A&A 367, 597–604 (2001)
DOI: 10.1051/0004-6361:20010007
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Astronomy & Astrophysics

Elemental abundance analyses with DAO spectrograms*

XXIV. The Mercury Manganese stars υ Her, ϕ Her, and HR 7018

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Received 16 October 2000 / Accepted 29 November 2000

Abstract. Elemental abundances analyses are performed for the Mercury-Manganese stars υ Her, ϕ Her, and HR 7018 consistent with previous studies of this series using spectrograms obtained with Reticon and CCD detectors. Comparisons of the first two analyses with those performed using coadded photographic plates show the general consistency of the derived elemental abundances. For υ Her and for ϕ Her, abundances were newly found for O, and for Al, V, Zn, and Ce, respectively. HR 7018 is discovered to be a single-lined spectroscopic binary. Its Sc abundance is the smallest of any class member with derived abundances and its Sr abundance the largest of any known HgMn star. A correlation analysis of the most complete abundance sets for 20 HgMn stars shows that the abundances of some elements are correlated with one another and some are functions of the stellar effective temperature.

Key words. stars: abundances – stars: individual: υ Her – stars: individual: ϕ Her – stars: individual: HR 7018 – stars: chemically peculiar

1. Introduction

This paper presents elemental abundance analyses of three Mercury-Manganese stars. Those of υ Her and of ϕ Her with new and higher quality Reticon and CCD spectrograms are studies of relatively bright and sharp-lined stars previously analyzed with data taken with photographic plates. Comparison of these results can reveal discrepancies and thus can check the consistency of studies made a decade apart and thus that of all stars analyzed in this series. The other study that of HR 7018 uses similar materials and increases the number of stars which show moderate rotation.

The main sequence Mercury-Manganese (Hg-Mn) stars are peculiar B type stars with effective temperatures between 10 500 K and 15 000 K. They show a wide variety of abundance anomalies with both depletions (e.g., N, Roby et al. 1999) and enhancements (e.g., Hg, Leckrone et al. 1991). These are thought to be produced in an extremely hydrodynamically stable environment from the separation of elements by radiatively-driven diffusion and gravitational settling (Michaud 1970). Various investigators have suggested that these stars are important laboratories for the study of hydrodynamical effects. For example, exploratory calculations by Seaton (1996) using Opacity Project data suggest that their manganese rich atmospheres are a time variable surface result of radiatively-driven diffusion deep in the stellar envelope. With results from many stars one can look at the dependences on stellar parameters and make comparisons with theoretical predictions.

The HgMn stars υ Her (HD 144206, HR 5982) and ϕ Her (HD 145389, HR 6023) were analyzed by Adelman (1992, Paper X) and Adelman (1988, Paper V), respectively. υ Her is an example of an Fe and Ni-poor HgMn star. The later is a SB1 system as no lines of the companion have yet been detected. Thus the light ratio between the components is large and it is appropriate to treat ϕ Her as a single star.

Bidelman (1988) and Abt & Morrell (1995) classified HR 7018 (HD 172728) as an A0 Hg-Y-Zr and A0 III:p(HgSrMnSi) star, respectively. Woolf & Lambert (1999) recently derived the Hg abundances of all three

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* Table 6 is only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via
`http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/367/597`

stars and found −6.18 for υ Her, −6.19 for ϕ Her, and −5.96 for HR 7018.

2. Changes in analyses

Since 1987 improvements in the analyses of this series, most of which have produced small subtle changes have been implemented. These follow:

1. The spectroscopic material was initially coadded photographic spectra with a typical $S/N = 80$. Except for Paper I (Adelman & Hill 1987), the reciprocal dispersion was 2.4 Å mm^{-1}. Later the spectrograms were obtained with electronic detectors, first a Reticon and then CCDs with $S/N = 200$ typical. The continua and line profiles are better defined and weaker features can be measured. Some weak lines now can be divided into components while others have disappeared. Both Reticons and CCDs are operated as linear devices while the photographic plates were not. The electronic detectors are affected by cosmic rays whose effects are better removed for CCDs than for Reticons. Some Reticon spectra showed four-point noise. In Adelman (1991, Paper VII), the equivalent widths from spectra obtained with photographic plates and with Reticons of the same star were found not to be systematically different from one another.

