CONTRIBUTED PAPER

FLUORESCENCE PROCESSES AND LINE IDENTIFICATIONS IN THE UV SPECTRA OF COOL STARS

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ABSTRACT

Fluorescence processes active in the outer atmospheres of non-coronal cool stars and the UV lines they produce are summarized. Eight new pumping processes and 21 new fluorescent line products are discussed. The new processes, which produce 12 lines, involve energy levels not previously known to be radiatively populated. Four of these are examples of self-fluorescence, whereby one or more lines of Fe II photo-excite through coincident lines the upper levels of other Fe II lines seen in emission, while two others explain the selective excitation of solitary Ni II and Si I lines. Nine of the line products are newly recognized decays from levels in Fe I and Fe II already known to be radiatively populated.

Keywords: Fluorescence, Cool Stars, Chromospheres, Line Identifications, Fe II

1. INTRODUCTION

The fluorescence processes of importance to the UV spectrum of single, non-coronal cool stars (giants > K2, supergiants > G8) generally involve the radiative excitation of an atomic energy level by photons emitted from other ions or from other levels of the same ion, since there is no strong UV continuum source in these objects. The electrons then radiatively decay from the excited level, producing line radiation during one or more subsequent downward transition(s). There is only one clear case identified so far of fluorescence involving molecules in the UV spectra of these stars, the Ayres *et al.* O I - CO process (Ref. 1).

The outer atmosphere of a non-coronal cool star is an ideal local for the operation of such line fluorescence processes. The low densities typical of late-type stellar chromospheres (log N_e 9.0) imply a low rate of collisional de-excitations and allow the radiative decay of levels populated by selective radiative pumping. In addition, there are many strong sources of line radiation and many possible upward transitions from highly populated low-lying levels of abundant elements, especially in Fe II. There can thus be many chance coincidences between potential pumps and possible upward transitions.

In this paper we summarize all of the fluorescent processes known to be operating in the outer atmosphere of non-coronal cool stars, and provide more details on the new processes and UV line identifications reported by Carpenter *et al.* (Ref. 2) for the M-giant Gamma Crucis. A companion paper by Johansson and Carpenter (this volume, Ref. 3) further discusses the two processes which involve new energy levels recently found in laboratory analysis of Cr II and Fe II.

2. FLUORESCENCE PROCESSES NOT PRODUCING FE II

A number of fluorescence processes which do not produce Fe II lines have been known for some time. These include the Lyman Beta - O I (UV 2), the O I (UV 2) - S I (UV 9), the O I (UV 2) - CO, the Fe II (UV 3/34)/Si II - Co II (UV 8), and Mg II (UV 1) - Fe I (UV 44) fluorescence mechanisms. Further details on these processes and lines, as well as the new ones discussed below, are given in Table 1, along with appropriate references.

Carpenter *et al.* (Ref. 2) identify three new processes and fluorescent lines, as well as a line (Fe I (UV 12) at 2355.9 Å) newly recognized as the result of the well-known Mg II - Fe I pump that produces the UV 44 lines above 2800 Å. The first involves the pumping of a new level of Cr II by hydrogen Lyman-alpha, the details of which are given in Ref. 3. The other two processes explain lines whose identities have long been suspected, but whose excitation mechanisms were unknown. A strong line at 2416 Å had been tentatively identified with Ni II (UV 20) (Ref. 4), but no plausible excitation mechanism was known. We now believe that the upper level of this line is radiatively excited by the Si II (UV 0.01) lines near 2335 Å, through a coincident Ni II (UV 20) line. The situation is similar regarding the Si I (UV 1) line at 2516 Å (Ref. 5), whose upper level we believe to be populated by the 2507 Å Fe II line pumping a coincident Si I (UV 1) line. The Fe II line is itself a fluorescent line whose upper level is pumped by Lyman-alpha, so that the Si I line can be, in the end, attributed to Lyman alpha as well.

