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BERYLLIUM ABUNDANCES IN Hg-Mn STARS

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ABSTRACT

The Hg-Mn stars show anomalous line strengths of many chemical elements including Be. We have observed the Be II resonance doublet at λλ 3130, 3131 at 6.7 Å mm^{-1} in 43 Hg-Mn stars and 10 normal stars in the same temperature range with the coudé spectrograph of the 2.24 m University of Hawaii telescope at Mauna Kea. Measured equivalent widths of the two lines and/or the blend of the doublet have been compared with predictions from (1) LTE model atmospheres and (2) non-LTE line formation in non-LTE model atmospheres. (For strong Be II lines, the LTE calculations result in more Be by factors of 2 to 4 than do the non-LTE calculations.) Overabundances of factors of $20-2\times10^4$ relative to solar have been found for 75% of the Hg-Mn stars. The 25% with little or no Be are typically among the cooler Hg-Mn stars, but for the stars with Be excesses, there is only marginal evidence for a correlation of the size of the overabundance and temperature. It is suggested that diffusion driven by radiation pressure is responsible for the observed Be abundance anomalies.

Subject headings: stars: abundances — stars: peculiar A

I. INTRODUCTION

The intrinsically slowly rotating stars ($v \sin i \lesssim 100$) in the temperature range $T_e = 11{,}000–16{,}000$ K (late B stars) called Hg-Mn stars show anomalous line strengths of many chemical elements. In addition to Hg and Mn, they are characterized by large overabundances of Be, Ga, Xe, and Pt (e.g., Heacox 1979).

The resonance lines of Be II at λλ3130, 3131 were reported to be very strong in four of 10 Hg-Mn stars observed by Sargent and Jugaku (1962). They estimated that Be/H was about 100 times the solar value in κ Cnc, 112 Her, μ Lep, and υ Her. Boesgaard and Heacox (1973) derived a Be/H of 2.5×10^{-9} or 180 times solar for κ Cnc. Seventy percent of a sample of 32 Hg-Mn stars and 100% of the hottest of those stars were found to have enhanced Be II lines by Heacox, Wolff, and Boesgaard (1976). They noted that the large variation in the strength of the Be II lines was not correlated with either effective temperature or projected rotational velocity and concluded that "slow rotation is neither sufficient nor necessary to induce a relatively large beryllium abundance."

Heacox (1979) observed 21 Hg-Mn and six normal stars and determined LTE abundances for 21 elements including Be. These LTE abundances correspond to upper limits of <6 up to values of 1.8×10^4 times solar.[1] Heacox found that only in those stars where Mn is very overabundant is Be overabundant and that, further, only when Be is overabundant does the Xe II λ4603 line appear. He found that the Be II lines were often formed above optical depths of $\tau_c \sim 10^{-2}$, and while recommending that non-LTE analyses should be made, he suggested that the large overabundances would probably not be eliminated even then.

Recently *IUE* observations of the Be II lines in 10 early-type peculiar stars, including five Hg-Mn stars, have been made by Sadakane and Jugaku (1981). They find strong lines in all five, including HR 4072, a star not in Heacox's (1979) or Sargent and Jugaku's (1962) samples.

In this paper we discuss observations and analyses of Be abundances in 43 Hg-Mn stars and 10 normal stars. Abundances have been determined in both LTE and non-LTE conditions.

II. OBSERVATIONS

Spectrograms at 6.7 Å mm^{-1} have been obtained for a total of 53 stars with the coudé spectrograph of the 2.2 m telescope at Mauna Kea Observatory. The spectra cover the range from 3100–4000 Å with good exposure density at the Be II resonance doublet λλ3130, 3131. The plates (IIa-O emulsion baked in air) were calibrated

[1]The solar value is taken to be Be/H$=1.4\times10^{-11}$ from Chmielewski, Müller, and Brault (1975) and is equivalent to the mean of 1.31×10^{-11} for 27 F and G stars from Boesgaard (1976).

