A&A 447, 685–690 (2006)
DOI: 10.1051/0004-6361:20053581


**Astronomy & Astrophysics**

# Elemental abundance analyses with DAO spectrograms

## XXIX. The mercury-manganese stars 53 Tau, $\beta$ Tau, $\gamma$ Crv, and $\upsilon$ Her*

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Received 6 June 2005 / Accepted 4 October 2005

**ABSTRACT**

We performed elemental abundances analyses of the mercury-manganese (HgMn) stars 53 Tau, $\beta$ Tau, and $\gamma$ Crv consistent with previous studies of similar stars in this series. The derived $\upsilon \sin i$ values for the last two stars are 59 and 32 km s$^{-1}$, respectively, both of which are greater than those of HgMn stars previously studied. For 53 Tau this analysis using selected wavelength regions replaces one performed with coadded photographic spectra. A stricter upper limit is placed on any Hg II $\lambda$3984 line. The abundances of $\beta$ Tau are usually greater than those of $\gamma$ Crv. But the later star has a Hg II $\lambda$3984 line which the former lacks. Our analysis of $\upsilon$ Her, which was performed with spectrograms obtained with CCD detectors, is extended by using additional spectrograms to increase the range of wavelengths covered longward of $\lambda$4800. Minor changes in the derived abundances result.

**Key words.** stars: abundances – stars: individual: 53 Tau – stars: individual: $\beta$ Tau – stars: individual: $\gamma$ Crv – stars: individual: $\upsilon$ Her – stars: chemically peculiar

## 1. Introduction

The mercury-manganese (Hg-Mn) stars are stable peculiar main sequence 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). They are important laboratories for studying 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. Adelman et al. (2002) reported the first spectrum variability in this stellar class of Hg II $\lambda$3984 in $\alpha$ And A, a discovery whose implications are still just being explored (see, e.g., Kockukhov et al. 2005). With results from many stars one can look at the dependences on stellar parameters and make comparisons with theoretical predictions (see, e.g., Adelman et al. 2001).

This paper presents elemental abundance analyses of four mercury-manganese stars. Adelman (1987, Paper II) performed an elemental abundance analysis of 53 Tau (HD 27295, HR 1339, HIP 21071) using coadded photographic IIaO spectra taken with the long camera of the Dominion Astrophysical Observatory (DAO) coudé spectrograph. That it is an anomalous HgMn star was confirmed as it lacks a Hg II $\lambda$3984 line even at the 2 mÅ level. Previously, the most important analysis was that of Auer et al. (1966). The value of $\upsilon \sin i$ was estimated to be $\leq$5 km s$^{-1}$. It is a known SB0 system. Cowley (1972) classified it as B9 IV.

The analyses of $\beta$ Tau (Elnath, HR 1791, HD 35497, 112 Tau) and of $\gamma$ Crv (HR 4662, HD 106625, 4 Crv) are the first for this series to investigate class members whose spectral

* Tables 4–8 are 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/447/685

lines show this amount of rotation. Both have been discussed in many papers, e.g., Schneider's (1981) catalog and bibliography of HgMn stars. $\beta$ Tau is one of the least variable stars in Hipparcos photometry (Adelman 2001). Its spectral type of B7 III was first given by Johnson & Morgan (1953). Houk & Smith-Moore (1988) list $\gamma$ Crv as a B8 III star. Cowley & Crawford (1971) classified it as a probable mercury star. Subsequently Cowley & Cowley (1971) confirm this identification. Frémat & Houziaux (1997) performed an elemental abundance analysis.

The HgMn star $\upsilon$ Her (HD 144206, HR 5982), spectral type B9 III (Cowley et al. 1969), was analyzed by Adelman (1992, Paper X) with coadded photographic plates and by Adelman et al. (2001) (Paper XXIV) with $S/N \geq 200$ Reticon and CCD spectrograms. $\upsilon$ Her is an example of an Fe and Ni-poor HgMn star. Dolk et al. (2002) tried to determine the Nd and Pr abundances in a group of HgMn stars including $\gamma$ Crv and $\upsilon$ Her. They find log Nd/H = −9.60 and −9.50, respectively.

