Re II and other exotic spectra in HD 65949

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Abstract. Powerful astronomical spectra reveal an urgent need for additional work on atomic lines, levels, and oscillator strengths. The star HD 65949 provides some excellent examples of species rarely identified in stellar spectra. For example, the Re II spectrum is well developed, with 17 lines between 3731 Å and 4904 Å, attributed wholly or partially to Re II. Classifications and oscillator strengths are lacking for a number of these lines. The spectrum of Os II is well identified. Of 14 lines attributed wholly or partially to Os II, only one has an entry in the VALD database. We find strong evidence that Te II is present. There are *no* Te II lines in the VALD database. Ru II is clearly present, but oscillator strengths for lines in the visual are lacking. There is excellent to marginal evidence for a number of less commonly identified species, including Kr II, Nb II, Sb II, Xe II, Pr III, Ho III, Au II, and Pt II (probably ^{198}Pt), to be present in the spectrum of HD 65949. The line Hg II λ3984 is of outstanding strength, and all three lines of Multiplet 1 of Hg I are present, even though the surface temperature of HD 65949 is relatively high. Finally, we present the case of an unidentified line at 3859.63 Å of 24 mÅ equivalent width, which could be the same feature seen in magnetic chemically peculiar stars. It is typically blended with a putative U II line used in cosmochronology.

1. Introduction

A variety of chemically-peculiar (CP) stars is found on or near the upper main sequence. Most of these fall into one of two main groups: the magnetic silicon stars, or the non-magnetic mercury-manganese (HgMn) stars. HD 65949 shares characteristics of both of these groups (Cowley et al. 2006, [1] henceforth Paper I). Intermediate-dispersion spectra of HD 65949 obtained by Abt & Morgan (1969) [2] already revealed the outstanding strength of Hg II λ3984, a signature feature of the HgMn stars. An estimate of the mercury abundance presented in Paper I was higher than any other published value. Yet, HD 65949 is quite unlike the typical HgMn stars. The Mn II spectrum is present, but much weaker than expected for an HgMn star with its surface temperature near 13 000 K.

Hubrig et al (2006) [3] had measured a magnetic field of the order of a few hundred Gauss. This field is weaker than typical for a silicon star. Moreover, two characteristic features of silicon stars were missing; the spectrum of Si II was not particularly strong, and the second spectra of the lanthanides were only weakly present.

HD 65949 may be grouped with two other "misfits" near its temperature and surface gravity: HR 6870 (HD 168733, [4]), and HR 6000 (HD 144667, [5]). All three spectra are distinct, as can be seen from Figs. 1 and 3 of Paper I.

In Paper I, several uncommon atomic spectra were found to be definitely or possibly present in the spectrum of HD 65949. We review these in the sections that follow, along with work done subsequently on the model atmosphere and spectrum of the star. We do not claim any "first" identifications, but draw attention to several atomic spectra found in HD 65949 that are rarely found in stellar spectra.

2. Observations

This paper is based primarily on one of four spectra taken with the ESO/FEROS echelle spectrograph in October 2005. The usable wavelength coverage is from 3530 to 9220 Å, but the spectra are not of good quality to the violet of ca. 3590 Å. The resolving power is about 48 000, and the signal-to-noise (S/N) ratio reaches up to 250. Wavelength and equivalent width measurements were made on the spectrum after it was mildly Fourier-filtered.

3. An atmospheric model

3.1. Basic parameters

HD 65949 is a mid-range, main-sequence B-type star. For such objects, the Balmer line profiles are far more sensitive to the surface gravity ($\log(g)$) than the effective temperature (T_{eff}). The effective temperature, obtained from UBV and Strömgren photometry, spans a range from 12 200 K to 13 600 K, depending on the system and calibration. Details may be found at `http://www.astro.lsa.umich.edu/~cowley/hd65949`. We find good to excellent fits of Hα, Hβ, and Hδ within this temperature range for gravity $\log(g) = 4.0$.