TABLE 1

STARS OBSERVED AND RESULTS

HR	Name	W(3130) (mÅ)	W(3131) (mÅ)	$T(10^3$ K)	Log g (cgs)	v sin i (km s^{-1})	Log Be/H+12 (LTE)	Log Be/H+12 (NLTE)
				Hg-Mn Stars				
15	α And	62	49	13.8	4.0	53	3.1	3.0
149	...	121	92	12.0	3.5	28	4.1	3.5
364	87 Psc	≤140	≤90	13.0	4.0	25	<4.4	<4.0
746	...	152	126	12.6	4.1	30	4.9	4.4
1079	6 Tau	≤35	≤20	12.0	4.1	90	<2.4	<2.4
1149	20 Tau	40	20	13.3	3.5	35	2.5	2.5
1194	...	131	92	14.6	4.6	30	4.4	3.9
1339	53 Tau	≤7	≤7	11.9	4.2	<6	<1.6	<1.5
1402	...	143	100	13.9	4.4	70	4.6	4.0
1445	...	130	≤90	12.9	4.0	76	4.3	3.7
1484	93 Tau	91	61	14.5	4.4	50	3.5	3.3
1576	...	214	...	13.8	4.4	90	5.7	...
1702	μ Lep	113	90	12.7	3.8	20	4.1	3.6
1728	AR Aur	31	19	10.9	4.4	40	2.1_5	1.9
1791	β Tau	——211——		13.6	3.8	80	4.2	3.7
2130	64 Ori	53	34	13.1	4.0	5	2.8	2.7_5
2519	33 Gem	185	152	14.2	4.2	35	5.3	5.0
2605	40 Gem	158	104	13.9	4.1	50	4.7_5	4.3
2657	γ CMa	143	104	14.1	4.	...	4.5	4.1
2676	...	≤27	≤12	13.8	3.9	25	<2.3	<2.1
2844	...	≤50	≤15	12.4	3.8	35	<2.5	<2.4
3059	ζ CMi	89	41	13.5	3.5	30	3.2_5	3.1
3201	...	≤48	≤30	12.9	3.9	70	<2.7	<2.6
3623	χ Cnc	156	117	13.5	4.0	6	4.9	4.2
5475	π^1 Boo	≤24	≤22	13.0	3.2	16	<2.3	<2.3
5971	ι CrB	108	72	11.0	4.1	3	3.6	3.1
5982	υ Her	115	89	12.0	3.9	11	4.0	3.5
6023	φ Her	≤30	≤7	11.6	4.0	12	<2.1	<1.9
6158	28 Her	170	174	11.0	3.9	5	5.1	4.7_5
6532	...	≤12	≤14	11.1	4.2	15	<1.8	<1.6
6690	...	≤49	≤53	11.9	3.8	80	<2.9	$<2.6_5$
6997	...	120	≤100	14.4	3.8	40	4.4	3.8
7245	...	110	85	12.3	3.8	5	3.9	3.5
7361	...	128	88	13.5	3.8	<5	4.3	3.7_5
7493	46 Aql	37	21	12.9	3.7	5	2.5	2.4_5
7664	...	83	67	13.1	3.8	10	3.4	3.3
8404	21 Peg	≤41	≤22	10.5	3.5	5	<2.3	<1.8
8535	...	——238——		15.3	4.0	50	4.7	4.1
8723	...	——392——		13.0	3.8	70	5.6_5	5.4
8753	...	173	106	12.8	4.4	35	4.9	4.5
8902	...	208	187	12.2	3.7	35	5.6	5.4
8915	69 Peg	179	191	10.8	3.8	25	5.3	4.8_5
8937	β Scl	137	85	12.5	4.2	22	4.3	3.6
				Normal Stars				
154	π And	≤14	≤14	15.0	4.1	35	<2.1	<2.2
811	π Cet	≤30	≤20	13.1	3.9	12	<2.4	<2.4
2223	72 Ori	≤22	≤15	13.4	4.3	70	<2.2	<2.2
5291	α Dra	≤24	≤24	10.0	3.7	12	<2.0	<1.7
6092	τ Her	≤10	≤10	15.0	3.6	27	$<1.9_5$	<2.0
6396	ζ Dra	≤12	≤12	13.0	3.5	28	$<1.9_5$	<1.9
7001	α Lyr	≤7	≤7	9.7	4.0	15	<1.3	<1.0
7115	...	≤15	≤15	14.3	4.0	60	<2.1	<2.1
7338	...	≤39	≤30	10.2	4.0	5	<2.3	<1.9
7773	ν Cap	≤80	≤58	10.2	4.0	15	<2.9	<2.5