## 2. Measurement of the spectrograms

We obtained DAO 2.4 Å mm$^{-1}$ CCD spectrograms with typical signal-to-noise ratios of at least 200. Using the SITe2 and SITe4 CCDs with wavelength coverages of 63 Å and 147 Å, respectively, our spectra have wavelength ranges of $\lambda\lambda$3824−4247, 4378−4523, and 4655−4793 for 53 Tau, $\lambda\lambda$3824−4935, 4990−5042, and 6660−6690 for $\beta$ Tau and $\lambda\lambda$3830−4927 for $\gamma$ Crv. For $\upsilon$ Her new SITe4 spectrograms centered at $\lambda$4864, $\lambda$5002, $\lambda$5140, $\lambda$5278, and $\lambda$6562 were measured. For the one centered at $\lambda$6562 much of the region covered was overlain with telluric lines and was not studied. In addition 20 Å mm$^{-1}$ DAO spectrograms containing the H$\gamma$ region were obtained for all stars.

The stellar exposures were flat fielded with the exposures of an incandescent lamp centered in the Coudé mirror train as it was viewed through a filter to eliminate light of other orders. 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). Most spectra were corrected for scattered light in the reduction process using program CCDSPEC (Gulliver & Hill 2002). For the older spectra a 3.5% correction was used (Gulliver et al. 1996).

Gaussian profiles were fit through the stellar metal lines of 53 Tau and $\upsilon$ Her except for strong He I lines for which Lorentzian profiles were used. For both $\beta$ Tau and $\gamma$ Crv rotation profiles were used for all but the strongest metal lines. For them and most He I lines Gaussian profiles were used. Still for the strongest He I lines Lorentzian profiles were employed.

Table 1 contains our own and recent literature values of $\upsilon \sin i$ for the four stars of this paper. Our value for each star tends to be among the smallest. The agreement for the two faster rotators is greater than that for the two sharp-lined stars.

We identified the stellar lines 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, Nilsson et al. (1991) for Y II, and Dolk et al. (2002) for Nd III. In addition to H I and the species with abundances in Table 9, lines of Mg I for 53 Tau and of Si III and P II for $\beta$ Tau were found. A Si III line might be blended in $\gamma$ Crv.

**Table 1.** Rotational velocities determinations.

| Star | $\upsilon \sin i$ (km s$^{-1}$) | References |
|---|---|---|
| 53 Tau | ≤5 | Adelman (1987) |
| | 10 | Abt & Morrell (1995) |
| | 6 | Wolff & Lambert (1999) |
| | 20 | Abt et al. (2002) |
| | 18 | Royer et al. (2002) |
| | 5.5 | This Paper |
| $\beta$ Tau | 60 | Abt et al. (2002) |
| | 64 | Royer (2002) |
| | 59 | This Paper |
| $\gamma$ Crv | 30 | Abt et al. (2002) |
| | 36 | Dolk et al. (2002) |
| | 32 | This Paper |
| $\upsilon$ Her | 10 | Abt & Morrell (1995) |
| | 7.5 | Adelman et al. (2001) |
| | 18 | Abt et al. (2002) |
| | 11 | Dolk et al. (2002) |
| | 20 | Royer (2002) |
| | 7.5 | This Paper |

Using the 53 Tau spectrum which contains the Hg II $\lambda$3984 line region, we set a new upper limit of 0.75 mÅ, a factor of four less than Adelman (1987). The spectral range covered by the CCD exposures is less than that covered by the coadded photographic spectra, but the S/N ratios are at least 200 compared to 80, respectively. That lines of Si III, Sc II, Cr I, Ga II, and Ba II previously found (Adelman 1987) were not is due to the reduced wavelength coverage. The only new abundance is from one P II line. The Mg I lines yielded much smaller Mg abundances than the Mg II lines and were not used. The only new species found for $\upsilon$ Her was Zn II. No Hg II $\lambda$3984 line was seen in $\beta$ Tau which is like 53 Tau in this respect.

