Peculiar Versus Normal Phenomena in A-Type and Related Stars
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ABUNDANCE CORRELATIONS IN MERCURY-MANGANESE STARS

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ABSTRACT Elemental abundances from recent spectrum-synthesis analyses of the ultraviolet spectra of normal and HgMn-type late-B stars are examined for inter-correlations and for correlations with stellar parameters by use of standard statistical techniques. A few marginally significant correlations are apparent in the normal-star sample. In the HgMn sample, significant correlations with $T_{\rm eff}$ are identified for Mn, Cu, and Ga. Strong inter-correlations are also identified in this sample for the abundances of two triads of elements (Mg-Al-Cr and Mn-Cu-Ga). Trivariate correlation analysis is used to demonstrate that these element-element inter-correlations are statistically *independent* of both $T_{\rm eff}$ and $\log g$. The correlated behaviour of these characteristically anomalous elements casts new light on the apparent heterogeneity of the HgMn class of peculiar stars, and may have important implications for the diffusion model which has been advocated as an explanation of the HgMn phenomenon.

INTRODUCTION

In this paper, the principal results from a statistical analysis of elemental abundances in 14 normal and 26 HgMn and related late-B stars are reported. The abundance dataset used here originates from recent detailed spectrum-synthesis analyses of ultraviolet (*IUE*) spectra; it benefits from a high degree of internal consistency and provides a view of many interesting, but optically unobservable elements (Smith & Dworetsky 1990*a*, *b*; Smith 1992*a*, *b*). A total of sixteen elements is investigated for inter-correlations and for correlations with stellar parameters by making use of standard bivariate and (in some cases) trivariate techniques.

ANALYSIS

The degree of association between variables in the abundance dataset is measured here by using Pearson's *linear* correlation coefficient, r_P, and Spearman's *rank-order* correlation coefficient, r_S (see, *e.g.*, Press *et al.* 1986). In certain instances it will also be of interest to examine the relationship between two vari-

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ables with the influence of one or more other variables removed, in which case a *partial* correlation coefficient is employed (see, *e.g.*, Fisher 1970). For all correlation coefficients, the two-sided *significances* are determined by using the method described by Press *et al.* (1986).

Linear and rank-order correlation coefficients were computed for all combinations of interest in stellar parameters and elemental abundances using data from Smith (1992*b*). Normal and HgMn stars were considered in two separate samples. Upper limits on abundances were treated as detections since there are, apparently, no statistically rigorous techniques yet developed for the treatment of *truncated* probability distributions typified by the censored data points in the correlation diagrams under study here (*cf.* Howarth & Prinja 1989).

RESULTS

Some selected results from the bivariate correlation analysis on the normal and HgMn samples are presented in table I. For each variable, the correlation coefficients are given with r_P above r_S. With a few exceptions, only those variables for which the significances of *both* the linear and rank-order coefficients are better than 1 % are discussed further here.

Effective Temperature

In the normal-star sample, the only significant correlation in evidence between abundance and $T_{\rm eff}$ appears to be for N, although it seems likely that this is a manifestation of some form of systematic error in the analysis of the ultraviolet N I lines (Smith & Dworetsky 1990*a*; Smith 1992*b*).

In the HgMn sample, Mn and Pt are strongly correlated with $T_{\rm eff}$, and Al and Cr moderately so. These results belie the fact that the Cu and Ga abundances also show striking dependences on $T_{\rm eff}$ (Smith 1992*b*), the formal correlation significances of which are diminished by the presence of a small subgroup of 'anomalous' HgMn stars in both cases (*cf.* comments by Cowley 1980).

The significant correlation between Pt abundance and $T_{\rm eff}$ is interesting since it confirms the view that the Pt-anomaly is confined to cool HgMn stars (Dworetsky & Vaughan 1973). However, since the adopted sample of Pt abundances is heavily censored, it would not be appropriate to place too much faith in the precise *value* of correlation coefficient obtained here.