by means of a xenon lamp and an internal calibrator of 14 strips of known intensity. All spectrograms were traced on a Boller and Chivers microphotometer and equivalent widths of the two Be lines were measured. The Hg-Mn stars were chosen from the lists of Wolff and Wolff (1974) and Wolff and Preston (1978), plus four others selected because visual inspection by S. C. Wolff or G. W. Preston (1974, private communication) suggests probable membership in the Hg-Mn category. (One of the latter, 21 Peg, is called normal by Cowley 1980.) The list of stars and measured equivalent widths are given in Table 1. Figure 1 shows some examples of the Be II region in these stars.

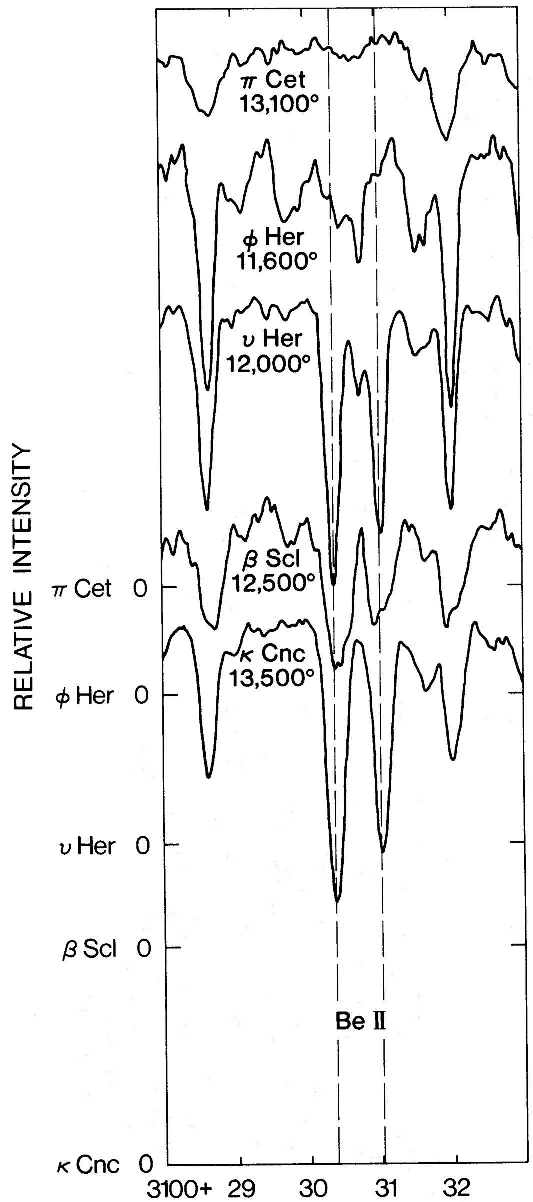

FIG. 1.—Examples of intensity tracings in the Be II region of one normal star (π Cet) and four Hg-Mn stars, three with strong Be lines and one (φ Her) with little or no Be.

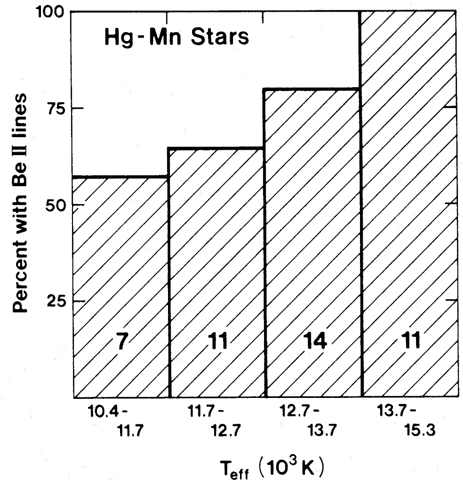

FIG. 2.—The frequency of occurrence of Hg-Mn stars with strong Be II lines as a function of temperature. The number within the shaded area is the total number of Hg-Mn stars observed in that temperature interval. Those intervals were chosen to be approximately equal in range of temperature and to contain roughly the same number of stars.

