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Line identifications and preliminary abundances from the red spectrum of HD 101065 (Przybylski's star)[⋆,⋆⋆]

C.R. Cowley[1] **and G. Mathys**[2]

[1] Department of Astronomy, University of Michigan, Dennison Building, Ann Arbor, MI 48109 1090, USA
[2] European Southern Observatory, Casilla 19001, Santiago 19, Chili

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Abstract. We have made a line identification list and derived preliminary abundances for the extreme peculiar star HD 101065 (Przybylski's star), based on a spectrum recorded at ESO with the CASPEC spectrograph. The line list covers the range 5445–6587 Å. We find iron to be mildly deficient, possibly not as much as an order of magnitude, while the lanthanide rare earths are enhanced by some 4 dex. Abundances rather like this are found in the hotter Ap stars. However, spectra of the latter are quite different in appearance from HD 101065. Insight into how this can be is illustrated from a synthesis of the region containing the strong iron lines $\lambda\lambda\ 4383$, 4404, and 4415. Advantage is taken of the achieved line identifications to determine the longitudinal magnetic field of the star from the analysis of the Nd II lines of its spectrum: (-1408 ± 50) G.

Key words: stars: individual: HD 101065 – stars: abundances – stars: chemically peculiar – stars: magnetic fields

1. Introduction

It is generally acknowledged that the spectrum of HD 101065 may be the most unusual of all stellar spectra (Wegner et al. 1983). It's discoverer, A. Przybylski (1961), insisted that the ubiquitous Fe I spectrum was weak or absent altogether (Przybylski 1977). However, Wegner & Petford (1974) concluded from a coarse analysis of the spectrum that the iron group was present with roughly solar abundances, if normal sources of continuous opacity could be assumed. The question of iron, as well as the temperature of HD 101065 was debated by Przybylski and Wegner and several coworkers in a series of papers in the 1970's and into the 1980's (Kurtz & Wegner 1979; Wegner et al. 1983).

There is no question that the strongest spectral lines in the star generally belong to the lanthanides rather than the iron group, and this very fact makes identifications of the latter species difficult. Cowley et al. (1977) used wavelength coincidence statistics to demonstrate the weak presence of the iron group. The question of the relative abundances of the elements depends critically on the assumed temperature of the star.

There is evidence that the structure of the atmosphere itself is unusual, giving rise to conflicting temperature estimates. For example, not only are rather strong lines of the third spectra of the rare earths present, but some first spectra are present as well (Wegner & Petford 1974, and below). The Hα profile has a sharp core, that cannot be reconciled with any Kurucz (1993) profile from a model with $T_{\rm e}$ hotter than 6000K. The wings can reasonably be fit by models with $T_{\rm e}$ of 7500K. Both Przybylski and Wegner have suggested that severe line blanketing could modify the atmospheric structure of the star, but no detailed models have been constructed that try to take this into account.

If the atmospheric structure of HD 101065 is severely distorted by line blanketing, the effect can be correctly modeled, only if a reasonable estimate of the abundances is available. HD 101065 is *so* peculiar, that one must be prepared for a failure of the usual modeling approach. It remains to be seen if the procedure will in fact converge.

The current paper represents a first step toward detailed modeling of the spectrum of HD 101065. We present a conventional line identification list, which has been prepared with modern analytical tools, based on model-dependent calculations as well as impartial coincidence statistics.

2. The observations and their reduction

The spectrum of HD 101065 analyzed here was obtained in June 1992, with the ESO Cassegrain Echelle Spectrograph CASPEC (Randich & Pasquini 1996) fed by the ESO 3.6 m telescope. The integration time was 35 minutes, and the Heliocentric Julian Date of the middle of the exposure is 2448782.542. The original purpose of the observation was to study the star's magnetic field: accordingly, the CASPEC built-in Zeeman analyzer was inserted in the incoming light beam, to split it into two beams of opposite circular polarizations. The two resulting spectra were recorded simultaneously on the spectrograph CCD detector, with the echelle orders interleaved. Details of the instrumental setup have been given by Mathys & Hubrig (1997). It is sufficient to mention here that the spectra cover the wavelength range

Send offprint requests to: G. Mathys

⋆ Based on observations obtained at the European Southern Observatory, La Silla, Chile (ESO programme No. 49.7-029)