Table 1.
FLUORESCENCE PROCESSES NOT PRODUCING Fe II LINES

Fluorescent Features	Pumped Transitions	Pumps	Reference for Process
S I (UV 9) 1295.6 1296.2 1302.8	S I (UV 9) 1302.3 1305.9	O I (UV 2) 1302.2 1306.0	Brown & Jordan 1980 (Ref. 11)
O I (UV 2) 1302.2 1304.9 1306.0	O I (UV 4) 1025.8	H I (UV 2) 1025.7	Haisch et al. 1977 (Ref. 12)
Cr II (#) 1347.0	Cr II (#) 1215.8	H I (UV 1) 1215.7	Carpenter et al. 1988 (Ref. 2)
CO (A-X) 1300-1800	CO (A-X) 1215-1217 1302-1306 1656-1658	H I (UV 1) 1215.7 O I (UV 2) 1302-1306 C I (UV 2) 1656-1658	Ayres, Moos, and Linsky 1981 (Ref. 1)
Co II (UV 8) 2330.4	Co II (UV 8) 2344.3	Fe II (UV 3) 2343.5 2344.3 Si II (UV 0.01) 2343.5 Fe II (UV 35) 2344.0	Carpenter, Wing, & Stencel 1982 (Ref. 13)
Ni II (UV 20) 2416.1	Ni II (UV 20) 2334.6	Si II (UV 0.01) 2334.4 2334.6	Carpenter et al. 1988 (Ref. 2)
Si I (UV 1&42) 2516.1 2970.4	Si I (UV 1) 2506.9	Fe II (#) 2506.8	Carpenter et al. 1988 (Ref. 2) single line; blended with UV 60 & mutilated by Fe I absorption
Fe I (UV 44) 2823.3 2844.0	Fe I (UV 44) 2795.5	Mg II (UV 1) 2795.5	van der Hucht et al 1979 (Ref. 14) Carpenter & Wing 1979 (Ref. 15)
Fe I (UV 12) 2355.9	Fe I (UV 44) 2795.5	Mg II (UV 1) 2795.5	Carpenter et al. 1988 (Ref. 2)
Fe I (UV 3,3,45) 2826.0 2827.9 2825.1	Fe I (UV 3,3,45) 2803.2 2795.0 2797.8	Mg II (UV 1) 2802.7 2795.5 2795.5	Eaton & Johnson 1988 (Ref. 16)

= the transition has not been assigned a multiplet number in C. Moore's tabulations (Ref. 9); see Carpenter *et al.* (Ref. 2) for transition information.

3. FE II SELF-FLUORESCENCE PROCESSES

The very large number of Fe II lines blanketing the 2000 - 3200 Å spectral region almost guarantee the existence of this special case of fluorescence, in which a ion pumps itself to produce emission lines from levels that are too high to be populated collisionally. Carpenter *et al.* (Ref. 3) identify the first observed examples of this phenomenon in cool giants. They list four levels in Fe II that appear to be populated by such a mechanism in the chromosphere of Gamma Crucis.

The processes that populate the first two levels are illustrated in Figure 1, which shows two separate lines from UV 1 (at 2631 and 2599 Å) pumping UV 171 and UV 265 lines to produce a total of 5 fluorescent lines from UV 158, UV 171, and UV 207.

Figure 2 illustrates a process in which two different emission lines, from two different multiplets (UV 1 and UV 3 at 2628 and 2539 Å, respectively), pump the *same* upper level to produce two emission features at 2741 and 2435 Å, from UV 260 and UV 180, respectively.

Finally, Figure 3 shows one additional possible self-fluorescence process. There appear to be 3 distinct pumps through 3 separate lines for one upper level. However, only one fluorescent product is visible in the Gamma Crucis spectrum and we cannot be as confident about this process as the other two. The line we do see, from UV 161 at 2482 Å, is quite strong, but the next strongest transitions from this upper level at 2827 Å (UV 131) and 2427 Å (UV 114) are not seen. However, the gf-values for the latter two lines are more than 1.5 orders of magnitude weaker than for the UV 161 line and it is reasonable for them to be too weak to be observed.