Stellar effective temperatures were determined by comparing the intrinsic Strömgren c_1 and m_1 indices as tabulated by Philip, Miller, and Relyea (1976) to the computed indices of Relyea and Kurucz (1978). These temperatures are also given in Table 1. For the coolest stars, strong Be II lines are seen in 57% of the stars and are undetectable in the other 43%. The percentage with strong Be II lines increases with temperature until 100% of the hottest stars in the sample show strong Be II lines. Figure 2 shows a histogram of the percentage of stars with Be as a function of temperature.

Surface gravities were found from Balmer line profiles where available (see Heacox 1979), but we note (below) that the abundances are very insensitive to the value of $\log g$, and that the non-LTE abundance calculations were done only for $\log g = 4.0$.

III. ABUNDANCES

a) LTE Abundances

The line-blanketed model atmospheres of Kurucz, Peytremann, and Avrett (KPA) (1974) were used to determine the LTE abundances. A microturbulence of 0 km s^{-1} was used in the calculations. (There is little compelling evidence for microturbulence in these stars; see discussion by Heacox 1979.) We note, however, that due to the great strength of the Be II lines in many of these stars, the lines are saturated and fall on the flat or damping portion of the curve of growth. This fact by itself makes the inferred LTE abundances less reliable than those for weak lines on the linear part of the curve of growth. In addition to thermal broadening, by far the dominant effect, the LTE calculations included radiation, van der Waals and Stark broadening. The electron impact theory of Griem (1974) was used to calculate Stark parameters. The *gf*-values for this resonance doublet, 0.67 and 0.34, are from Wiese, Smith, and Glennon (1966). The abundance results are listed in Table 1, but with more reservations than usual for LTE abundances. As shown by Heacox (1977) these results for Be are not very sensitive to errors in either $T_{\rm eff}$ or log *g*. An increase of 350 K in $T_{\rm eff}$ will increase the Be abundance by less than 15%, and an increase of 0.2 dex in log *g* could increase the abundance by 10%–20%. If there is microturbulence of as much as 3 km s^{-1}, Heacox's (1977) work shows that the LTE abundances should be smaller by a factor of about 2 for $\log \mathrm{Be/H} + 12 \gtrsim 4.0$.

b) *Non-LTE Beryllium Abundances*

Non-LTE statistical equilibrium equations, together with transfer equations, have been solved for Be II and for three non-LTE radiative equilibrium, model atmospheres, with $T_{\rm eff} = 10{,}000$, 12,500, and 15,000 K, and $g = 10^4$ cgs (Borsenberger and Gros 1978). The method followed is described in Borsenberger, Michaud, and Praderie (1979, 1981). A homogeneous distribution of Be in the atmosphere is assumed.

The atomic model for Be II includes the six lower levels and the continuum; all lines connecting the six levels are included in the computations. More details on the atomic data will be given elsewhere (Borsenberger, Michaud, and Praderie 1982). The microturbulence parameter is taken equal to 0 km s^{-1}.

The ionization equilibrium of Be in these atmospheres favors Be^+ over a large range of optical depths. Thus, Be^+ is very similar to B^+, but opposite to Ca^+ and Sr^+, which are mainly twice ionized in the same atmospheres (Borsenberger, Michaud, and Praderie 1979, 1981).

The run of the departure coefficient b_1 at solar abundance $\mathrm{Be/H} = 1.4 \times 10^{-11}$ shows a minimum around $\tau_{5000} = 10^{-2}$. There, it reaches values as small as 0.1. Going outward in the atmosphere, b_1 rises steeply due to the depopulation of the higher levels by de-excitation toward the ground as the lines become optically thin. This overpopulation of the ground level reaches a maximum around $\tau_{5000} = 3 \times 10^{-6}$, then b_1 decreases slowly outward. The same trend exists for larger abundances, but the maximum value of b_1 depends on Be/H: for example, at $T_{\rm eff} = 12{,}500$ K, b_1 is 3 at maximum for a solar abundance, but is as high as 34 for Be/H equal to 10^5 the solar value. At solar abundance, the population of the Be^+ ground level is close to what it would be in LTE because of the dominance of the first ionization stage over all others. If the departure coefficients differ from 1, it is due to the difference between the LTE and the non-LTE Be^{++} ground level population, because of

