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IDENTIFICATION OF NEW FLUORESCENCE PROCESSES IN THE UV SPECTRA OF COOL STARS FROM NEW ENERGY LEVELS OF FE II AND CR II

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ABSTRACT

We present two new fluorescence processes operating in atmospheres of cool stars, symbiotic stars and the sun and identify two emission lines, at 1347.03 and 1360.17 A, as fluorescence lines of Cr II and Fe II. The lines are due to transitions from highly excited levels, which are populated radiatively by the hydrogen Lyman alpha line due to accidental wavelength coincidences. Three new energy levels, one in Cr II and two in Fe II, are reported.

Keywords: Atomic Energy Levels, Fluorescence, Line Identifications, Cool Stars

1. INTRODUCTION

Far ultraviolet spectra of cool stars show a number of emission lines in the wavelength region 1200 - 2000 A. At a very early stage of the analysis of low resolution spectra, it became obvious that the identities of the lines were not easily established. The explanation of the strong O I lines around 1300 A as fluorescence lines, pumped by Lyman beta of hydrogen, suggested that the lines in the Lyman series could be a powerful source for photoexcitation.

Based on an extended laboratory analysis of Fe II (Ref. 1), Brown, Ferraz and Jordan (Ref. 2) discussed the possibilities of photoexcitation of Fe II in cool stars due to close coincidences between some new Fe II lines and Lyman alpha. This was later confirmed by Johansson and Jordan (Ref. 3), who identified a large number of emission features in IUE spectra of cool stars as fluorescence lines of Fe II. In particular, there was one line at 1869 A, which is quite prominent in many IUE spectra, not only of cool stars (cf. Ref. 4). It happened to coincide with an unclassified Fe II line, tabulated in Ref. 1. The line was identified by Johansson and Jordan (Ref. 3) under the assumption that it shared its upper level with another Fe II transition, which had about the same wavelength as Lyman alpha. This case of Lyman alpha pumping differed from other fluorescence processes in that it led to the discovery of a new energy level in Fe II at 13.4 eV.

In the present paper we give two new examples of "astro-atomic spectroscopy", where unidentified emission lines in cool stars have contributed additional information to the analysis of laboratory spectra in the search for new energy levels. The discoveries were made in connection with an extensive analysis of the ultraviolet spectrum of Gamma Crusis by Carpenter et al. (Ref. 5), where a number of other new fluorescence processes and lines were also found. These are discussed in a companion paper by Carpenter and Johansson (this volume, Ref. 6). Two lines at 1347 and 1360 A have now been identified as transitions in Cr II and Fe II, whose upper levels are excited by Lyman alpha. Both lines appear also in the solar spectrum as strong features (Ref. 7). This is the first time Cr II is proposed to contribute to the fluorescence spectrum of cool stars below 2000 A.

2. IDENTIFICATION OF THE 1347 A FEATURE

Three lines around 1350 A in the spectrum of Gamma Crusis and other cool stars are also present in the solar spectrum, where they show an unusual spatial distribution (Refs. 7,8). Jordan has in Ref. 8 given tentative identifications for the features at 1360 and 1366 A, but there is no plausible explanation for the line at 1347.03 A.

There is a line at 1347.04 A in the laboratory spectrum of Cr II (Ref. 9), that has been assigned to the $3d^5\ a^4G_{11/2}$ - $3d^4(^5D)5p\ ^4F_{9/2}$ transition. The upper level may be photoexcited by Lyman alpha in a transition from $3d^6(^5D)4s\ a^6D_{9/2}$ at a wavelength of 1215.76 A, which is only 0.09 A larger than the rest wavelength of Lyman alpha. The calculated oscillator strength for the pumped transition is -1.76 (log gf). (All calculated values of oscillator strengths and energy levels in this paper are from new theoretical calculations by Kurucz (Refs. 10,11)). For the fluorescence line at 1347.03 A the log-gf value is -1.28. The next strongest laboratory line (log gf = -1.51) from the $5p\ ^4F_{9/2}$ level appears at 1615.64 A. There is a line in the spectrum of Gamma Cru at 1615.66 A, primarily assigned to multiplet 2.01 of C I. These are the three strongest transitions from the $5p\ ^4F_{9/2}$ level in the ultraviolet region. The fourth largest gf value (log gf = -2.5) in this region belongs to the transition to $3d^6(^5D)4s$ $a^4D_{7/2}$ at 1338.25 A. This line is observed in the

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laboratory spectrum and coincides also with an unidentified feature in the solar spectrum (Ref. 7) with a spatial distribution similar to that of the 1347 A line. The faintness of the 1347 line in the spectrum of Gamma Cru (Ref. 5) and a difference of one order of magnitude in the oscillator strength may explain why the 1338 A line cannot be distinguished from the noise in the stellar spectrum.