⋆⋆ Table 2 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/Abstract.html

Table 1. Fraction of identified lines

Intensity	Number of measured lines	Number of identified lines	Percentage of identified lines
0	222	28	12.6
1	222	61	27.5
2	269	123	45.7
3	163	106	65.0
4	107	88	82.2
5	51	45	88.2
6	31	31	100.0
10	1	1	100.0

5400–6800 Å, with gaps of a few Angströms between consecutive echelle orders, and that a resolving power $\lambda/\Delta\lambda \sim 1.8\,10^4$ was achieved throughout this range. The present observation of Przybylski's star has been reduced in the same manner as described by Mathys & Hubrig for spectra of other magnetic Ap stars obtained during the same night.

Spectra for the two polarizations were first interpolated at 0.02 Å intervals, and added together. The resulting spectrum was then analyzed in 22 40.94 Å stretches, with a small amount of overlap. The software program CSPEC was discussed by Cowley (1996). Individual radial velocities were determined by cross correlation with synthetic spectra based on a provisional model. The model assumed an effective temperature of 6500 K, and a $\log g$ of 3.5. The iron group was initially assumed to be deficient by 2.0 dex, while the lanthanides were enhanced by 4.0 dex. The continuum chosen by GM was generally found satisfactory, but small adjustments were occasionally made after comparisons with the synthetic spectra. All of the spectra analyzed in this work have been Fourier filtered.

Initially, each 40.94 Å (2048 points) region was analyzed separately, using radial velocities that differed by as much as 2.4 km s^{-1}, but were more typically within the overall rms of 1.7 km s^{-1}. Some 841 wavelengths were measured, and intensities were estimated visually. Plots were prepared which displayed the observed spectrum and the converged synthetic fits with the program MERSEN from which provisional abundances may be made.

From the consideration of the whole spectrum, a value of $+9.0$ km s^{-1} was derived for the heliocentric radial velocity of the star. The corresponding correction was next applied to the entire spectrum, which was remeasured, using frames that displayed only 5.1 Å intervals at a time. The new list contained 1066 lines, excluding a few duplicates from overlapping regions, that have been averaged in our final tables. Central depths as well as line positions were measured. The depths were transformed into a crude measure of metal-line intensity. Only Hα has an intensity of 10; the remaining lines range from 0 to 6.

Suggested identifications were made for 483 of the 1066 measured lines, so that more than half of the features remain unidentified. However, the identified fraction increases rapidly with line intensity, as shown in Table 1.

We have compared our measurements with unpublished lists obtained from Brian Warner (1966) and Gary Wegner (1976). The lists compare very poorly for weak lines, but the correspondence increases with line strength. As we will point out below, our lines of intensity 0 contain little or no useful information.

Most of the lines that we have called intensity 5 or stronger may be found on Warner's list within 0.1 Å, which appears to be the overall measurement accuracy. Our own measurements are slightly better; we estimate between 0.05 and 0.1 Å. The accuracy of any measurement depends on the feature being measured.

3. Element identifications

We have performed standard wavelength coincidence statistics using line lists prepared especially for this study. The laboratory lines are mostly from Meggers et al. (1975). The "standard list" used by CRC and coworkers was also used, but it was constructed at a time when most of the effort was on the analysis of blue-violet spectra, so its coverage of visible wavelengths is not complete. We present below, the results from the former list. The individual line identifications achieved using that list are presented in Table 2, which is 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/Abstract.html`.

The WCS survey included a search for 89 atoms and atomic ions, plus a small number of lanthanide oxides. Of these $\geq 95\%$ confidence levels were found for the presence of 20 species. These results are summarized in Table 3. All statistics are based on 1000 trials with nonsense wavelengths, and a tolerance for coincidence of 100 mÅ. The asterisks in the first column of the table are to draw attention to the most significant results. Significant, quite significant, and highly significant results have respectively one, two, or three asterisks. Briefly, the column labeled "Prob chance" gives the Monte Carlo probability that the coincidences are due to chance. The "Significance" gives the number of standard deviations that the coincidences on the laboratory lines (Hits lab) are from the coincidences on the nonsense wavelengths (Hits random). A detailed description of WCS is given by Cowley & Hensberge (1981).