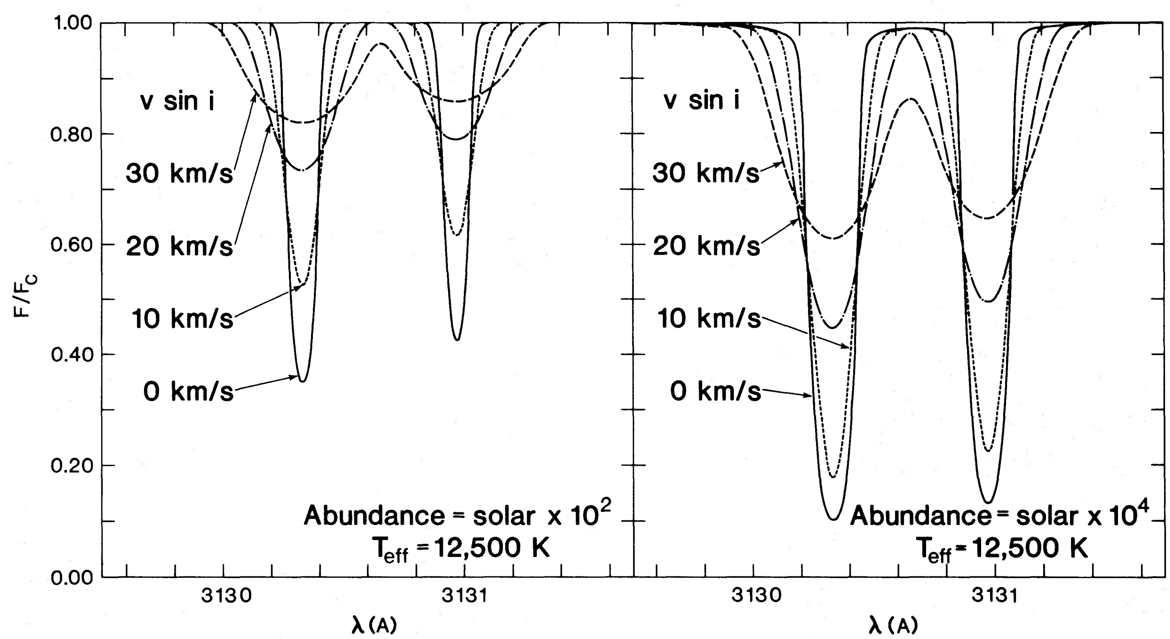

FIG. 3.—Line profiles of the Be II lines calculated in non-LTE at $T = 12{,}500$ K and $\log g = 4.0$ for abundances of 10^2 and 10^4 times the solar abundance. The effect of rotation at 10, 20, and 30 km s^{-1} on the profile shape is shown.

the sensitivity of the latter to the excitation and deexcitation processes in Be^+.

The consequence of this behavior is that, around the solar abundance, the abundance determination does not suffer too much from being derived in LTE, since the resonance lines are formed in deep layers where the Be^+ ground level population is close to its LTE value. This situation prevails up to Be/H equal to 100 times the solar abundance. For larger overabundances, the resonance lines are formed higher in the atmosphere where b_1 is significantly larger than 1. Hence an LTE analysis will lead to an overestimate of Be abundance.

There is a second factor that contributes to the differences in abundance inferred from LTE and non-LTE model atmosphere analyses. The temperatures in the outer layers of the atmosphere where the Be lines are formed are lower in the KPA line-blanketed LTE model atmospheres than in the non-LTE models since the latter are not blanketed. This difference in temperature means that a lower Be abundance would be derived from the non-LTE model atmosphere even if non-LTE effects in the line formation process were neglected.