2. No corrections were applied for the scattered light in the dispersion direction with the coadded photographic plate studies. Later a 3.5% correction was used (Gulliver et al. 1996) for the Reticon and CCD based analyses which increases the equivalent widths by 3.5% and hence the abundances of weak lines by this percentage. Further, it subtly effects the derived microturbulences. In an improvement in the CCD extraction code, which is now being tested, the scattered light is removed as a function of wavelength. This should eliminate much of the 0.5% uncertainty using the mean scattered light correction.

3. In the first papers the model atmospheres were calculated using the ATLAS6 code (Kurucz 1979). Later ATLAS9 (Kurucz 1993) models, which better represent the line opacities, were used. Scaled solar opacity line distribution functions are available for a range of metallicties and microturbulences. For some stars such upgrades produced small changes in their derived effective temperatures and surface gravities (see, e.g., Adelman & Rayle 2000). The program BALMER (Peterson & Kurucz, private communication) was used to calculate the Hγ profiles initially. Later the Hγ spectral region was synthesized using the program SYNTHE (Kurucz & Avrett 1981). This reduces the errors in the surface gravity determinations as the effects of blending metal lines are seen. The use of 20 Å mm^{-1} Reticon and CCD spectrograms rather than coadded spectrograms also helps. But for stars with wide Balmer line profiles and for F stars properly placing the continuum is still somewhat of an art.

4. The He I line profiles were initially calculated with Program OMEGA (Shipman, private communication; Shipman & Strom 1970) and later with Program SYNSPEC (Hubeny et al. 1994). This made little difference as the line broadening theories are the same. One has to fit the profiles rather than the equivalent widths as the observed He I line profiles can be affected by blending components which are not easily removed using the fitting functions.

5. As improved gf values have become available, these more accurate values have been used. Some important substitutions have been Wiese et al. (1996) for C, N, and O replacing those of earlier NIST (NBS) publications, Lanz & Artru (1985) for Si II multiplets 1 and 3 replacing those of Wiese et al. (1969), Lawler & Dakin (1989) for Sc II replacing those of of Martin et al. (1988) which replaced those of Wiese & Fuhr (1975), Biemont et al. (1989) for V II replacing those of Martin et al. (1988) which replaced those of Younger et al. (1978), and Martin et al. (1988) and Fuhr et al. (1988) replacing those of various previous studies for many iron peak element lines. The shift in the studied spectral region between the spectra obtained photographically and with the electronic detectors might result in slight systematic errors as the gf value quality is somewhat wavelength dependent. Many gf value improvements remove systematic errors while preserving the mean values of the derived abunances. But for example, the V II gf values of Biemont et al. (1989) are systematically offset with respect to those of Martin et al. (1988).

6. The line damping constants are now calculated using the damping constants as γ's instead of the logarithm formulation used in an earlier version of WIDTH. This does not produce any differences except for the strongest lines.

7. Some studies of atomic spectra have become available with more accurate and precise wavelengths. Examples are in given Sect. 3 of this paper. They have helped improve the line identifications.

8. In some stars, the weak metal lines have rotational profiles and stronger metal lines Gaussian profiles due to the convolution of the instrumental with the stellar metal line profiles. While initially only rotational profiles were used in such cases, later both were used with a cross-over equivalent width region where which profile to use depends on the best match to the line profile. The initial approach truncated the equivalent widths of very strong lines and reduced the derived microturbulence.

9. There have also been modifications to the best solar abundances which produce changes in the interpretation of the results.

