si spectrum (Chunakova et al. 1983). However, Hubrig & Launhardt (1992) have recently questioned the existence of a field in 33 Gem; this coupled with enhanced manganese and mercury (Smith 1992) support its identification as a HgMn star.

8.2.2. 36 Lyn $\equiv$ HD 79158

The near-normal abundances of manganese and mercury (Smith 1992) in this star, coupled with the secure detection of a photospheric magnetic field (Borra et al. 1983), formally dissociate it from the HgMn class. In the context of this analysis, the peculiar nature of 36 Lyn largely rests on a mild overabundance of iron.

8.2.3. HR 6000 $\equiv$ HD 144667

As discussed in Sect. 2, this is possibly the youngest star grouped in the HgMn sample examined in this study. Although

not normally considered a ‘classic’ member of the HgMn class, the high manganese abundance derived for this star coupled with the its extremely weak He I spectrum (Andersen et al. 1984) would seem to indicate that it is, at least, a closely related object.

8.2.4. 46 Aql $\equiv$ HD 186122

The results from this study have confirmed the status of this object as an example of a hot, mild HgMn star (cf. Cowley 1980). In terms of the elements examined in this paper, it is atypical of the class only in view of its unusually low chromium abundance.

8.3. Radiative diffusion: comparison with observations

Detailed atmospheric radiative acceleration calculations do not appear to have been carried out for Cr, Fe, Co, and Ni. The only predictions for the diffusion of these elements in late-B star atmospheres is provided by the early work of Michaud (1970). He found that the radiation force transferred to Cr and Fe due to photoionisation alone is approximately equal to gravitational acceleration, whereas for Ni it is significantly less. These schematic calculations are in good qualitative agreement with the results obtained here, particularly with regards to the general depletion of Ni derived for the HgMn stars. More detailed radiative acceleration calculations are evidently required for these elements.

For manganese, however, elaborate atmospheric diffusion calculations have been carried out by Alecian & Michaud (1981). They showed that the radiative acceleration on Mn II is sufficient to support overabundances of a factor of 30, 300–500, and 3000 in the line-forming regions of stars with effective temperatures of 10 000, 12 000, and 15 000 K respectively. Manganese is bound to stars with $T_{\text{eff}} \lesssim 13\,000$ K since the radiative acceleration becomes smaller than gravity in the upper atmosphere where a Mn II/Mn III ionisation trap forms. Above this threshold, however, the radiative acceleration on Mn III at solar abundance is sufficient to drive it out of the star. Alecian & Michaud argue that below 17 000 K, the Mn particle flux from the envelope is higher than that out of the atmosphere and thus an accumulation of Mn develops which reaches equilibrium with gravity (due to saturation effects in the lines) in 10^4 to 10^5 years.

Alecian & Michaud’s envelope of maximum overabundances is illustrated in Fig. 9 where it is compared with the mean manganese abundances derived for the programme stars. The envelope encloses all of the observations, reproduces the observed correlation with effective temperature, and even reflects the slight ‘kink’ in the observations near 12 000 K. However, Alecian & Michaud’s theoretical envelope represents the *maximum* overabundance which can develop in a stratified atmosphere rather than the *apparent* overabundance of manganese that would be inferred under the conventional assumption of vertical atmospheric homogeneity. Since the abundances derived here were obtained under this simplifying assumption, it is necessary to modify the theoretical envelope accordingly. In practice this was achieved by computing a series of Mn II resonance-

line profiles for effective temperatures in the range 10 000–15 000 K and for various assumed atmospheric distributions of manganese. Following Alecian (1982), highly schematic distributions were adopted in which Mn is enhanced by its maximum overabundance factor in atmospheric strata above a fixed threshold in optical depth, and is present at normal abundance below. The intention of this is, of course, simply to explore the qualitative effects of stratification—no implication that step-like abundance gradients exist in reality is intended. Threshold logarithmic optical depths in the range -1 to -3 were used. Equivalent widths were calculated from the line profiles thus derived and were subsequently used to re-evaluate corresponding abundances under the conventional assumption of vertical chemical homogeneity.

Apparent abundance curves corresponding to various threshold optical depths ($\tau_0 \equiv$ continuum optical depth at $5000 \text{ \AA}$) in the atmospheric distribution of manganese are illustrated in Fig. 9. The overabundance envelope defined by the observations in the abundance- T_{eff} plane can be reproduced by the stratified diffusion model if it is assumed that the base of the atmospheric manganese ‘cloud’ varies from $\log \tau_0 \sim -3$ at 10 000 K to $\log \tau_0 \sim -2$ at 15 000 K. This makes sense in the context of Alecian & Michaud’s model since below 13 000 K the manganese accumulation develops in a high-lying ionisation trap, whereas at higher effective temperatures it can only accumulate in the form of a dynamic equilibrium distribution which would presumably extend deeper into the atmosphere. However, it would be inappropriate to take the interpretation further than this in the absence of detailed calculations of the equilibrium distributions of Mn and in view of our simplistic (i.e., LTE) treatment of the atmospheres of these stars. The value of the schematic calculations undertaken here is that they indicate how the predictions of diffusion theory can be reconciled with observed abundances by making due allowance for the effects of chemical stratification on the analysis.