Figure 3 shows line profiles for the Be II blend calculated in non-LTE for $T = 12{,}500$ K and $\log g = 4.0$ for Be overabundances of 10^2 and 10^4 times the solar values. The effect on the profile shape due to stellar rotation of $v \sin i$ of 10, 20, and 30 km s^{-1} is also shown.

c) *Results*

Calculations with the same microturbulence (0 km s^{-1}) have been carried out in LTE and non-LTE for the Be II resonance doublet. Figure 4 shows the resulting curves of growth for Be for two models with effective temperatures 10,000 and 15,000 K. The effects of departures from LTE are more apparent for low temperatures and high Be abundances. In these cases the assumption of LTE can result in overestimation of the Be abundance by factors of 2 to 4. This effect is especially important in the Hg-Mn stars which have very strong Be II lines.

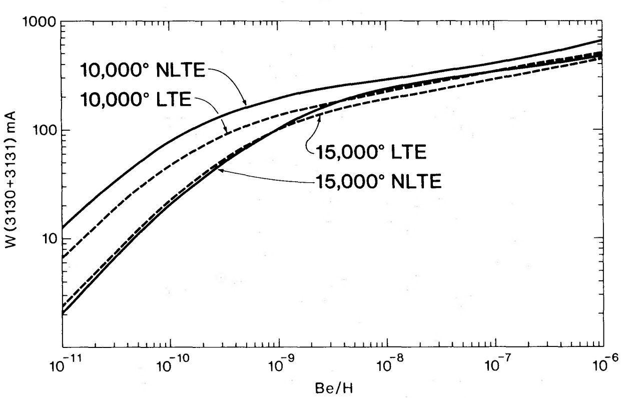

FIG. 4.—Curves of growth for the total Be II blend for 10,000 K and 15,000 K and $\log g = 4.0$ in LTE and non-LTE. The solid lines are for non-LTE, the dashed for LTE; the curves for 15,000 K fall below those for 10,000 K. The calculations for all cases assumed a microturbulence of 0 km s^{-1}. The effects of non-LTE are more noticeable at the lower temperatures and for large abundances.

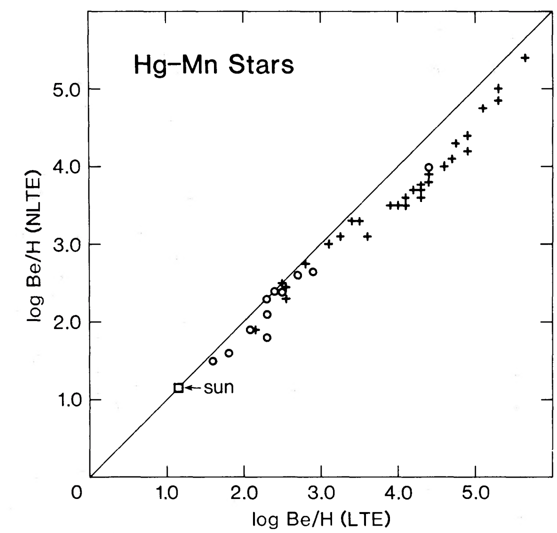

FIG. 5.—Logarithmic Be/H abundances for the Hg-Mn stars as calculated in both LTE and non-LTE. The open circles represent upper limits; the open square is the Sun. The straight line corresponds to equality between the LTE and non-LTE results. At large overabundances ($\gtrsim 200$ times solar) the LTE results are 2 to 4 times greater than those including the effects of departures from LTE.

The values for Be/H abundances determined through both LTE and non-LTE calculations for the Hg-Mn and normal stars are given in the last two columns of Table 1. Figure 5 shows the abundance results for LTE and non-LTE calculations for the 43 Hg-Mn stars we observed. In all cases the non-LTE abundances are less than or equal to the LTE abundances, and for Be/H greater than ~ 200 times the solar value they are less by factors of 2 to 4.