3. The spectra

For each star we obtained 17 Dominion Astrophysical Observatory (DAO) 2.4 Å mm^{-1} Reticon or CCD spectrograms with a typical signal-to-noise ratio of 200 and a wavelength coverage of 67 or 63 Å, respectively. (For HR 7018, the spectrum at λ4630 was defective and not studied.) The central wavelengths between λ3830 and λ4740 had 55 Å offsets. In addition 20 Å mm^{-1} DAO spectrograms containing the Hγ region were obtained for all three stars and 2.4 Å mm^{-1} spectra centered at λ4905, λ5015, and λ5070 for υ Her and ϕ Her and at λ5840 for υ Her. The exposures were flat fielded with the exposures of an incandescent lamp placed in the Coudé mirror train as viewed through a filter to eliminate first order light. A central stop removed light from the beam in the same manner as the secondary mirror of the telescope. The spectra were rectified with the interactive computer graphics program REDUCE (Hill et al. 1982). A correction of 3.5% was applied for scattered light in the dispersion direction (Gulliver et al. 1996).

Gaussian profiles were fit through the stellar metal lines of ϕ Her and υ Her except for strong He I lines for which Lorentzian profiles were used. For HR 7018, rotational line profiles were fit through the weaker stellar metal lines, while Gaussian profiles for those with equivalent widths of about 60 mÅ and greater, and Lorentzian profiles were appropriate for the stronger He I lines. Rotational velocity estimates based on clearly single medium strength lines near λ4481 are 7.5 km s^{-1} for υ Her, 8 km s^{-1} for ϕ Her, and 29 km s^{-1} for HR 7018. Paper X gives 7 km s^{-1} for υ Her, which is essentially the same result, while for ϕ Her Paper V gives 10 km s^{-1}, which reflects a slight increase due to imperfect registration of the coadded photographic plates. Abt & Morrell (1995) found $v \sin i = 30$ km s^{-1} for HR 7018 in excellent agreement with our value.

The stellar lines were identified with the general references A Multiplet Table of Astrophysical Interest (Moore 1945) and Wavelengths and Transition Probabilities for Atoms and Atomic Ions, Part 1 (Reader & Corliss 1980) as well as Svendenius et al. (1983) for P II, Pettersson (1983) for S II, Huldt et al. (1982) for Ti II, Catalan et al. (1964) for Mn I, Iglesias & Velasco (1964) for Mn II, Nave et al. (1994) for Fe I, and Dworetsky (1971), Johansson (1978), Guthrie (1985), and Adelman (1987) for Fe II, and Isberg & Litzen (1985) for Ga II.

In Paper X lines of H I, He I, C II, Mg I, Mg II, Si II, Si III, P II, S II, Ca I, Ca II, Sc II, Ti II, Cr II, Mn I, Mn II, Fe I, Fe II, Fe III, Ni II, Ga II, Sr, Y II, Zr II, Ba II, Hg I and Hg II were found in the spectrum of υ Her. These species are all present and lines of O I were also found. In Paper V lines of H I, He I, C II, Mg I, Mg II, Si II, S II, Ca I, Ca II, Sc II, Ti II, Cr I, Cr II, Mn I, Mn II, Fe I, Fe II, Fe III, Ni II, Ga II, Sr, Y II, Zr II, Ba II, Hg I, Hg II and possibly Y III were identified in ϕ Her. These species are confirmed to be present and in addition Al II, V II, Ni I, Zn I, Zn II, and Ce II have at least one line present. HR 7018 exhibits lines of H I, He I, C II, O I, Mg I, Mg II, Si II, S II, Ca I, Ca II, Sc II, Ti II, Cr I, Cr II, Mn I, Mn II, Fe I, Fe II, Sr II, Y II, Zr II, Ba II, and Hg II, and perhaps Hg I.

We compared the stellar and laboratory wavelengths after corrections were applied for the Earth's orbital velocity to find the radial velocities. For υ Her, the mean radial velocity from 20 spectra is 4.0 ± 0.5 km s^{-1}. This strongly suggests that υ Her is a single star. For ϕ Her, a known single-lined spectroscopic binary, the mean radial velocity is -16.1 ± 2.2 km s^{-1}. The individual values are given in Table 1 both for completeness and as with other values they can be used to improve the orbit. For HR 7018 Abt & Biggs (1972) tabulate two dissimilar values of +18 and −11 km s^{-1} while we find from 18 spectrograms a mean value of -12.1 ± 2.6 km s^{-1} which indicates this star is a spectroscopic binary as are many HgMn stars. As no lines of the secondary were seen, we treat this star as single. These radial velocities are also given in Table 1.