These Fe II self-fluorescence processes are summarized in Table 2.

Table 2.
SELF-FLUORESCENCE: Fe II LINES PUMPED BY Fe II LINES

Fluorescent Features	Pumped Transitions	Pumps	Comments
Fe II (UV 180 &UV 260)	Fe II (UV 203 &UV 165)	Fe II (UV 1 &UV 3)	
2434.9	2628.6	2628.3	Both lines pump
2741.4	2359.1	2359.1	same upper level
Fe II (UV 161)	Fe II (UV 161 UV 198)	Fe II (UV 33, UV 207, UV 63)	uncertain
2482.1	2493.2	2493.2	
		2493.3	
	2769.4	2768.9	
Fe II (UV 207)	Fe II (UV 265)	Fe II (UV 1)	
2497.8	2599.5	2599.4	single line;
2493.2			blended with UV 33 line
Fe II (UV 158)	Fe II (UV 171)	Fe II (UV 1)	
2538.8	2631.0	2631.0	
2548.6			
Fe II (UV 171)	Fe II (UV 171)	Fe II (UV 1)	
2619.1	2631.0	2631.0	

Reference: Carpenter *et al.* 1988 (Ref. 2).

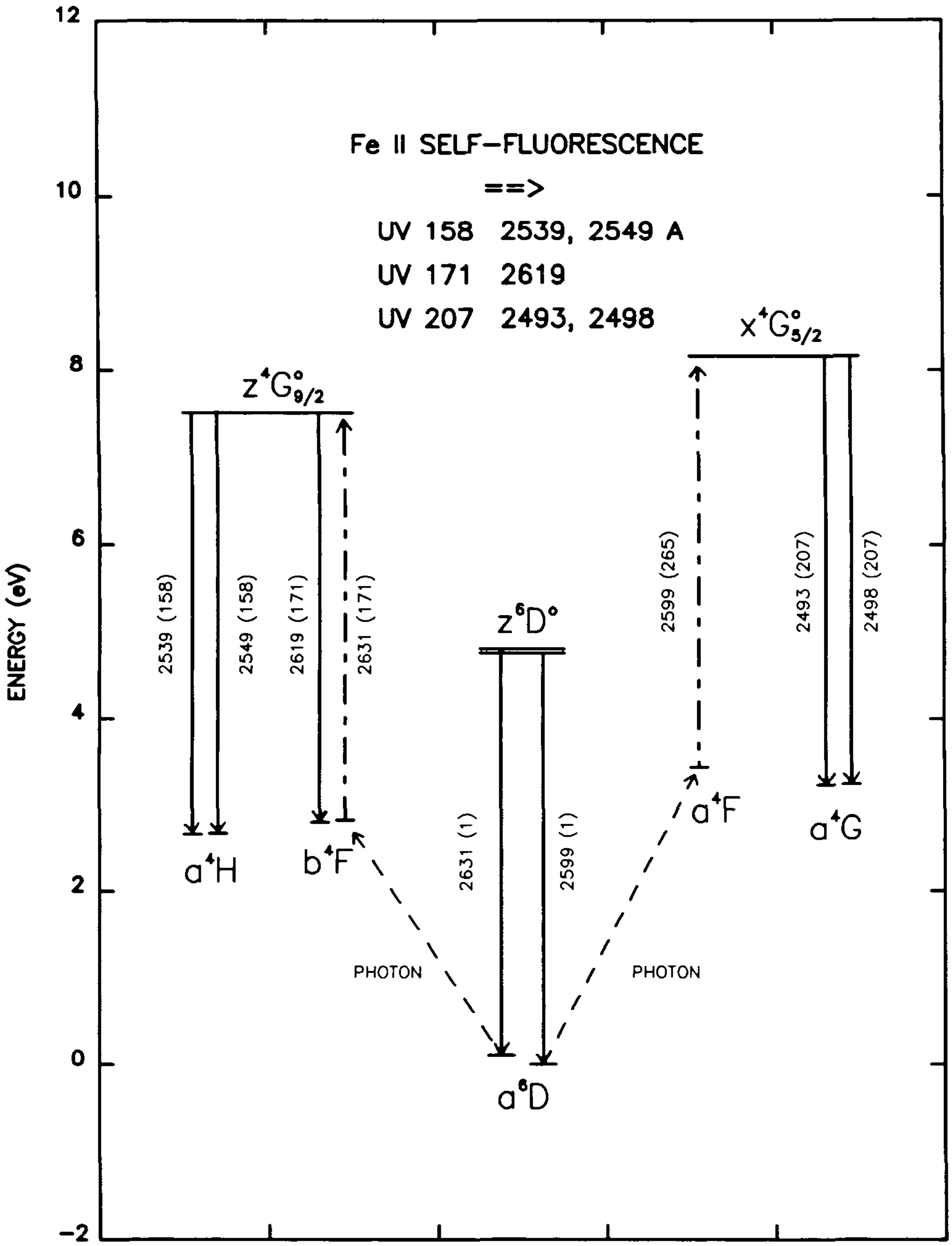

Figure 1. Partial Grotrian diagram illustrating 2 Fe II self-fluorescence processes which pump two separate levels of Fe II to produce a total of 5 fluorescent line products.

4. LYMAN-ALPHA/FE II FLUORESCENCE PROCESSES

The most prolific pump in the outer atmospheres of these stars is by far the hydrogen Lyman-alpha line near 1216 Å. This line is very broad in the non-coronal stars, extending over approximately 5 Å, for example, in the M-giant Gamma Crucis and has over two dozen coincidences with Fe II transitions with well-populated lower levels. At typical chromospheric temperatures on the order of 10,000 K, Fe II levels up to about 6.0 eV can be populated by collisions. Many lines are seen from these levels, which include the UV multiplets 1 - 5, 32 - 36, and 60 - 64. The various Lyman alpha pumps however are able to populate a number of energy levels which lie well above these collisionally-excited states, up