In Paper I, we used a T_{eff} of 13 600 K, at the high end of the photometric values. We now find that a lower temperature gives abundance equality among Fe I, II, III, and adopt that value, $T_{\mathrm{eff}} = 12 600$ K, along with $\log(g) = 4.0$. In doing this, we assume the iron abundance is constant throughout the atmosphere. Much new work indicates this assumption may not be true, but for the present, it is a useful working assumption.

We now obtain the following values for $\log(N_{\mathrm{Fe}}/N_{\mathrm{total}})$, the logarithmic ratio of the iron abundance to the sum of all abundances: Fe I, -3.95 (21); Fe II, -4.12 (101); Fe III, -3.97 (7). The values in parenthesis indicate the number of equivalent widths used for each determination. Oscillator strengths for Fe I, II were taken from Fuhr & Wiese (2006) [6], while the VALD values (Kupka et al 2000 [7]) were used for Fe III. Our model atmosphere has a helium abundance of 0.5 solar and an iron abundance of $\log(N_{\mathrm{Fe}}/N_{\mathrm{total}}) = -4.1$, with the remaining abundances being similar to their solar-system values.

3.2. The helium and oxygen abundances

Abundance determinations were not systematically carried out for all identified spectra. We mention here two elements whose abundances can be significant for the structure of the atmosphere. We made a rough estimate of the helium abundance from seven He I lines, by a line-fitting technique using Voigt profiles. We find $\log(N_{\mathrm{He}}/N_{\mathrm{total}}) = -1.40$; helium is about half of its abundance in the sun. Iron is about a factor of 3 above its solar abundance. We estimated the oxygen abundance from 10 O I lines, excluding the strong triplet, 7772, 7774, and 7775 Å, which is sensitive to NLTE, to be $\log(N_{\mathrm{O}}/N_{\mathrm{total}}) = -3.32$, which is very nearly solar ($\log(N_{\mathrm{O}}/N_{\mathrm{total}})_{\odot} = 3.38$).

4. The Re II spectrum

4.1. Wavelengths and identifications

Figure 2 of Paper I shows a feature in the red wing of the Hg II $\lambda3984$ line that was difficult to identify. It turned out to be one of the weaker lines of Re II classified by Meggers, Catalán, & Sales (1958) [8].