Table 1. Radial velocities for υ Her and HR 7018

central λ(Å)	Heliocentric Julian Date	RV (km s^{-1})
ϕ Her		
4190	2447751.774	−17.0
4520	2448141.716	−17.1
4685	2448705.595	−16.0
4740	2448706.919	−17.2
4245	2449134.966	−22.0
4080	2449394.993	−17.8
4630	2450166.925	−14.2
4465	2450168.062	−13.3
4410	2450169.025	−13.5
4905	2450591.731	−16.8
5070	2450592.987	−16.5
5015	2450593.984	−16.8
4355	2450595.909	−16.7
3970	2450653.998	−14.8
4025	2450654.991	−14.7
4135	2450655.816	−14.0
4300	2450657.001	−13.9
4575	2450658.996	−12.9
3860	2450943.849	−17.3
3915	2451028.854	−18.1
HR 7018		
4520	2448378.937	−10.0
4245	2448379.926	−7.9
4465	2448474.776	−11.1
4685	2448706.014	−12.6
3860	2448758.839	−10.8
3860	2448758.839	−10.8
4080	2448849.719	−11.2
4190	2449200.726	−11.0
4740	2449891.792	−11.2
4520	2449923.750	−12.0
4300	2450657.001	−14.2
4410	2450657.813	−15.2
4135	2450697.953	−14.7
3970	2451000.900	−10.9
3970	2451292.019	−6.2
4575	2451399.843	−15.0
4355	2451407.713	−12.6
3915	2451441.913	−14.8
4025	2451513.835	−16.5

Table 2. Effective temperature and surface gravity determinations

Star	$T_{\rm eff}$(K)	log g	Method
υ Her	12 015	3.70	Napiwotzki et al.(1993) with *uvbyβ* photometry
	11 950	3.70	Spectrophotometry and Hγ profile fitting, solar model, ξ = 0.0 km s^{-1}
ϕ Her	11 782	3.95	Napiwotzki et al. (1993) with *uvbyβ* photometry
	11 500	4.00	Spectrophotometry and Hγ profile fitting, solar model, ξ = 0.0 km s^{-1}
	11 500	4.00	Spectrophotometry and Hγ profile fitting, [+0.2] model, ξ = 0.0 km s^{-1}
HR 7018	10 714	3.98	Napiwotzki et al. (1993) with *uvbyβ* photometry
	10 505	4.02	Napiwotzki et al. (1993) with *uvbyβ* photometry & corrections from Adelman & Rayle (2000)
	10 505	3.90	Hγ profile fitting adjustment to previous value

4. The abundance analyses

Table 2 gives our effective temperature and surface gravity estimates with the last values for each star being those adopted. We began with the computer program of Napiwotzki et al. (1993) and the homogeneous mean *uvbyβ* data of Hauck & Mermilliod (1980). The uncertainties are about ±150 K and ±0.2 dex (Lemke 1989). To refine these values we calculated synthetic spectra of the Hγ regions from ATLAS9 model atmospheres (Kurucz 1993) with Program SYNTHE (Kurucz & Avrett 1981) and predicted fluxes with ATLAS9 for comparison with the observations from Adelman & Pyper (1979) for υ Her and from Adelman & Pyper (1983) for ϕ Her. We estimate the errors to be slightly less than those from photometry (see also Adelman & Rayle 2000). For υ Her and ϕ Her the adopted values are slightly different from $T_{\rm eff} = 11\,900$ K, log $g = 3.6$ of Paper X and $T_{\rm eff} = 11\,325$ K, log $g = 3.55$ of Paper V, respectively. The larger values of surface gravity are due to how the regions near Hγ were normalized, the scattered light correction, and the slightly larger values of $T_{\rm eff}$ (50 K and 175 K, respectively). As there are no spectrophotometric measurements for HR 7018, we corrected the photometrically derived values with the offsets to the photometric values found by Adelman & Rayle (2000). Then we compared the Hγ profile of the star with that of the model with these adjusted parameters and made another slight correction of the gravity.