Surface Gravity

The abundances of all elements heavier than carbon appear to be marginally anti-correlated with $\log g$ for the normal stars, although there are only three highly significant anti-correlations (Co, Zn, and Ga), and a handful of marginally significant ones (Cr, Ni, and Cu) in this sample. In contrast, there appear to be no significant correlations with $\log g$ in evidence amongst the HgMn stars.

The absence of significant correlations between abundance and surface gravity amongst the HgMn sample is worthy of comment inasmuch as $\log g$ is effectively a parametric measure of stellar age. While it might be tempting to infer that this is indicative of a lack of time-dependence in the HgMn phenomenon, it should be noted that $\log g$ does not change measurably until late in the main-sequence lifetime of late-B stars (Maeder & Meynet 1988) whereas abundance anomalies characteristic of HgMn stars develop within $\sim 10^7$ years (Abt 1979).

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Rotation
There are no statistically significant correlations between abundance and projected equatorial rotational velocity for either the normal or HgMn samples. Since the inclination factor ($\sin i$) may obscure rotation-velocity dependences in the abundance data, a visual search was conducted for correlated envelopes in abundance *versus* $v \sin i$ diagrams, although none were unambiguously identified. Therefore, while stellar rotation may be an inhibitory factor in the development of chemical anomalies in HgMn stars above a threshold of $\sim 100\,\mathrm{km\,s^{-1}}$ (Wolff & Wolff 1974; Wolff & Preston 1978), in stars below that threshold, such as those investigated here, it does not appear to influence the *magnitude* of resultant abundance anomalies significantly. This conclusion is consistent with the predictions of Michaud's (1981) parameter-free diffusion model in which HgMn abundance anomalies are expected to develop independently of $v \sin i$ below $90\,\mathrm{km\,s^{-1}}$.

Abundances
The first aspect of the abundance inter-correlations amongst the normal stars worthy of note is that there is a predominance of positive correlation coefficients (whether statistically significant or not) for elements heavier than carbon. In contrast, Be, B, and C appear to anti-correlate with heavier elements. The positive correlations amongst the heavier elements might be interpreted as a 'metallicity' effect; that is, the principal component of variation amongst these stars is their global metallicity.

There is only one highly significant inter-correlation between abundances in the normal-star sample (Co-Zn) and two marginally significant ones (N-Ni and Cr-Ni) which, according to visual inspection, deserve comment. Since N (and to a lesser degree Ni) is correlated with $T_{\rm eff}$, and Cr, Co, Ni, and Zn are all anti-correlated with $\log g$, partial correlation coefficients at constant $T_{\rm eff}$ and constant $\log g$ were computed for these elements (see table II). These calculations show that when the contribution of $T_{\rm eff}$ and $\log g$ dependences are removed from observed abundance-abundance correlations, the resultant partial correlations are *not* statistically significant. Thus the N-Ni and Co-Zn correlations simply reflect strong underlying relationships with the stellar parameters $T_{\rm eff}$ and $\log g$ respectively.

The metallicity effect seen in the normal-star correlation coefficients is not present in the HgMn sample. There are, however, many significant inter-correlations amongst the abundances in this sample. Particularly interesting are those seen in the triads Mg-Al-Cr and Mn-Cu-Ga; these are illustrated in figure 1.

At first inspection, the inter-correlations amongst the Mn-Cu-Ga triad might be thought to reflect the underlying dependence of each of these elements on effective temperature. On the other hand, the inter-correlations in the Mg-Al-Cr triad do not appear to originate from any obvious mutual dependence on atmospheric parameters. These hypotheses were tested by computing partial correlation coefficients at constant $T_{\rm eff}$ and constant $\log g$ for these two triads of abundances (see table II). The results show that with the exceptions of Al-Cr and Cu-Ga, there are strong correlations between the derived abundances *independent* of mutual variation in $T_{\rm eff}$. This result suggests—although it does not demonstrate conclusively—that the mechanisms responsible for the Mg, Al, and Cr abundance variations in these stars share a common identity. Similarly, the same is indicated for the abundance variations in Mn, Cu, and Ga.