We can estimate the expected number of chance ($\geq 95\%$ confidence) results following Cowley & Hensberge. The expected number is about 0.025 times the number of *absent* species sought. Probably no more than two of the species in Table 3 that are flagged with an asterisk are due to chance. Of the 4 coincidences for Pm II, 3 are reasonably identified with other spectra. Table 3 contains species with $> 90\%$ confidence results. Roughly 3 or 4 are reasonably attributed to chance.

Ca I is surely present in HD 101065, even though the present statistics are not impressive. Fe I and Fe II will be discussed below. Ni I, Zr I, Ce I, Gd I, and W I deserve further study.

Our digitized intensity data has made possible some special tests not readily available in earlier WCS studies, where only the

Table 3. WCS analysis

	Spectra	Lines sought	Hits lab	Hits random	σ	Prob. chance	Significance	References for line lists
	Ca I	25	9	5.11	1.99	0.057	1.96	Meggers et al. (1975); $\lambda > 5000$ Å
*	Fe I	31	14	6.01	2.12	0.000	3.77	Meggers et al. (1975); $\lambda > 5000$ Å
	Fe II	28	9	5.72	2.07	0.095	1.59	Reader & Corliss (1980); $\lambda > 5000$ Å
	Co I	48	14	8.81	2.57	0.036	2.02	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 2$
	Ni I	23	8	4.58	1.97	0.077	1.74	Meggers et al. (1975); $\lambda > 5000$ Å
	Y II	9	5	2.00	1.25	0.032	2.41	Meggers et al. (1975); $\lambda > 5000$ Å
	Zr I	60	16	10.50	2.81	0.042	1.96	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 29$
	Mo I	57	19	11.77	2.87	0.017	2.52	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 26$
*	La I	43	16	8.99	2.62	0.005	2.68	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 50$
**	La II	47	26	9.28	2.63	0.000	6.36	Meggers et al. (1975); $\lambda > 5000$ Å
	Ce I	48	14	9.03	2.70	0.049	1.84	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 55$
***	Ce II	73	45	13.60	3.21	0.000	9.78	Meggers et al. (1975); $\lambda > 5000$ Å
*	Pr II	44	16	8.51	2.65	0.005	2.83	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 55$
***	Nd II	85	60	16.42	3.60	0.000	12.11	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 20$
*	Pm II	4	4	0.93	0.82	0.001	3.74	Meggers et al. (1951); $I \geq 40$
***	Sm II	50	33	9.27	2.75	0.000	8.64	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 23$
	Eu II	8	5	1.66	1.13	0.015	2.96	Meggers et al. (1975); $\lambda > 5000$ Å
**	Gd II	43	24	7.80	2.54	0.000	6.38	Meggers et al. (1975); $\lambda > 5000$ Å
**	Dy II	15	9	2.62	1.47	0.000	4.35	Meggers et al. (1975); $\lambda > 5000$ Å
*	Ho I	58	19	10.85	2.85	0.002	2.86	Meggers et al. (1975); $\lambda > 5000$ Å
	Lu II	12	5	1.71	1.22	0.017	2.70	Meggers et al. (1975); $\lambda > 5000$ Å
	W I	77	22	15.79	3.56	0.061	1.75	Meggers et al. (1975); $\lambda > 5000$ Å; $I \geq 10$

wavelengths were digitized. We ran WCS against the 222 lines of intensity 0, and found no $\geq 95\%$ confidence results beyond those expected by chance. This was true for both tolerances of 0.100 and 0.250 Å. *The intensity 0 lines have therefore been purged from our final list.*

A similar WCS test, with only intensity 1 lines showed 9 (± 0.100 Å) and 10 (± 0.250 Å) species with $\geq 95\%$ confidence. The number expected by chance is about 2. Surprisingly, there was little overlap with the two tolerances, but Fe I showed up in both instances.

Advantage was taken of the achieved line identifications to exploit the observation for its original purpose and to diagnose the magnetic field of the star. The mean longitudinal field, the crossover, and the mean quadratic field were determined in the same way as described by Mathys & Hubrig (1997), from the analysis of a sample of 15 Nd II lines that appear to be reasonably free from blends. The Landé factors of the levels between which the considered transitions occur were taken from Martin et al. (1978). The only previously published results about the magnetic field of HD 101065 are three determinations of its longitudinal field ranging from -2100 to -2500 G, with estimated uncertainties of 450 G (Wolff & Hagen 1976). The value derived here for the longitudinal field, (-1408 ± 50) G, is marginally smaller (in absolute value), but not inconsistent with these older measurements, even less so because virtually nothing is known about the variability of the field. Crossover was only marginally detected, with a measured value of (-2670 ± 980) km s^{-1} G. No significant quadratic field could be measured, with a 3σ upper limit of 8.7 kG which is only a weak constraint. Hence, there is no indication in the various pieces of information available for the presence of a very strong magnetic field, so that it appears reasonable, in a first approximation, to neglect the latter in abundance determinations.