To show the effects of errors in effective temperature and surface gravity on the metal abundances in Table 3 we indicate the changes in abundances due to a 100 K change in effective temperature and a 0.2 dex change in log g. These were calculated using the values for ϕ Her and are approximately correct for the other stars of this paper. The sensitivities to effective temperature are such that when the temperature is increased so are these abundances, but for surface gravity often the neutral and singly-ionized species have opposite dependences.

Table 3. Changes in derived abundances with temperature and surface gravity errors

Species	$\Delta T_{\rm eff}$(100K)	Δlog g(0.2)
C II	0.01	0.15
O I	0.00	−0.02
Mg I	0.02	−0.11
Mg II	0.00	0.01
Al II	0.00	0.07
Si II	0.01	0.04
S II	0.00	0.13
Ca I	0.05	−0.18
Ca II	0.03	−0.11
Sc II	0.04	−0.03
Ti II	0.03	−0.01
V II	0.02	0.01
Cr I	0.03	−0.09
Cr II	0.01	0.04
Mn I	0.03	−0.10
Mn II	0.01	0.03
Fe I	0.04	−0.06
Fe II	0.03	0.06
Fe III	0.00	0.17
Ni I	0.02	−0.06
Ni II	0.01	0.07
Zn I	0.01	−0.06
Zn II	0.01	0.11
Ga II	0.05	0.09
Sr II	0.04	−0.05
Y II	0.04	−0.05
Zr II	0.03	−0.03
Ba II	0.02	−0.07
Ce II	0.03	0.05
Hg I	0.01	−0.06
Hg II	0.01	0.05

Note: The changes in abundance were calculated for solar models with $T_{\rm eff} = 11\,600$ and 11 500 K and log $g = 4.0$, and with $T_{\rm eff} = 11\,500$ K and log $g = 4.2$ and 4.0.

The helium and metal abundances were determined using programs SYNSPEC (Hubeny et al. 1994) and WIDTH9 (Kurucz 1993), respectively, with metal line damping constants from Kurucz & Bell (1995) or semiclassical approximations in their absence. Abundances from Fe I and II lines were derived for a range of possible microturbulences whose adopted values (Table 4) result in the derived abundances being independent of the equivalent widths (ξ_1) and having a minimal scatter about the mean (ξ_2) (Blackwell et al. 1982). For υ Her and ϕ Her, we find 0.5 km s^{-1} and 0.1 km s^{-1} rather than 0.0 km s^{-1} in Paper X and 0.4 km s^{-1} in Paper V, respectively. For the

Table 4. Microturbulence determinations from Fe I and Fe II lines

Species	Number of lines	ξ_1 (km s^{-1})	log $N/N_{\rm T}$	ξ_2 (km s^{-1})	log $N/N_{\rm T}$	gf values
υ Her						
Fe II	42	0.7	-4.78 ± 0.17	0.8	-4.79 ± 0.17	MF
	109	0.2	-4.71 ± 0.21	0.3	-4.72 ± 0.21	MF+KX
	adopted	0.5				
ϕ Her						
Fe I	56	0.0	-4.24 ± 0.21	0.0	-4.24 ± 0.21	MF
	63	0.0	-4.20 ± 0.24	0.0	-4.20 ± 0.24	MF+KX
Fe II	40	0.3	-4.47 ± 0.17	0.0	-4.46 ± 0.17	MF
	122	0.4	-4.47 ± 0.23	0.2	-4.47 ± 0.22	MF+KX
	adopted	0.1				
HR 7018						
Fe II	60	0.4	-4.30 ± 0.25	0.5	-4.31 ± 0.25	MF+KX
	adopted	0.4				

gf value references: MF = Fuhr et al. (1988), KX = Kurucz & Bell (1995).
Note: For ξ_1 and ξ_2 the abundances are found so that there is no trend of values for lines of different equivalent widths and have minimum scatter about the mean, respectively.

Table 5. He/H determinations

Star	λ(Å)	He/H
υ Her	3867	0.03
	4009	0.03
	4026	0.03
	4121	0.03
	4143	0.03
	4388	0.03
	4472	0.03
	4713	0.03
	4922	0.03
	average	0.03
ϕ Her	4026	0.06
	4121	0.06
	4143	0.07
	4388	0.07
	4472	0.05
	4713	0.06
	4922	0.06
	average	0.06
HR 7018	4026	0.05
	4472	0.05
	4471	0.06
	average	0.05

former star and HR 7018 the Fe I lines were too few and too weak to use to determine the microturbulence. From Fe II lines a value of 0.4 km s^{-1} was derived for HR 7018.