Table 1. Stellar and laboratory Re lines

$\lambda^*(\text{Å})$	Cent(i)	ID_1	ID_2
3731.66	0.92	.66 Re II (10Hcw)	
3742.30	0.66	.26 Re II-.133	.32 Mo II-.017
3772.99	1.00	.02 Re II (15cw)	
3776.27	0.92	.30 Re (20c.24Wl)wm,uc	
3800.93	0.87	.95 Re II (100cw)	
3830.57	0.90	.52 Re II (8h)	.62 Re (10h) wm,uc
3839.54	0.99	.54 Re II (10h)	
3847.69	0.93	.72 Re II (10Hw)	
3858.53	0.96	.53 Re (5h) wm,uc	
3873.50	1.00	.60 Re (6hw) wm,uc	
3898.57	0.94	.60 Fe II-.247	.50 Re (5h) wm,uc
3910.59	0.99	.59 Re (3h) wm,uc	
3913.48	0.90	.47 Ti II-.294	.49 Re (3hw) wm,uc
3915.40	0.90	.38 Re II (10h)	
3926.27	0.95	.28 Re (4Hw) wm,uc	
3939.34	0.95	.38 Re (5h) wm,uc	
3947.45	0.90	.43 Re (10h) wm,uc	
3952.11	0.98	.12 Fe II-.034	.10 Re (3h) wm,uc
4031.41cw	0.88	.44 Fe II-.101	.42 Re II (20c6)
4042.77	0.92	.78 Re (3) wm,uc	
4043.09	0.97	.10 Re (3) wm,uc	
4056.90	0.91	.91 N I-.010	.91 Re (10h) wm,uc
4062.51br	0.91	.40 Re (4h) whm uc	
4069.10br	0.82	.12 Re (30c.26Wl)wm,uc	
4091.96	0.91	.96 Re II (20h)	.94 Cr II-.005
4135.41	0.95	.43 Re (2h) wm,uc	
4146.77	0.97	.70 Re (5c.21Wl) wm,uc	+
4149.51	0.96	.46 Re (5Hw) wm,uc	
4231.51	0.95	.53 Re (20c.28Wl)wm,uc	
4240.22	0.96	.18 Re (4cw) wm,uc	
4248.31	0.97	.27 Re (4h) wm,uc	
4269.98	0.96	.94 Re (20c.39Wl)wm,uc	
4289.11	0.98	.09 Re (4h) wm,uc	
4311.68	0.91	.68 Re II (20h)	.67 Mo II-.018
4316.53	0.96	.52 Re (4h) wm,uc	
4330.68	0.98	.79 Ti II-.100	.69 Re (9) wm,uc
4356.29	0.99	.29 Re (6) wm,uc	.29 N I-.094
4380.97	0.99	.00 Re II (10cwl)	
4389.55	0.98	.60 Re II (10cwl)	
4423.00	0.91	.02 Re II (20c)	
4452.71db	0.93	.68 Re II (10)	.82 Dy III-.005
4473.31	0.93	.31 Re (20) wm,uc	
4481.29	0.46	.32 Mg II-.315	.32 Re II (100c)
4489.97	0.98	.99 Re (8c) wm,uc	
4519.05	0.97	.09 Re (5) wm,uc	
4520.96	0.95	.97 Re II (20c)	
4584.50	0.98	.49 Re (30c.51Ws)wm,uc	(remeasure v br)
4596.54	0.91	.56 Re (100h) wm,uc	
4673.26	0.87	.26 Si II-.205	.15 Re (100c) wm,uc
4690.92	0.98	.90 Re (10h) wm,uc	
4703.61	0.98	.70 Re (10cw) wm,uc	
4714.75	0.98	.78 Re (10) wm,uc	
4724.65	0.98	.62 Re (4) wm,uc	
4765.77	0.98	.81 Re (8h) wm,uc	
4904.35	0.94	.33 Re II (10cw)	
4909.74	0.97	.71 Re (4cw) wm,uc	
5070.62	0.95	.58 Fe II-.161	.64 Re (3h) wm,uc
5099.20	0.97	.20 Re (5c) wm,uc	
5286.65	0.96	.68 Re (5h) wm,uc	

After tests with weak lines in the original study of the rhenium spectrum by Meggers (1952) [9], it became clear that many unclassified rhenium lines were also present in HD 65949. Table 1 lists 59 stellar features that are primarily or partially due to rhenium, mostly attributed to Re II. All of the unclassified laboratory lines listed in our table are present in the spark spectrum, but absent in the arc spectrum.

The first column of Table 1 gives the wavelength in the stellar spectrum and the second column gives the intensity at the line core in units of the continuum. The very weak feature near $\lambda3773$ has Cent(i) equal to 1.00 due to a slight misplacement of the continuum. The columns labeled ID_1 and ID_2 indicate primary (dominant) and secondary contributors to the stellar feature. Entries are the laboratory wavelength (fractional part of an angstrom only), the spectrum, the intensity and description of the laboratory line (e.g. c means complex, w wide, db double, br broad, etc., see references cited for further details). The ionization stage of lines identified as 'Re' is unclassified (uc). The feature at $\lambda4146.77$ is suspected of having an unidentified contributor because of the wavelength discrepancy. Intensity parameters (IP) are given for non-Re II lines. Such lines are estimated to be strong if IP is greater than 0.1. Thus, Mo II $\lambda3742.017$ probably does not dominate the nearby stellar feature, while the stellar feature at $\lambda4031.41$ is mostly Fe II.