We compared the stellar and laboratory wavelengths after corrections were applied for the Earth's orbital velocity to find the radial velocities. Table 2 presents our measured radial velocities. That 53 Tau, $\beta$ Tau, and $\gamma$ Crv are spectroscopic binaries is evident from the data presented. Additional measurements are needed to define orbits. Spectrograms further to the red might show lines of their companions.

For $\upsilon$ Her, the mean radial velocity from 20 spectra (Adelman et al. 2001) was 4.0 ± 0.5 km s$^{-1}$. Including those from this paper, the average becomes 4.1 ± 0.5 km s$^{-1}$. Thus either $\upsilon$ Her is single star or any possible companion orbits it nearly in the plane of the sky.

**Table 2.** Radial velocities determinations.

| Star | Central $\lambda$(Å) | Heliocentric Julian Date | $RV$ (km s$^{-1}$) |
|---|---|---|---|
| 53 Tau | 3898 | 2 452 571.9431 | −1.6 |
| | 4036 | 2 452 529.0090 | 20.3 |
| | 4036 | 2 452 570.9332 | −12.7 |
| | 4174 | 2 453 354.8775 | 21.8 |
| | 4174 | 2 453 354.9213 | 22.8 |
| | 4450 | 2 453 306.0369 | 22.4 |
| | 4450 | 2 453 306.0804 | 22.6 |
| | 4726 | 2 453 337.8531 | 23.3 |
| $\beta$ Tau | 3898 | 2 452 572.0490 | −51.4 |
| | 4036 | 2 452 571.0521 | −48.1 |
| | 4174 | 2 451 945.6889 | 38.0 |
| | 4312 | 2 451 932.7654 | −2.8 |
| | 4410 | 2 451 116.9890 | 8.8 |
| | 4465 | 2 451 115.9449 | 8.2 |
| | 4520 | 2 450 529.8994 | 11.8 |
| | 4588 | 2 451 883.8865 | −35.6 |
| | 4685 | 2 450 537.6797 | 18.1 |
| | 4740 | 2 450 691.9556 | 9.1 |
| | 4864 | 2 452 332.6813 | 32.0 |
| | 5015 | 2 451 470.8866 | −13.1 |
| | 5070 | 2 450 816.7741 | 13.6 |
| | 6680 | 2 451 473.9047 | −53.4: |
| $\gamma$ Crv | 3898 | 2 452 368.8169 | 15.1 |
| | 4036 | 2 452 020.8416 | 47.9 |
| | 4135 | 2 451 540.1081 | −60.5 |
| | 4190 | 2 450 963.8564 | −2.1 |
| | 4245 | 2 451 593.9229 | −37.0 |
| | 4300 | 2 451 291.0070 | −3.6 |
| | 4355 | 2 450 965.8462 | −4.8 |
| | 4450 | 2 452 050.7180 | 88.0 |
| | 4588 | 2 452 367.6597 | 18.9 |
| | 4726 | 2 452 330.9167 | −9.6 |
| | 4864 | 2 451 677.7572 | 77.4 |
| $\upsilon$ Her | 4864 | 2 452 332.9464 | 4.4 |
| | 5002 | 2 453 170.7910 | 4.2 |
| | 5140 | 2 453 214.7599 | 4.6 |
| | 5278 | 2 453 575.7540 | 4.5 |
| | 6562 | 2 452 064.8160 | 4.3 |
| | average | | 4.1 ± 0.5 |