to an excitation energy of over 13 eV. In the UV we observe both direct decays from these high-energy levels and secondary cascades from intermediate levels populated by some of the direct decays. Decays from these high-lying levels also assist in the population of the collisionally-excited levels below 6 eV, so that many of the lines from relatively low-lying upper levels are, in part, powered by Lyman-alpha photons as well.

Many of the Lyman-alpha/Fe II fluorescent features seen in these stars have been recognized for some time. In particular, several UV multiplets in the region above 2800 A were identified by Brown, Ferraz, and Jordan (Ref. 6) and Johansson and Jordan (Ref. 7) as originating from Lyman-alpha pumping processes. The UV 380, 399, and 391 lines are produced by secondary cascades from the directly pumped levels. In addition, Johansson and Jordan (Ref. 7) identified several features near 1300, 1870, 2407, 2431 and 2500 Å as direct decays from pumped levels and Jordan (Ref. 8) has added a line near 1366 Å.

Carpenter *et al.* (Ref. 2) have recently identified 9 new fluorescent products in the spectrum of Gamma Cru, which result from both previously recognized and new Lyman-alpha pumps. One of these is a secondary cascade (UV 363 at 2537 Å), while the rest are direct decays from the pumped levels. One of the direct decays is from a newly identified level of Fe II at 13.00 eV that produces a line at 1360 A (see Ref. 3 for details). The remaining lines at 1369, 2415, 2457.0, 2457.1, 2430, 2439, and 2448 A involve previously known energy levels. None of these transitions has been given a multiplet number in Moore (Ref. 9), but the specifics of the transitions are given in Ref. 2.