IV. DISCUSSION AND CONCLUSIONS

We find that the trace element Be is overabundant relative to the value in the sun and normal stars by factors of $20–2 \times 10^4$ in 75% of the Hg-Mn stars observed. Diffusion driven by radiation pressure, as first proposed by Michaud (1970), can account for some of the abundance anomalies in Hg-Mn stars (e.g., see Heacox 1979). Both the calculations of Mn diffusion of Alecian and Michaud (1981) and the observed Mn abundances of Heacox (1979) show that Mn is increasingly overabundant with increasing temperature. According to Heacox, Be is overabundant in those stars where Mn is especially overabundant. Our results shown in Figure 2 (the frequency of finding Be II lines at different temperatures) are consistent with the preceding

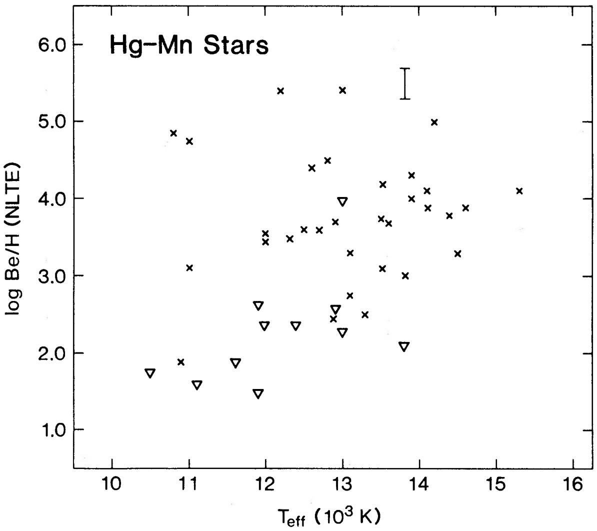

FIG. 6

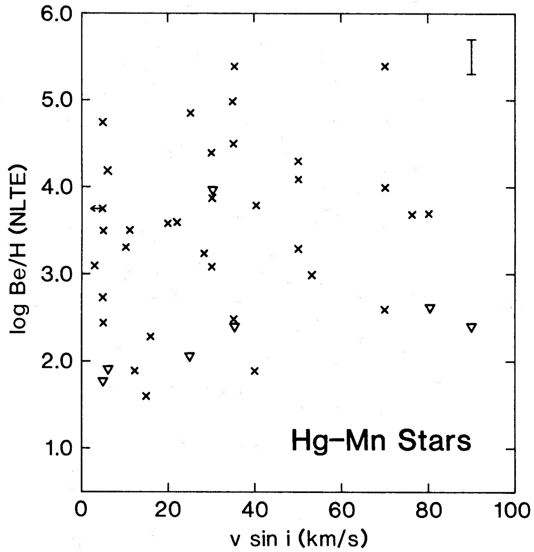

FIG. 7

FIG. 6.—Logarithmic abundances of Be/H for the Hg-Mn stars calculated in non-LTE as a function of stellar effective temperature. The open triangles represent upper limit abundances. The line at $T = 13{,}800$ K is HR 1576 for which we plot the LTE abundance from $\lambda 3130$ only as the upper horizontal bar and that abundance reduced by a factor of 2.5 as the lower horizontal bar to represent the probable non-LTE abundance. A weak temperature dependence may be present and most noticeable by the lack of points in the lower right.

FIG. 7.—The distribution of abundances of Be/H determined in non-LTE with projected rotational velocity. The symbols are the same as in Fig. 6. The degree of overabundance of Be is unrelated to $v \sin i$, implying that factors other than rotation dominate in producing abundance anomalies.

two statements: those stars with no detectable Be lines are almost all in the cooler half of the temperature range. In Figure 6 we show the non-LTE Be/H abundances plotted against effective temperature for the Hg-Mn stars. A marginal dependence of Be on temperature may be present: there is an absence of points in the lower right and an indication that Be overabundances are more likely in the hotter Hg-Mn stars.

Recently Borsenberger *et al.* (1981) have calculated the radiative acceleration on Be in model atmospheres representative of Hg-Mn stars. For a 12,500 K star, they find that Be is bound to the star due to its ionization to a rare gas, Be^{++}, and that an equilibrium accumulation of Be^{+} ions is possible up to about 10^5 times the solar abundance for optical depths τ_{5000} larger than 10^{-4}. However, if the initial abundance were solar, the available Be reservoir is insufficient to produce an overabundance of 10^5 and they suggest that the layers above $\tau_{5000} \sim 10^{-2}$ could be mixed by turbulence in the outer layers and the apparent abundance of Be increased by these large factors even with the available reservoir. Those calculations are quite consistent with the observed Be overabundances and are suggestive that diffusion is the mechanism responsible for the overabundances. (However, both the abundance calculations and the calculations of the radiative forces assume that Be is homogeneously distributed throughout the atmosphere; this is surely no longer the case once diffusion begins to operate.)

