Unidentified lines in the spectra of two iron overabundant CP stars: Are they Fe II lines?

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Abstract. The analysis of the high-resolution UVES spectra of the chemically peculiar stars HR 6000 and 46 Aql has revealed the presence of an impressive number of unidentified lines, mostly concentrated in the regions 4404-4411 Å and 5100-5300 Å. Almost all of the unidentified lines are the same in both stars, which both have an iron abundance enhancement of the order of +0.7 dex over the solar value. The parameters adopted for HR 6000 and 46 Aql are $T_{\text{eff}}=12850$ K, $\log g=4.1$ and $T_{\text{eff}}=12750$ K, $\log g=3.8$, respectively. We show that some of the unknown lines can be identified as high-excitation (lower EP 13 eV) Fe II and that most of them appear as unclassified lines in laboratory iron spectra.

1. Introduction
Stellar spectra observed at high resolution and high signal-to-noise ratios (S/N) are a fundamental extension of laboratory studies on the atomic and molecular structure. Chemically peculiar (CP) stars are especially well suited to stimulate new laboratory measurements in that their overabundant elements may show spectrum transitions and isotopic and hyperfine structures never before studied. We present a spectrum analysis of two slow-rotating, iron-enhanced B-type CP stars, HR 6000 and HD 186122 (46 Aql), which have a very large number of unidentified spectral lines on the basis of the available lists of atomic line data. The analyzed spectra were taken at the European Southern Observatory using the Very Large Telescope Ultraviolet and Visible Echelle Spectrograph (UVES) at a resolving power $R = 80 000 - 110 000$ and with S/N between 300 and 350. We show that some of the unknown lines can be identified as high-excitation Fe II and that most of them appear as unclassified lines in laboratory iron spectra.

2. Unpredicted lines
The very rich line spectrum of HR 6000 can be reproduced only partially by a synthetic spectrum computed with the chemical abundances and model parameters effective temperature ($T_{\text{eff}}=12850$ K), gravity ($\log g=4.10$), microturbulent velocity ($\xi = 0.0 \text{ km s}^{-1}$), and rotational velocity ($vsini=1.0 \text{ km s}^{-1}$) \cite{1}. We adopted the line list taken from the Kurucz database\textsuperscript{1} and

\textsuperscript{1} http://kurucz.harvard.edu/LINELISTS/GF100/
Figure 1. Upper panel: the observed spectra of the three CP stars HR 6000 ([Fe/H]=+0.7) (black full line), 46 Aql ([Fe/H]=0.65) (blue dotted line), and HD 175640 ([Fe/H]=−0.3) (green full line) are compared with the synthetic spectrum computed for HR 6000 (red full line). The unpredicted lines are marked with a question mark. Lower panel: the observed spectrum of HR 6000 (black line) is compared with two synthetic spectra, the one computed without the new Fe II lines (blue line) and the other computed with them (red line). For the lines at λλ 5176.711, 5177.3896, 5177.7762, and 5179.530 Å, the energy in cm$^{-1}$ of the lower and upper levels is: (103706,123018), (103644,122954), (103644,122953), and (103760,123008). The corresponding log $gf$ values obtained by fitting the observed spectral lines are: 0.65, 1.35, 0.65, 0.79.
Table 1. Unanalyzed lines in the 5175-5181 Å region.

| Stellar ID | ID | Lab(grating) | Lab(FTS) | Notes |
|------------|----|--------------|----------|-------|
| 5175.52    | Fe | 5175.496     | 3        |       |
| 5175.95    |    |              |          |       |
| 5176.25    |    |              |          |       |
| 5176.72    | Fe II | 5176.712∗ | med Fe unid | 5176.711 | 13  (3¹H)4d ¹K₁₅/₂ − (3³H)4f 018₁₅/₂ |
| 5177.394   | Fe II | 5177.392 | strong Fe unid | 5177.3896 | 83  (3¹H)4d ¹K₁₇/₂ − (3³H₆)4f [9]₁₉/₂ |
| 5177.637   | Fe | 5177.632∗ | weak Fe unid | 5177.632 | 7  |
| 5177.77    | Fe II | 5177.773∗ | weak Fe id | 5177.7762 | 11  (3¹H)4d ¹K₁₇/₂ − (3³H₆)4f [9]₁₇/₂ |
| 5178.0     |    |              |          |       |
| 5178.08    |    |              |          |       |
| 5178.53    | Fe | 5178.50∗ | med Fe unid | 5178.530 | 6 unclassified |
| 5178.87    |    |              |          |       |
| 5179.14∗   | Fe II | 5179.175 | double | 5179.139 | 14  (3¹D)4d ¹D₇/₂ − (3¹D)4f [3]₁₅/₂ |
| 5179.23∗   | Fe II | 5179.548 | strong Fe II | not obs. | (3³G)4p x³F₁₂/₂ − (3¹D)4d e³G₅/₂ |
| 5180.62    |    |              |          |       |
| 5180.84    | Fe | 5180.854∗ | weak Fe unid |       |       |
| 5180.97    |    |              |          |       |