## 3. The abundance analyses

We adopted the effective temperature and surface gravity estimates of Adelman & Rayle (2000) (see the bottom of Table 9). The spectrophotometry was from Adelman & Pyper (1979), Schild et al. (1971), Davis & Webb (1974), and Adelman & Pyper (1979), respectively, for 53 Tau, $\beta$ Tau, $\gamma$ Crv, and $\upsilon$ Her. The H$\gamma$ profiles were extracted from 20 Å mm$^{-1}$ DAO spectrograms. We calculated synthetic spectra of the H$\gamma$ regions from ATLAS9 model atmospheres (Kurucz 1993) with Program SYNTHE (Kurucz & Avrett 1981) and predicted fluxes with ATLAS9 for comparison with the observations. Starting values used the program of Napiwotzki et al. (1993) and the homogeneous mean *uvbyβ* data of Hauck & Mermilliod (1998). The uncertainties from the use of Strömgren photometry are about ±150 K and ±0.2 dex (Lemke 1989). The adjustments slightly reduce them. For $\gamma$ Crv Frémat & Houziaux (1997) derived $T_{\rm eff}$ = 12 000 K from Strömgren photometry and compared computed and observed H$\delta$ profiles to find log $g$ = 3.5. The agreement with our values is not too bad considering that they used IIa-O spectrograms in this region.

To show the effects of errors in effective temperature and surface gravity on the metal abundances, Adelman et al. (2001) in their Table 3 indicated 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 $\phi$ Her and are approximately correct for the 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.

The helium and metal abundances were derived using programs SYNSPEC (Hubeny et al. 1994) and WIDTH9 (Kurucz 1993), respectively, with metal line damping constants from Kurucz & Bell (1995) or semi-classical approximations in their absence. Abundances from Fe I and II lines were derived for a range of possible microturbulences whose adopted values (Table 3) result in the derived abundances being independent of the equivalent widths ($\xi_1$) and having a minimal scatter about the mean ($\xi_2$) (Blackwell, Shallis & Simmons 1982).

For 53 Tau, the Fe I lines are too weak and too few for a determination of the microturbulence. There is only one Fe II line which is slightly beyond the linear part of the curve of growth. Thus no determination is possible from these species. We tried Ti II and Cr II lines, but again the strongest lines are slightly beyond the linear part of the curve of growth. With 44 Ti II lines the microturbulence suggested is about 1 km s$^{-1}$, but with 22 Cr II lines we get a suggestion that there is no microturbulence. We did not use the Mn II lines as some of the stronger ones probably require that their hyperfine patterns be used to calculate their abundances. Thus we adopt zero microturbulence for 53 Tau as this value is close to that for most HgMn stars.

The results for $\beta$ Tau and for $\gamma$ Crv are similar to those of other HgMn stars of this series. For $\upsilon$ Her, we find 0.0 km s$^{-1}$ rather than 0.5 km s$^{-1}$ in our last study. The Fe I lines were too few and too weak to determine the microturbulence. We adopted the results of Dolk et al. (2002) for the analysis of the Nd III lines. As for Hg II $\lambda$3984, Woolf & Lambert (1999) have a slightly greater resolution than our material and a proper analysis of the isotopic splitting, we use their results rather than our simplier analysis.

The helium abundances (Table 4) were derived by comparing the line profiles with theoretical predictions which were convolved with the rotational velocity and the instrumental profile. For each star the He/H values are fairly consistent from line to line. For 53 Tau they about 2.5 times larger than those in Adelman (1987) due to the increased *S/N* revealing more of

**Table 3.** Microturbulence determinations from Fe II lines.

| Star | Number of Lines | $\xi_1$ (km s$^{-1}$) | log $N/N_T$ | $\xi_2$ (km s$^{-1}$) | log $N/N_T$ | $gf$ values |
|---|---|---|---|---|---|---|
| $\beta$ Tau | 36 | 0.0 | −4.61 ± 0.20 | 0.2 | −4.61 ± 0.20 | N4+KX |
| | adopted | 0.1 | | | | |
| $\gamma$ Crv | 25 | 0.0 | −5.13 ± 0.17 | 0.0 | −5.13 ± 0.17 | N4 |
| | adopted | 0.0 | | | | |
| $\upsilon$ Her | 58 | 0.0 | −4.72 ± 0.14 | 0.0 | −4.72 ± 0.14 | MF+N4 |
| | 173 | 0.0 | −4.65 ± 0.17 | 0.0 | −4.65 ± 0.17 | MF+N4+KX |
| | adopted | 0.0 | | | | |