The stars observed cover a range of projected rotational velocities, $v \sin i$. Rotation, through the effects of meridional circulation, might be expected to reduce the effects of diffusion and result in a decreasing upper envelope in Figure 7 of Be abundance versus $v \sin i$. Such a trend is not discernible in Figure 7. While slow rotation is a necessary condition for a star to be a Hg-Mn star, within the Hg-Mn star group, factors other than rotation, such as turbulence, must control the degree of element overabundance.

We can summarize as follows: most Hg-Mn stars show the Be II resonance lines to be very enhanced. Those without Be II lines are preferentially the coolest stars in the sample. Abundances calculated in LTE and non-LTE result in large overabundances of Be (20–2×10^4) relative to normal stars, and those determined in LTE are only factors of 2 to 4 times larger than those in non-LTE for the highest overabundances. Calculations of the upward radiative forces on Be^{+} ions indicate that diffusion in stable stellar atmospheres could result in Be overabundances (Borsenberger *et al.* 1981). The weak trend of overabundance with temperature could be compatible with diffusion also. Thus it appears plausible that diffusion is responsible for the large overabundances of Be in 32 of our 43 Hg-Mn stars.

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REFERENCES

Alecian, G., and Michaud, G. 1981, *Ap. J.*, **245**, 226.
Boesgaard, A. M. 1976, *Ap. J.*, **210**, 466.
Boesgaard, A. M., and Heacox, W. D. 1973, *Ap. J.* (*Letters*), **185**, L27.
Borsenberger, J., and Gros, M. 1978, *Astr. Ap. Suppl.*, **31**, 291.
Borsenberger, J., Michaud, G., and Praderie, F. 1979, *Astr. Ap.*, **76**, 287.
______. 1981, *Ap. J.*, **243**, 533.
______. 1982, in preparation.
Borsenberger, J., Radiman, I., Michaud, G., and Praderie, F. 1981, *Liège Colloquium*, p. 389.
Chmielewski, Y., Müller, E., and Brault, J. W. 1975, *Astr. Ap.*, **42**, 37.
Cowley, C. R. 1980, *Pub. A.S.P.*, **92**, 159.
Griem, H. R. 1974, *Spectral Line Broadening by Plasmas* (New York: Academic Press).
Heacox, W. D. 1977, Ph.D. thesis, University of Hawaii.
Heacox, W. D. 1979, *Ap. J. Suppl.*, **41**, 675.
Heacox, W. D., Wolff, S. C., and Boesgaard, A. M. 1976, *Pub. A.S.P.*, **88**, 607.
Kurucz, R. L., Peytremann, E., and Avrett, E. H. 1974, *Blanketed Model Atmospheres for Early-Type Stars* (Washington: Smithsonian Institution) (KPA).
Michaud, G., 1970, *Ap. J.*, **160**, 641.
Philip, A. G. D., Miller, T. M., and Relyea, L. 1976, *Dudley Obs. Rept.*, **12**.
Relyea, L. J., and Kurucz, R. L. 1978, *Ap. J. Suppl.*, **37**, 45.
Sadakane, K., and Jugaku, J. 1981, *Pub. A.S.P.*, in press.
Sargent, W. L. W., and Jugaku, J. 1962, *Pub. A.S.P.*, **74**, 408.
Wiese, W. L., Smith, W. M., and Glennon, B. M. 1966, *Atomic Transition Probabilities, NSRDS-NBS 4* (Washington, D.C.: U.S. Government Printing Office).
Wolff, S. C., and Preston, G. W. 1978, *Ap. J. Suppl.*, **37**, 371.
Wolff, S. C., and Wolff, R. J. 1974, *Ap. J.*, **194**, 65.

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