4.2. Rhenium abundance

Only one usable Re II line, $\lambda3742.30$, has a recent oscillator strength (Palmeri, et al. 2005 [10]) and is bolded in Table 1. The measured equivalent width from our spectrum is 74 mÅ. We have recalculated the abundance, using the revised model, but there remains an uncertainty due to unknown hyperfine structure (HFS). Laboratory spectra show significant HFS for lines of Re I, II, due to the large nuclear magnetic moment and electric quadrupole moment of rhenium. Measurements of HFS for Multiplet UV1 of Re II have been presented by Wahlgren et al. (1997) [11]. If we use a microturbulence of 4 km s^{-1} to attempt to allow for the HFS, we find $\log(N_{Re}/N_{total}) = -6.45$, which corresponds to an excess of 5.36 dex over the solar value. The HFS for optical lines will be measured in the near future to investigate the potentially extraordinary abundance for rhenium implied by our calculations.

5. Osmium

We claim a robust identification of Os II. Stellar and laboratory wavelengths are listed in Table 2. The format is similar to that of Table 1. The laboratory wavelengths are from van Kleef (1960) [12], and comprise all lines with intensities greater than unity with the exception of $\lambda4371.15$, which was *not* present at a detectible level in our spectra.

A wavelength coincidence statistics (WCS) run (cf. Cowley & Hensberge 1981 [13]) shows that finding eight out of nine lines within 60 mÅ has a probability of less than one in 5000 of occurring by chance.

Unfortunately, none of these Os II lines have oscillator strengths listed in VALD. The line at $\lambda3848.78$ Å is included among the Os II lines for which Ivarsson et al (2004) [14] present recent experimental oscillator strengths.

6. Tellurium

Te II is almost certainly present, though we cannot call the identification "robust." WCS places the coincidences significant at the < 0.001 level, but only the strongest lines of Sansonetti & Martin (2003) [15] are clearly present. A listing of observed lines is given in Table 3. Intensities and laboratory wavelengths (fraction of an angstrom only) are from [15]; where no transition probabilities are given.

Table 2. Stellar and laboratory Os II lines

$\lambda^*(\text{Å})$	ID$_1$	ID$_2$
3692.69	.64 OsII (6)	
3706.63	.64 OsII (1)	.55 Au II
3810.93	.92 OsII (1)	.90 P II
3817.84	.84 OsII (1)	
3848.78	.81 OsII (1)	
3894.87	.89 OsII (2)	
4050.13	.14 OsII (1)	.08 S II
4109.08	.09 OsII (1)	
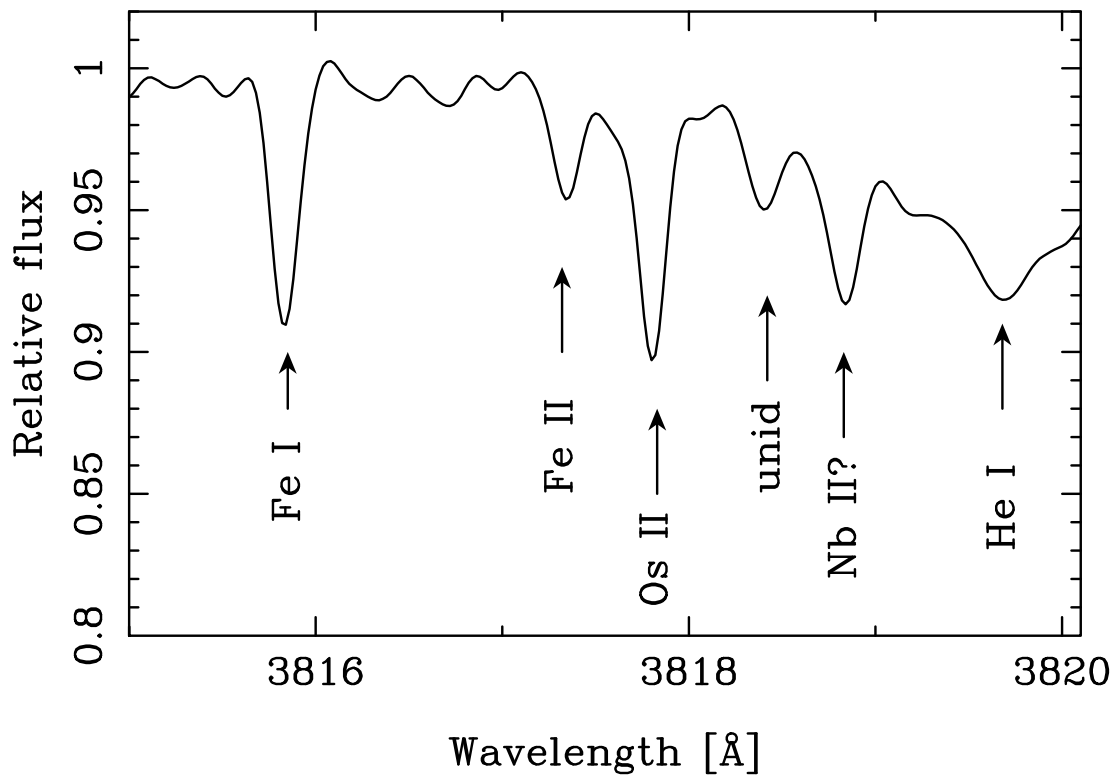
Figure 1. Os II λ3817.84. See url address given in text for complete identifications.