$gf$ value references: MF = Fuhr et al. (1988), KX = Kurucz & Bell (1995), and N4 = Fuhr (2005).
Note: For $\xi_1$ and $\xi_2$ 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 9.** Comparison of derived and solar abundances (log N/H).

| Species | 53 Tau | $\beta$ Tau | $\gamma$ Crv | $\upsilon$ Her | Sun |
|---|---|---|---|---|---|
| He I | −1.38 ± 0.09 | −1.15 ± 0.06 | −1.17 ± 0.06 | −1.51 ± 0.00 | −1.07 |
| C II | −3.85 ± 0.10 | −3.62 ± 0.10 | −3.71 ± 0.12 | −4.04 ± 0.18 | −3.71 |
| O I | ... | ... | ... | −3.57 ± 0.09 | −3.34 |
| Mg II | −4.99 ± 0.14 | −4.83 ± 0.08 | −5.02 ± 0.13 | −5.04 ± 0.04 | −4.47 |
| Al II | −6.87 | ... | ... | ... | −5.63 |
| Si II | −4.82 ± 0.23 | −5.57 ± 0.18 | −5.60 ± 0.25 | −5.06 ± 0.25 | −4.49 |
| Si III | ... | ... | ... | −4.66 | −4.49 |
| P II | −6.45 | ... | −5.96 | −5.99 ± 0.13 | −6.64 |
| S II | −5.76 | −5.05 ± 0.14 | −5.33 | −5.07 ± 0.15 | −4.86 |
| Ca I | −5.32 | ... | ... | | −5.69 |
| Ca II | −5.65 | −5.60 | −5.75 | −6.04 | −5.69 |
| Sc II | ... | ... | −8.22 | −8.95 ± 0.07 | −8.95 |
| Ti II | −5.77 ± 0.20 | −6.22 ± 0.20 | −5.79 ± 0.20 | −6.10 ± 0.20 | −7.10 |
| Cr II | −5.91 ± 0.16 | −5.85 ± 0.18 | −6.34 ± 0.17 | −5.99 ± 0.18 | −6.36 |
| Mn I | −4.68 ± 0.10 | ... | −5.05 ± 0.22 | −4.61 ± 0.14 | −6.61 |
| Mn II | −4.69 ± 0.19 | −4.84 ± 0.15 | −5.32 ± 0.20 | −4.77 ± 0.19 | −6.61 |
| Fe I | −5.44 ± 0.14 | ... | ... | −4.66 ± 0.16 | −4.55 |
| Fe II | −5.27 ± 0.18 | −4.57 ± 0.20 | −5.10 ± 0.17 | −4.65 ± 0.16 | −4.55 |
| Fe III | −4.77 | −4.26 | ... | −4.55 | −4.55 |
| Ni II | −6.65 ± 0.26 | −6.26 ± 0.19 | ... | −6.78 ± 0.19 | −5.78 |
| Zn I | ... | ... | −5.63 | ... | −7.40 |
| Zn II | ... | ... | ... | −6.92 | −7.40 |
| Ga II | ... | ... | ... | −5.67 ± 0.06 | −9.12 |
| Sr II | −8.11 ± 0.18 | ... | −9.04 | −7.85 ± 0.25 | −9.08 |
| Y II | −8.00 ± 0.20 | ... | ... | −7.45 ± 0.17 | −9.79 |
| Zr II | −7.46 ± 0.20 | ... | −7.95 ± 0.12 | −8.08 | −9.41 |
| Ba II | ... | −7.80 | ... | −8.74 ± 0.01 | −9.83 |
| Nd III | ... | ... | −9.60 | −9.50 | −10.55 |
| Hg I | ... | ... | ... | −5.94 | −10.87 |
| Hg II | ... | ... | −7.42 | −6.12 | −10.87 |
| | | | | | |
| $T_{\rm eff}$(K) | 11 700 | 13 250 | 12 125 | 11 950 | |
| log $g$ | 4.25 | 3.65 | 3.70 | 3.70 | |