The atomic structure of Cr II is quite similar to the structure of Fe II as regards the $3d^4nl$ system. The $3d^4$ core of Cr III has exactly the same set of spectroscopic terms as the $3d^6$ core of Fe III, since ten 3d electrons make up a closed shell. The ^4F level of $3d^4(^5D)5p$ in Cr II, which is pumped by Lyman alpha, belongs to the same category of levels as the 5p levels, which are found to be pumped in Fe II (Ref. 3). The pumped transition is in both cases a 4s-5p transition. The most probable decay from 5p is down to 5s, which means that the strongest fluorescence lines in both elements, due to this particular process, should occur in the infrared region. A number of strong 5s-5p lines of Fe II has been observed in various emission line objects.

3. IDENTIFICATION OF THE 1360 A FEATURE

The line at 1360.17 A has been observed in spectra of cool stars and other objects e.g. RR Tel (Ref. 4) and the sun (Ref. 7). A line with the same wavelength was reported in a laboratory investigation of iron at the Vatican Observatory (Ref. 12) in 1965. This line was included by Kelly and Palumbo in their compilation of atomic lines below 2000 A (Ref. 13) and was assigned to a strange LS-forbidden transition $a^6D_{7/2}$ - $x^2D_{5/2}$, which has a matching predicted wavelength but a calculated oscillator strength of -9.6 (log gf). This identification was adopted in the recent line list of the solar spectrum (Ref. 7). However, Jordan (Ref. 8) has proposed another transition in Fe II as a possible candidate for the 1360 A line. Since the classification suggested in Ref. 13 is very unlikely we will discuss the identification given by Jordan more in detail. The proposed $3d^7\ a^2G_{7/2}$ - $3d^6(b^3F)4p\ ^4G_{7/2}$ transition has a calculated log-gf value of -4.38 and a predicted wavelength at 1360.16 A. The upper level is supposed to combine strongly (log gf=0.240) with the $^4F_{5/2}$ level of the corresponding 4s subconfiguration, i.e. $3d^6(b^3F)4s\ ^4F_{5/2}$, which is confirmed by a strong laboratory line at 2515.12 A. However, there is no line observed at this wavelength in the spectrum of Gamma Cru, which makes the proposed identification for the 1360 A line doubtful. In addition, there is no way to excite the upper level by Lyman alpha pumping.

We propose that the line at 1360.17 A is assigned to a transition from a previously unknown level of Fe II. We have used the same technique as Johansson and Jordan (Ref. 3) applied to the 1869 A line, discussed above. We assume that the 1360 A line results from Lyman alpha pumping. The difference in wavenumber between Lyman alpha and the 1360 A line matches perfectly the difference in energy between the $b^4F_{9/2}$ and $b^4D_{5/2}$ levels of Fe II. That gives us a tentative level at 104907.7 cm^{-1} with J=7/2. In this energy range there are two unknown levels with J = 7/2, which both belong to the $3d^54s4p$ configuration. One of them is a ^6G level and the other one a ^4F level. The $3d^5(^2D)4s4p(^3P)\ ^4F_{7/2}$ level is predicted to be located at 104595 cm^{-1} and should have three strong transitions in the ultraviolet region. These are combinations with $b^4F_{9/2}$ (log gf=-1.45), $b^4F_{7/2}$ (log gf=-1.70) and $b^4D_{5/2}$ (log gf=-1.19). The corresponding wavelengths should be 1215.502, 1218.067 and 1360.178 A. The two latter lines are observed in the laboratory spectrum, while the line at 1215.502 is masked by Lyman alpha. In the stellar spectrum we only expect the line at 1360.178 A to be observed while the other two should be obscured by Lyman alpha. This means that there are two pumping transitions available for the upper level to be photoexcited by Lyman alpha in stellar atmospheres.

This fluorescence process represents a case, where two pumped transitions result in one observed fluorescence line. The few lines seen in the laboratory spectrum from the new energy level is quite unique in a complex atom but in full agreement with the results of the theoretical calculations. We should expect the same behaviour for the other fine structure levels of the $3d^5(^2D)4s4p\ ^4F$ term. We have found the $^4F_{9/2}$ level at 105407.5 cm^{-1}. This is 327 cm^{-1} above the predicted position, which agrees with the deviation (observed-calculated) of 312 cm^{-1} for the J=7/2 level. The only lines we find in the laboratory spectrum from the J=9/2 level are combinations to b^4F and b^4D levels, i.e. the same as for the J=7/2 level. However, in this case the transitions from b^4F appear below 1211 A, i.e. too far from Lyman alpha for an efficient pumping, which may explain why we cannot see the transition to $b^4D_{7/2}$ at 1352.73 A in the stellar spectrum.

4. SUMMARY

The identification of two emission features in the ultraviolet spectra of cool stars have confirmed one new energy level in Cr II and yielded a previously unknown level in Fe II. The emission lines at 1347 and 1360 A appear in the spectra of cool stars and the sun as a result of a selective excitation by the Lyman alpha line in hydrogen. These new fluorescence processes imply the need of atomic data even for highly excited levels in singly ionized atoms for the interpretation of spectra of cool stars.

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