Table 3. Stellar and laboratory Te II lines

$\lambda^*(\text{Å})$	Cent(i)	ID
4654.35	0.97	.37 Te II (900)
5576.40	0.95	.35 Te II (800)
5649.25	0.95	.26 Te II (800)
5666.20	0.97	.20 Te II (500)
5708.11	0.95	.12 Te II (1000)
5755.86	0.97	.85 Te II (800)
5974.70	0.98	.70 Te II (500)

7. Mercury

Mercury abundances were recalculated for relatively weak Hg I,II lines using a cooler model atmosphere than was used in Paper I. These lines contain relatively little isotopic information. We noted previously that the strong $\lambda 3984$ line indicates that the heavy isotope ^{204}Hg must be a major contributor to the feature.

Two Hg I lines ($\lambda\lambda 4358$, 5460) give $\log(N_{Hg}/N_{total}) = -4.94$, while Hg II ($\lambda\lambda 6149$, 7944) gives -4.46. The first and second spectra now disagree by 0.48 dex, while in Paper I, the difference was only 0.22 dex. Abundances from the neutral and ion states might be reconciled if an intermediate temperature were adopted. A stratified mercury abundance might also reconcile the differences.

8. Additional rare spectra

Paper I discussed the unambiguous identification of Pt II, and pointed out that the heavy platinum isotope ^{198}Pt probably dominated. Xe II is also clearly present. Less definite, though probably present, are Kr II, Nb II, Ru II, Sb II, Pr III, Ho III and Au II. No second spectra of the lanthanides are identified, probably due to the high temperatures in the stellar atmosphere.

9. The mysterious unidentified feature at $\lambda 3859$

Since Adelman's (1973) [16] extensive study, numerous uranium abundances in magnetic Ap stars have been claimed to be determined using a feature near the position of U II $\lambda 3859.5716$ [15]. However, the stellar position has been generally measured at a slightly longer wavelength. In the spectrum of magnetic Ap stars, the feature is often complex, and could accommodate both U II as well as a blending feature. Cowley & Arnold (1978) [17] discussed several possibilities for the blends. We measured an equivalent width of 24 mÅ for the line at 3859.63 Å. The line is symmetrical, and appears on all four FEROS exposures. It is unlikely to be any of the features suggested by [17] because of the temperature and abundances of HD 65949. We still cannot identify it, but suggest it could be involved in the blend seen in the cooler magnetic Ap stars. There is considerable interest in this feature, since it is used in cosmochronology [18].

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