TABLE I Correlation coefficients for selected elements

Correlations with T_{eff} (HgMn stars)				Correlations with $\log g$ (Normal stars)			
Element	Sample	r	$p(\%)$	Element	Sample	r	$p(\%)$
Al	25	−0.49	1.2	Cr	14	−0.53	5.0
		−0.50	1.0			−0.71	0.5
Cr	24	−0.51	1.2	Co*	14	−0.81	< 0.1
		−0.54	0.6			...	...
Mn	26	+0.50	0.8	Ni	14	−0.62	1.9
		+0.52	0.7			−0.76	0.1
Cu	26	+0.28	16.1	Cu	14	−0.62	1.7
		+0.31	12.7			−0.64	1.3
Ga	26	+0.32	10.7	Zn	14	−0.80	0.1
		+0.36	7.6			−0.85	< 0.1
Pt	26	−0.53	0.5	Ga	14	−0.73	0.3
		−0.61	0.1			−0.97	< 0.1

TABLE II Partial correlation coefficients for selected elements

Elements	Sample size	Bivariate correlation		Partial correlation at constant ... T_{eff}		$\log g$	
		r	p (%)	r	p (%)	r	p (%)
				Normal Sample			
Co - Zn*	14	+0.81	< 0.1	+0.81	< 0.1	+0.46	11.2
		+0.69	0.7	+0.69	0.7	...	...
N - Ni	14	+0.65	1.2	+0.40	17.1	+0.55	5.3
		+0.59	2.6	+0.17	57.2	+0.48	9.7
Cr - Ni	14	+0.74	0.3	+0.68	1.0	+0.62	2.4
		+0.56	3.8	+0.41	16.7	+0.04	88.5
				HgMn Sample			
Mg - Al	25	+0.61	0.1	+0.56	0.4	+0.60	0.2
		+0.61	0.1	+0.55	0.5	+0.60	0.2
Mg - Cr	24	+0.76	< 0.1	+0.75	< 0.1	+0.76	< 0.1
		+0.77	< 0.1	+0.75	< 0.1	+0.77	< 0.1
Al - Cr	23	+0.60	0.3	+0.46	3.0	+0.58	0.5
		+0.54	0.8	+0.37	9.0	+0.52	1.3
Mn - Cu	26	+0.69	< 0.1	+0.66	< 0.1	+0.77	< 0.1
		+0.68	< 0.1	+0.64	0.1	+0.78	< 0.1
Mn - Ga	26	+0.66	< 0.1	+0.61	0.1	+0.66	< 0.1
		+0.69	< 0.1	+0.63	0.1	+0.69	< 0.1
Cu - Ga	26	+0.28	18.2	+0.20	33.4	+0.41	4.2
		+0.39	5.7	+0.31	13.1	+0.50	1.2

NOTES: r and p are the correlation coefficient and correlation significance respectively (the Pearson coefficients are given above the Spearman).

*The Spearman correlation coefficient is indeterminate.