*a wavelengths marked with ∗ are Johansson’s (1978)[5] revised or new values.

*b Fourier transform spectrometer (FTS) measurements (Johansson, unpublished).

c “med Fe unid” means an unclassified iron line of medium strength, most probably Fe II; the meaning of “strong” and “weak” is analogous.

d 4f levels are given in J K notation.

e Lines present in the K07 line list for Fe II, but predicted as too weak; λ=5179.171 Å, log gf=−2.965; λ=5179.256 Å, log gf=−3.852.

implemented as described in [2]. Furthermore, for this work, several Fe II gf-values from [3] (K88) were replaced by more recent values (K07) available at the Kurucz website.

On the basis of this line list, numerous observed lines do not have a predicted counterpart and remain unidentified. The most impressive regions are 4404 to 4411 Å and 5100 to 5300 Å, which are crowded with unpredicted absorptions. The list of the unidentified lines in HR 6000 for the region 3900 to 7550 Å is available on the world-wide-web.

The iron overabundance [+0.7] of HR 6000 has lead us to suppose that most of the unpredicted absorptions are Fe II. In fact, we obtained analogous results from a preliminary spectral analysis of the iron-rich CP star 46 Aql (HD 186122), which has atmospheric parameters and chemical abundances similar to those of HR 6000. By using ATLAS9 models ([4]) and Strömgren photometry we obtained for 46 Aql the parameters Tₑff=12 750 K, log g=3.8, while we derived from its spectrum ξ=0.0 km s⁻¹, vsin i=1.0 km s⁻¹, and [Fe/H]=+0.65. Furthermore, the HgMn star HD 175640, which is moderately underabundant in iron [−0.3] ([2]), shows unpredicted lines in the UVES spectrum at the same wavelength as for HR 6000, but much less intense in accordance with the different iron abundance. Figure 1 (upper panel) compares the spectra of the three stars in the region 5175 to 5181 Å and shows that 17 lines are not predicted by the synthetic spectrum computed for HR 6000.

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2 http://kurucz.harvard.edu/atoms/2601/gf2601.pos
3 http://wwwuser.oat.ts.astro.it/castelli/stars/hr6000/unidentified.txt
3. Newly identified Fe II lines
The first column of Table 1 lists the lines in the region 5175 to 5181 Å shown in Figure 1 that are either not predicted by the synthetic spectrum or are predicted with an intensity that is too low. Column 2 shows that 10 of the 17 lines can be identified as Fe on the basis of laboratory iron spectra obtained by means of a pulsed hollow-cathode discharge ([5]) (J78) and, later on, by means of the UV Fourier transform spectrometer at Lund. Four stellar lines, observed at λλ 5176.72, 5177.394, 5177.77, and 5179.54 Å, have been identified as Fe II and classified as belonging to the newly discovered subconfiguration (3H)4d − (3H)4f. Four other iron lines, λλ 5175.52, 5177.637, 5178.53, and 5180.84 Å, although still unclassified, are considered to be Fe II to a very high probability. Finally, a medium intensity line observed both in stellar and laboratory spectra at 5179.14 Å was predicted with a lower intensity according to its Fe II classification. Possibly, its computed gf-value is lower and must be revised. Another stellar line, observed at 5179.23 Å and predicted with almost zero intensity to be Fe II 5179.256 Å, was not observed in the FTS spectrum and its origin remains unclear. Figure 1, lower panel, compares the observed spectrum of HR 6000 with two synthetic spectra, one computed without the newly identified Fe II lines and the other computed with the new lines included in the line list. This figure shows that thanks to the new identifications only the weakest features remain unknown. A similar analysis for other spectral regions, in particular the 4404 to 4411 Å range, has given analogous results.

References
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[5] Johansson S 1978, Physica Scripta, 18, 217