4. Preliminary abundances

We take the position here that definitive abundances cannot be determined for this star until the question of its atmospheric structure, particularly the effects of blanketing, is clarified. This will be the subject of subsequent studies currently planned by the authors and their collaborators.

All of the following statements are based on a model with an effective temperature of 6500 K, and $\log g = 3.5$. We make no claim that it is definitive (cf. references and discussion in Sect. 1).

Our model was constructed using programs described by Cowley (1996). The T-τ_{5000} relation is from an ATLAS9 calculation with iron-group abundances reduced by a factor of 10, except for Co, which was taken to be solar. The lanthanide abundances were increased by 4 dex. However, since solar ODF's were used, the abundance input to the model probably had little effect on T-τ_{5000}.

All oscillator strengths are from Kurucz (1993), but with substitutions from Fuhr et al. (1988) or Martin et al. (1988)

Table 4. Abundance calculations

Spectrum	N	$\log\varepsilon_0$	$\Delta\log\varepsilon$	$\hat{\sigma}$
Si I	35	0.0	+0.24	0.37
Ca I	10	−1.0	+0.27	0.30
Fe I	70	−1.0	+0.23	0.38
Ce II	39	+4.0	+0.16	0.37
Pr II	68	+4.0	0.00	0.37
Nd II	43	+4.0	+0.36	0.28
Sm II	12	+4.0	+0.40	0.20
Eu II	7	+4.0	+0.22	0.51
Gd II	10	+4.0	+0.29	0.43
Tb II	5	+4.0	+0.27	0.32
Dy II	5	+4.0	+0.00	0.37
Er II	9	+4.0	+0.15	0.27
Tm II	3	+4.0	+0.42	0.23
Yb II	8	+4.0	−0.03	0.33
Lu II	6	+4.0	−0.32	0.37
Hf II	3	+4.0	+0.31	0.25
Ir I	3	+2.0	+0.45	0.14

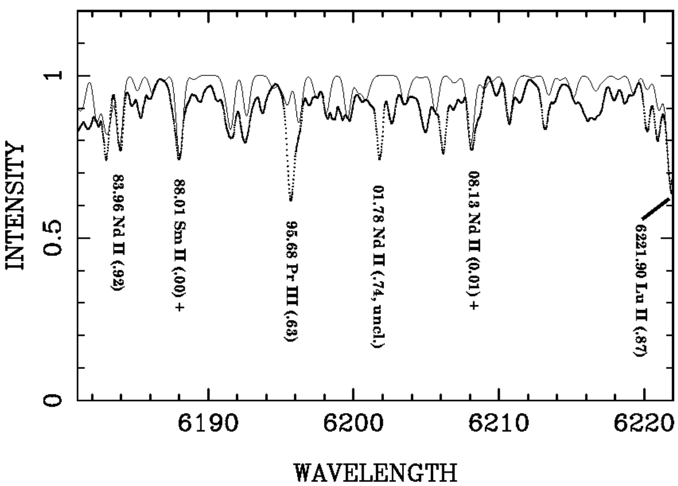

Fig. 1. Automatic fit (*thin line*) of a sample portion of the observed spectrum (*thick line*) of HD 101065

where values exist. The current calculations contain no provision for hyperfine structure.

The filtered stellar spectrum was fit by calculations that assumed $v\,\sin i = 0$ km s^{-1}, a microturbulence of 2 km s^{-1}, and an instrumental (Gaussian) width of 0.3 Å.

Each automatic fit (MERSEN) of the 22 frames mentioned above gives a correction to the initially assumed abundance for each line. A "fit" means that the average of three points centered on the laboratory wavelength was within 2% of the average depth for the corresponding three wavelengths of the observed spectrum. Many stellar features cannot be fit at all, and laboratory lines often fail to converge to the observations. A sample frame, with the results of an automatic fit are shown in Fig. 1.