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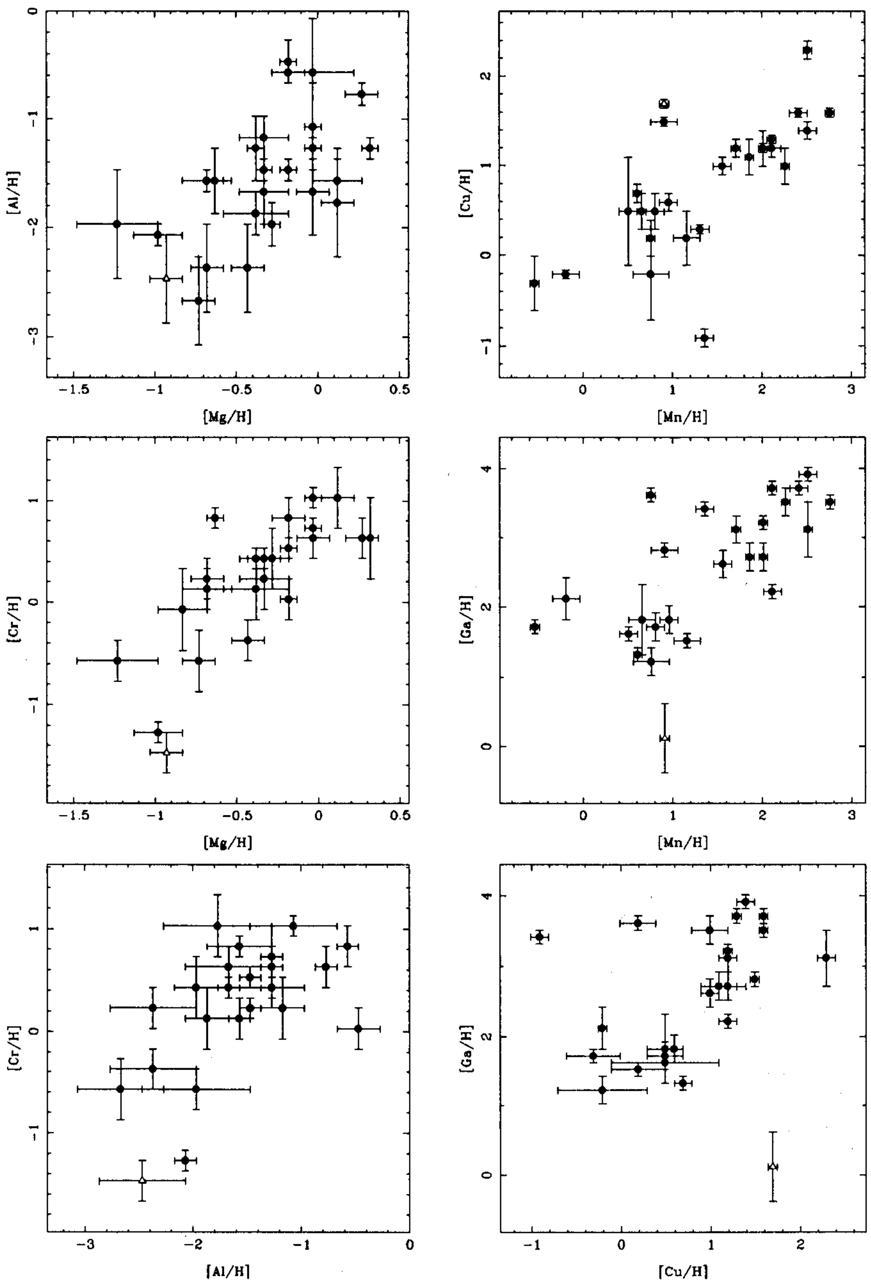

Fig. 1. Abundance-abundance correlation diagrams for HgMn stars showing the trivariate systems of Mg-Al-Cr on the left, and Mn-Cu-Ga on the right. Abundances are on a logarithmic scale with respect to solar values (Anders & Grevesse 1989). The open triangle represents the mild HgMn star 46 Aql.

CONCLUSIONS

The results of the bivariate analysis presented here confirm the extraordinary chemical heterogeneity previously regarded as characteristic of the HgMn class of peculiar stars (*e.g.*, Preston 1974). There are, nonetheless, indications that for some elements a common mechanism is responsible for this diversity of behaviour. The inter-correlations between the abundances in the element triads Mg-Al-Cr and Cu-Mn-Ga in particular are evidence of systematics in the abundance anomalies. That the inter-correlations are statistically significant *independently* of $T_{\rm eff}$ and $\log g$ in these two triads is particularly interesting. In the case of Cu-Mn-Ga, this suggests that the common mechanism is consistent in dictating which stars depart from the overall correlations of these elements with $T_{\rm eff}$. In the case of Mg-Al-Cr, the large star-to-star diversity in abundances hides what is otherwise a profound element-to-element consistency. The correlated behaviour of these elements in the atmospheres of HgMn stars affords a new, qualitative test of theories advanced in explanation of their chemistry.

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