The helium abundances (Table 5) were found by comparing the line profiles with theoretical predictions which were convolved with the rotational velocity and the instrumental profile. For all three stars the He/H values are fairly consistent from line to line. To convert log $N/N_{\rm T}$ values to log N/H values -0.02 dex, -0.03 dex, and -0.03 dex were added to values for υ Her, ϕ Her, and HR 7018, respectively. The He/H ratio of υ Her has increased by a factor of two relative to that of Paper X due to the weak line wings being much better defined. A similar effect was seen for ϕ Her.

Table 6, the analyses of the metal line spectra, contains for each line the multiplet number (Moore 1945), the laboratory wavelength, the logarithm of the gf-value and its source, the equivalent width in mÅ as observed, and the deduced abundance. Source references are given at the end of this table. For some species letters are used in place of multiplet numbers to indicate sources other than Moore (1945): C = Catalan et al. (1964), D = Dworetsky (1971), G = Guthrie (1985), H = Huldt et al. (1982), I = Iglesias & Velasco (1964), J = Johansson (1978), K = Kurucz & Bell (1995), and S = Svendenius et al. (1983).

5. Discussion

Table 7 compares the results of these studies of υ Her and of ϕ Her with those from Papers X and V, respectively. Most of the abundances agree well. Values from different species of the same element often tend to agree slightly better. But there are discrepancies. Those for He I are due to better defined line profiles. For υ Her, the Si II and Si III means agree less well, but the individual Si III result is in the range of those derived from Si II lines. P II and Ca II have abundances reduced by about 0.2 dex, but for Sr II the reverse is true. The Mn and Fe abundances have increased with those from Fe I and Fe II lines in better agreement. The abundance from one Zr II line is uncertain. For ϕ Her Mg I a different group of lines was used. For Si II the equivalent widths are systematically

Table 7. Comparison of results (log N/H)

	υ Her	
Species	Paper X	This Paper
He I	−1.82	−1.52
C II	−4.07	−3.98
O I	...	−3.57
Mg I	−5.56	−5.56
Mg II	−5.08	−5.06
Si II	−4.82	−5.11
Si III	−4.85	−4.67
P II	−5.82	−6.03
S II	−5.29	−5.18
Ca II	−5.83	−6.10
Sc II	−9.06	−8.96
Ti II	−6.26	−6.15
Cr II	−6.12	−6.04
Mn I	−4.70	−4.57
Mn II	−4.88	−4.75
Fe I	−4.76	−4.70
Fe II	−4.85	−4.72
Fe III	−4.68	−4.27
Ni II	−6.77	−6.79
Ga II	−5.64	−5.70
Sr II	−8.10	−7.92
Y II	−7.76	−7.59
Zr II	−8.95	−8.09
Ba II	−8.85	−8.77
Hg I	−6.02	−5.96
Hg II	−5.76	−5.75

	ϕ Her	
Species	Paper V	This Paper
He I	−1.62	−1.21
C II	−3.58	−3.76
Mg I	−5.28	−4.57
Mg II	−4.64	−4.78
Si II	−4.64	−4.95
S II	−4.91	−4.80
Ca I	−5.20	−5.14
Ca II	−5.36	−5.59
Sc II	−7.47	−7.39
Ti II	−6.37	−6.32
Cr I	−5.18	−5.16
Cr II	−5.50	−5.42
Mn I	−4.92	−4.89
Mn II	−5.08	−4.95
Fe I	−4.35	−4.19
Fe II	−4.59	−4.44
Fe III	−4.64	−4.35
Ni II	−6.26	−6.30
Ga II	−6.00	−5.85
Sr II	−8.34	−8.05
Y II	−6.72	−6.79
Zr II	−7.32	−7.30
Ba II	≤ -8.06	−7.69
Hg I	−6.33	−6.15
Hg II	−6.38	−6.41