The output from MERSEN identifies each laboratory line, and gives the logarithmic change in abundance from the starting value to that used in the final iteration. Each line is also

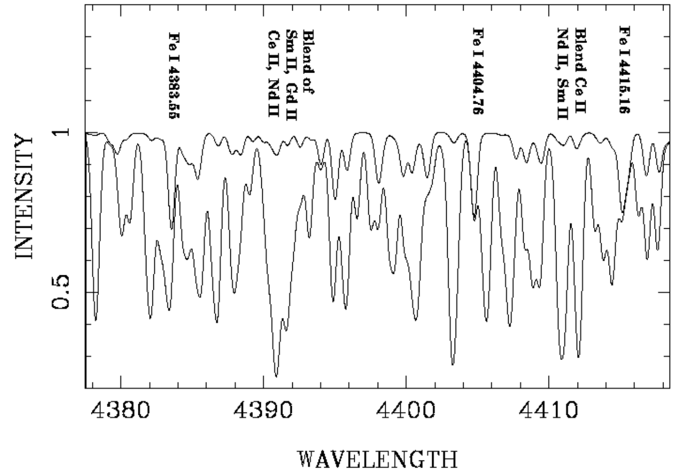

Fig. 2. Synthetic spectrum of a sample spectral region. *Upper spectrum*: solar abundances are assumed, except for the iron group elements, which are reduced by 1.0 dex. *Lower spectrum*: abundances of the lanthanides are increased by 4.0 dex

flagged for a convergence or lack thereof. The UNIX grep command made it simple to combine the results from the 22 output files of MERSEN into one file for each species, including only lines for which convergence has been achieved. Averages of the (logarithmic) changes from the initial assumptions were then taken.

A provision in these averages was made to omit "outliers," that is, points more than 2σ from the mean. However, this option proved to be of questionable value.

Table 4 shows the quantitative results for spectra with 3 lines or more for which MERSEN converged. The column labeled N is the number of lines on which the abundance is based, $\log\varepsilon_0$ gives the assumed abundance relative to solar (Anders & Grevesse 1989), $\Delta\log\varepsilon$ is the average change from the assumed abundance calculated by MERSEN, and $\hat{\sigma}$ is the sample standard deviation.

5. Conclusions

It appears that Wegner & Petford (1974) were much more nearly correct about abundances of the iron group than Przybylski as well as one of the authors of this paper (CRC) ever imagined. We find iron to be mildly deficient, possibly not as much as an order of magnitude, while the lanthanide rare earths are enhanced by some 4 dex. Abundances rather like this are found in the hotter Ap Stars. However, spectra of the latter are quite different in appearance from HD 101065. We may obtain insight into how this can be from a synthesis of the region containing the strong iron lines $\lambda\lambda$4383, 4404, and 4415. This is shown in Fig. 2.

In the upper spectrum (thin solid line), solar abundances are assumed, except for the iron group elements (Ca – Zn) which are reduced by 1.0 dex. In the lower spectrum, abundances of the lanthanides (La – Lu) are increased by 4.0 dex. It is clear that the two spectra look nothing like one another. Further, the *real* spectrum contains even more features since only classified lines can be used in the synthesis.

While absorptions are present at the positions of the Fe I lines, what right does one have to assume they are indeed due to that element? If we consider that they are weak, and that there are many unidentified lines in the stellar spectrum, there is little basis for assuming any individual feature is Fe I and not some unknown line from a lanthanide. It is not difficult to understand why Przybylski maintained that iron could not be identified.

However, if one considers enough features, one can gradually build evidence for the presence of Fe I. Wegner and Petford did this. These authors came to this problem unburdened by years of experience looking at spectra dominated by strong Fe I lines. Still, it is difficult to do this without prejudice. Fortunately, WCS confirms that the species is marginally present.

We have recalculated the spectrum with the iron group set at solar abundances, and looked carefully for those rare instances where the observed spectrum is actually higher than the calculated one. Of 34 regions examined, 20 were due to Fe I lines, the others to mostly Ca I. At least with our provisional model, iron cannot be completely normal in abundance. It also cannot be deficient by much more than 1 dex. A deficiency as large as 2 dex seems to be excluded.

Our identifications show obvious evidence of the third spectra of several lanthanides as well as the highly probable presence of several first spectra. These species should aid in fixing a final model. Definitive results must include line blanketing and detailed hyperfine structure.

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