Note: The solar Hg abundance is for meteorites, the Hg II abundances are from Woolf & Lambert (1999), and the Nd III abundances are from Dolk et al. (2002).

the line wings. To convert log $N/N_T$ values to log N/H values −0.02 dex, −0.04 dex, −0.03 dex, and −0.03 dex were added to values for 53 Tau, $\beta$ Tau, $\gamma$ Crv, and $\upsilon$ Her, respectively. As for $\upsilon$ Her there were no new unblended He I lines we used our previous result.

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. Table 5 contains the results for $\beta$ Tau and $\gamma$ Crv, Table 6 those for

53 Tau, and Table 7 those for $\upsilon$ Her. References for the $gf$ values are given at the end of Table 5. 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), H = Huldt et al. (1982), I = Iglesias & Velasco (1964), J = Johansson (1978), and S = Svendenius et al. (1983).

## 4. Discussion

Table 8 compares our results with the most recent studies of 53 Tau, $\gamma$ Crv, and $\upsilon$ Her. Our results and those of Adelman (1987) are in substantial agreement. The new He I result is larger as more of the weak ling wings have been found and the difference in the derived Ni values is primarily due to a change of $gf$ values. The derived abundances of $\gamma$ Crv only agree well with those found by Frémat & Houziaux (1997) for He, Fe and Zn. This is not unexpected as the DAO spectrograms are superior to the IIaO and IIaD spectrograms used by them in the region of overlap. For $\upsilon$ Her most of new abundances agree well with those from Adelman et al. (2001) as would be expected as the former are upgrades of the later. The new value from Mg I lines uses the b lines rather than most of the lines further to the blue. The substitution of the new NIST (Fuhr 2005) Fe I and Fe II $gf$ values for older values results in an order of 0.02 dex decrease. There is also a slight decrease of the rms error when more lines are used for the analysis of a particular atomic species.

This study's abundances are compared with the recent solar values of Asplund et al. (2005) in Table 9. Their light elements have mostly subsolar abundances. The iron peak elements tend to show overabundances as for example Mn, but some are solar or less, such as Ni. Elements beyond the iron peak when observed are overabundant. When we have performed statistically sufficient additional abundance analyses of HgMn stars, we will again perform a correlation of abundance analysis (see, e.g., Adelman et al. 2001 or 2003).

The lack of a Hg II $\lambda$3984 line indicates that $\beta$ Tau is a peculiar HgMn star as is 53 Tau. There is not a good explanation of this behavior. Recently, this line's profile in the HgMn star $\alpha$ And A was found to be peculiar (Ryabchikova et al. 1999) and later periodically variable (Adelman et al. 2002), the first known example of spectral variability among the HgMn stars. The most likely interpretation of this variability is an inhomogeneous Hg surface distribution combined with the 2.382 day stellar rotation period. Doppler mapping of the Hg distribution shows depleted elemental abundances close to the poles and that the distribution is concentrated in spots near the equator.

Recently Kockukhov et al. (2005) found that HR 1185 and HR 8723, two HgMn stars with some rotation and effective temperatures between 13 000 and 13 800 K showed inhomogeneous distributions of Hg. Differences between two observations of HR 8723 suggest variability of $\lambda$3984. But $\beta$ Tau with similar parameters lacks any detectable Hg line. Thus their explanation may be incomplete. We need additional observations of HgMn stars particularly of these three stars to further study possible Hg II $\lambda$3984 profile variability and then when found to examine both rotational and longer term variability.

*Acknowledgements.* SJA and AFG thank Dr. James E. Hesser, Director of the Dominion Astrophysical Observatory for the observing time. SJA's contribution to this paper was supported in part by grants from The Citadel Foundation. Financial support was provided to AFG by the National Sciences and Engineering Research Council of Canada. HC thanks the Research Fund of İstanbul University for supporting her studies.

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