Table 8. Comparison of derived and solar abundances (log N/H)

Species	υ Her	ϕ Her	HR 7018	Sun
He I	−1.52 ± 0.05	−1.21 ± 0.05	−1.28 ± 0.03	−1.01
C II	−3.98 ± 0.11	−3.76 ± 0.25	−3.31 ± 0.35	−3.45
O I	−3.57 ± 0.09	−3.17 ± 0.49	−3.44 ± 0.02	−3.13
Mg I	−5.56 ± 0.20	−4.57 ± 0.41	−4.43 ± 0.13	−4.42
Mg II	−5.06 ± 0.03	−4.78 ± 0.03	−4.47 ± 0.28	−4.42
Al II	...	−6.30	...	−5.53
Si II	−5.11 ± 0.28	−4.95 ± 0.22	−4.48 ± 0.18	−4.45
Si III	−4.67	...	...	−4.45
P II	−6.03 ± 0.02	...	...	−6.55
S II	−5.18 ± 0.13	−4.80 ± 0.19	−4.41 ± 0.25	−4.67
Ca I	...	−5.14	−5.65	−5.64
Ca II	−6.08	−5.59	−5.50	−5.64
Sc II	−8.96 ± 0.07	−7.39 ± 0.14	−9.73	−8.83
Ti II	−6.15 ± 0.25	−6.32 ± 0.29	−6.59 ± 0.23	−6.98
V II	...	−8.11	...	−8.00
Cr I	...	−5.16 ± 0.28	−5.51 ± 0.25	−6.33
Cr II	−6.04 ± 0.18	−5.42 ± 0.25	−5.61 ± 0.33	−6.33
Mn I	−4.57 ± 0.21	−4.89 ± 0.22	−5.39 ± 0.29	−6.61
Mn II	−4.75 ± 0.26	−4.95 ± 0.29	−5.26 ± 0.33	−6.61
Fe I	−4.70 ± 0.15	−4.19 ± 0.22	−4.32 ± 0.24	−4.50
Fe II	−4.72 ± 0.19	−4.44 ± 0.20	−4.29 ± 0.24	−4.50
Fe III	−4.27	−4.35	...	−4.50
Ni I	...	−5.55:	...	−5.75
Ni II	−6.79 ± 0.24	−6.30 ± 0.30	...	−5.75
Zn I	...	−5.80	...	−7.40
Zn II	...	−5.61	...	−7.40
Ga II	−5.70 ± 0.07	−5.85 ± 0.18	...	−9.12
Sr II	−7.92 ± 0.21	−8.05 ± 0.14	−6.35 ± 0.11	−9.03
Y II	−7.59 ± 0.21	−6.79 ± 0.23	−6.79 ± 0.24	−9.76
Zr II	−8.09:	−7.30 ± 0.25	−8.04 ± 0.29	−9.40
Ba II	−8.77	−7.69	−9.56	−9.87
Ce II	...	−7.63	...	−10.42
Hg I	−5.96	−6.15	...	−10.83
Hg II	−5.75	−6.41	−5.59	−10.83

Note: The solar Hg abundance is for meteorites.

smaller. The Hg abundances tend to differ by a factor of two relative to those of Woolf & Lambert (1999). This may be due to differences in treatment and/or in part to our equivalent widths being somewhat smaller, which might indicate variability (see also, Adelman et al. 2001).

This study's abundances are compared with those of the Sun (Grevesse et al. 1996) in Table 8. For υ Her and ϕ Her there are now abundances for O and for Al, V, Zn, and Ce, respectively. Of these only V has a solar abundance. Al is quite deficient while Zn and Ce are quite overabundant. The agreement of the derived Mg, Cr, and Fe abundance for neutral and singly-ionized lines is very good for HR 7018. The values from Ca I and Ca II and from Mn I and Mn II lines are in fair agreement. The derived Mg abundance is solar while those for most other HgMn stars are subsolar (Adelman 1994; Adelman & Pintado 2000). It is marginally sulfur rich while most HgMn stars are sulfur poor. Its Sc abundance is the smallest of any class members with derived abundances for this element. Those of ι CrB and 28 Her for which no lines were found may be less. In this regard it is like HR 7775 and 53 Tau which are somewhat unusual class members. HR 7018 may