A conspicuous feature of Fig. 9 is the presence of six HgMn stars which fall below the envelope of overabundance defined by the other class members at and above 13 000 K. Alecian & Michaud suggested that this could be the result of disruption of the Mn-enriched atmospheric strata due to horizontal instability. Alecian & Grappin (1984) have discussed a related mechanism in which overabundances which are rapidly constructed in the higher (low density) atmospheric strata develop density ‘holes’ due to subsequent screening of supportive radiation at deeper (high density) layers where overabundances develop on a longer time-scale. Michaud (1980) has also noted that once helium has disappeared from the outer stellar regions, thin layers of (for instance) manganese would be unstable because of the presence of an inverted μ -gradient. It is not clear whether these mechanisms would lead to periodic destruction of the manganese overabundance or reach a stable configuration at a lower equilibrium abundance. We note that the four most Mn-weak stars in the anomalous sub-group (36 Lyn, HR 2676, HR 7664, and 46 Aql) share exceptionally low surface gravities of 3.60–3.65 dex, suggesting that they may be ‘evolved’ HgMn stars. In contrast, the two most mildly anomalous stars in this sub-

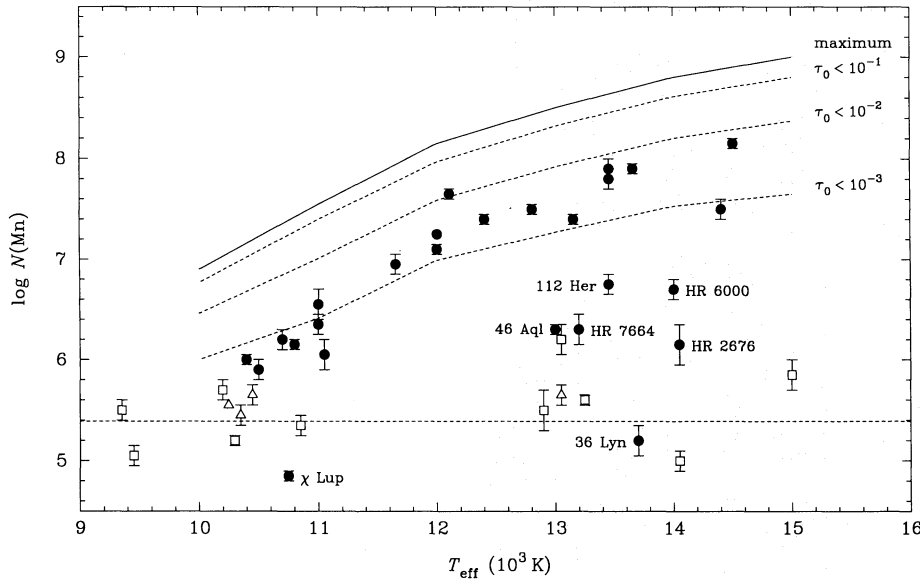


Fig. 9. The predictions of diffusion theory compared with manganese abundances ($\log N(\text{Mn})$) for normal stars (open squares), superficially normal stars (open triangles), and HgMn stars (filled circles). The upper continuous curve represents the maximum Mn abundance that can be supported in the atmosphere by radiative acceleration (Alecian & Michaud 1981). The lower dashed curves represent the associated manganese abundances that would be derived under the assumption of atmospheric homogeneity given three schematic distributions of Mn with depth. Each modified curve is labelled by the threshold optical depth (τ_0) above which the Mn accumulation is assumed to develop. The solar abundance (Anders & Grevesse 1989) is represented by the horizontal dashed line

group (112 Her and HR 6000) have rather high surface gravities of 4.15–4.30 dex which place them close to the zero-age main sequence for 3–5 $M_{\odot}$ stars (Bertelli et al. 1986). All of these anomalous stars lie above the 13 000 K threshold at which Alecian & Michaud's diffusion model switches from an ionisation trap to a dynamical equilibrium mechanism to effect an atmospheric accumulation of Mn ions. Accordingly, future radiative diffusion calculations for manganese might profitably examine the development of equilibrium atmospheric abundance gradients in models with various surface gravities.

9. Conclusions

The results from this study show for the first time the systematics of iron-peak elemental abundances in normal late-B and HgMn stars, based entirely on the analysis of resonance and other UV absorption lines of singly ionised species. In general, the abundances in the normal stars are close to solar values, but there are exceptions which imply that some normal stars have significantly non-solar abundances (e.g., α Lyr), or that there may be systematic errors in our analyses (e.g., neglect of non-LTE). In the HgMn stars, the ranges of implied abundances for chromium and iron appear to be too large to be explained by errors in the analysis. Strong deficiencies of cobalt and nickel, and gross enhancements of manganese, are found in most (but not all) HgMn stars.

For nearly all of the elements studied here there are small groups of conspicuously anomalous stars which depart from the more general behaviour of the majority HgMn class members, and moreover which differ in identity from element to element. This diversity in abundances appears to be a genuine characteristic of HgMn stars rather than an artifact of the analysis, and tends to confirm previous suggestions that the HgMn stars represent a chemically heterogeneous group.

The manganese abundances in the HgMn stars delineate a remarkably clear upper-envelope which is in qualitative agreement with the detailed diffusion calculations of Alecian & Michaud (1981). Schematic corrections for the effects of atmospheric chemical stratification on our analysis bring the observed and predicted manganese abundance envelopes into excellent quantitative agreement. No detailed atmospheric diffusion calculations have been published for the other iron-peak elements analysed here, although Michaud's (1970) early work has shown that the radiative force transferred to chromium and iron due to photoionisation is approximately equal to gravitational acceleration whereas for nickel it is significantly less; this is again in good qualitative agreement with our results. The gross deficiency of cobalt remains to be explained by diffusion theory. New and improved diffusion calculations are required to explore further the questions posed in the introduction to this paper.

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