Table 9. Significant correlations

Compared	Quantities	r	values
log He/H	log C/H	0.623	20
log He/H	log Mg/H	0.716	20
log He/H	log S/H	0.614	20
log He/H	log Cr/H	0.856	20
log He/H	log Fe/H	−0.444	20
log He/H	log Sr/H	0.494	19
log He/H	log Y/H	0.516	20
log He/H	$T_{\rm eff}$	−0.522	20
log C/H	log S/H	0.631	20
log C/H	log Cr/H	0.552	20
log Mg/H	log Cr/H	0.755	20
log Si/H	log Mn/H	0.475	20
log S/H	log Cr/H	0.668	20
log S/H	log Sr/H	0.616	19
log S/H	log Y/H	0.672	20
log S/H	$T_{\rm eff}$	−0.584	20
log Sc/H	log Mn/H	0.588	19
log Cr/H	log Fe/H	−0.473	20
log Cr/H	log Sr/H	0.538	19
log Cr/H	log Y/H	0.614	20
log Cr/H	$T_{\rm eff}$	−0.496	20
log Mn/H	log Fe/H	−0.600	20
log Mn/H	$T_{\rm eff}$	0.645	20
log Ni/H	log Sr/H	0.516	19
log Sr/H	log Y/H	0.776	19
Log Sr/H	$T_{\rm eff}$	−0.658	19

be the most Sr rich known HgMn star. It has one of the largest Y abundances for its class. It is somewhat surprising with of order 20 HgMn stars well studied, that the full abundance ranges for this class are still not finally determined.

Adelman (1992) performed a linear correlation analysis among abundances for 11 elements, the effective temperature, and surface gravity for 12 HgMn stars and found some of these quanitities are correlated. As there are now additional stars which are analyzed sufficiently consistently, a similar analysis was performed using the abundances derived from He I, C II, Mg I & II, Si II, S II, Ca I & II, Ti II, Cr II, Mn I & II, Fe II, Ni II, Sr II, and Y II lines, the effective temperatures and surface gravities of 20 HgMn stars. We used the results from the analyses of 3 stars in this paper, 7 from Adelman & Pintado (2000), 8 from Adelman (1992), 112 Her A from Adelman et al. (1998), and 46 Dra A from Ryabchikova et al. (1996). A correlation is regarded as significant if there is less than one chance in 20 for it to be due to chance, or $r \geq 0.444$ for 20 items, 0.456 for 19 items, and 0.497 for 16 items (Bevington & Robinson 1992).

Many of the correlations in Table 9 are similar to those in Adelman (1992). Correlations with C, Sc, and Ni abundances were not performed before. Here the helium abundances correlate with Mg and Cr abundances as before, but also with those of C, S, Fe, Sr, and Y. The temperature anticorrelation is new and needs confirmation. The Mg and Cr abundance correlation is confirmed, but that of Mg and Fe anticorrelating is not. Similarly the Si correlation with Mn is confirmed, but those with Ca and $T_{\rm eff}$ are not. The correlations of S with $T_{\rm eff}$, Sr, and Y are confirmed, but now it also correlates with Cr. The Cr correlations with Fe and Y are confirmed with the others are new. The temperature dependence of Mn is confirmed, but here it anticorrelates with Fe rather than Ca. The Sr anticorrelation with temperature is also new. The persistence of many correlations from study to study suggests that they may be real, but obtaining values for additional stars is still quite useful. For some elements values can be deduced only over part of the temperature range of the HgMn stars. In some cases study of $\lambda\lambda$ 4650–6000 can help fill in the gaps. As the comparison with theory is similar to that in Adelman (1992), the reader is referred to that reference.

Acknowledgements. SJA thanks Dr. James E. Hesser, Director of the Dominion Astrophysical Observatory for the observing time. His contribution to this paper was supported in part by grants from The Citadel Development Foundation as was that of KER. Financial support was provided to AFG by the National Sciences and Engineering Research Council of Canada.

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