Figure 4 is a partial Grotrian diagram for Fe II which shows the transitions which produce lines seen in the UV spectra of non-coronal stars. It includes the lines pumped and produced by the Lyman-alpha fluorescences as well as the lines originating from upper levels populated primarily by collisions. The electronic configurations and terms are indicated on the figure, but the terms have not been broken down into levels to avoid the production of an unreadable figure! Transitions labeled with four digits are individual lines or sets of lines, with the digits specifying wavelength in angstroms. Transition labels preceded by a "UV" indicate UV multiplet numbers, *i.e.* sets of lines. The upward transitions pumped by Lyman-alpha are grouped together so that multiple transitions to the same term can be represented by a single line. "IR" indicates an infrared line or multiplet. This one figure shows the origin of about 70 % of all the lines seen in the UV spectrum of non-coronal stars!

5. SUMMARY

Selective radiative excitation of spectral lines through line fluorescence processes are a prominent line formation mechanism in the outer atmospheres of late-type giant and supergiant stars. All the emission lines of Fe I, Ni II, Si I, Co II, CO, as well as numerous lines of O I, S I, Cr II, and lines from high-lying levels of Fe II are seen in the spectra of non-coronal stars solely because of these processes. Even the "collisionally-excited" Fe II emission lines arising from levels below 6 eV, which dominate the spectral region above 2200 Å, contain some contributions from the Lyman-alpha. This may help explain the very high opacity of these latter lines and thus the "line leakage" observed in these spectra (Ref.'s 2 and 10).

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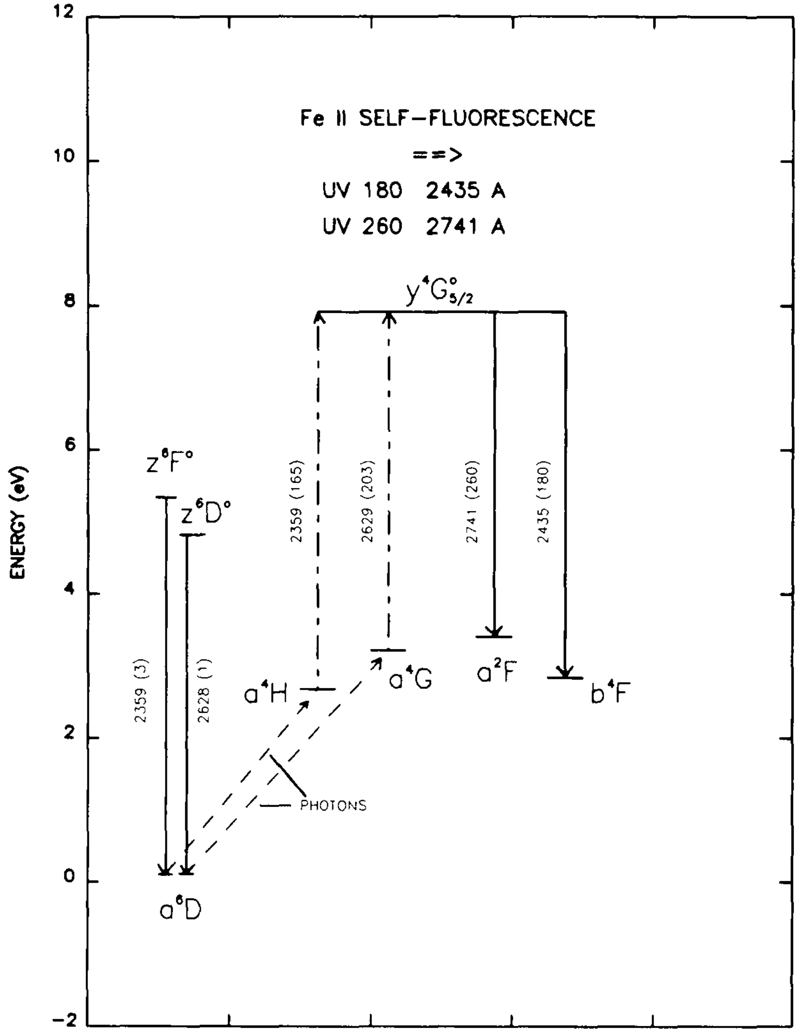

Figure 2. Partial Grotrian diagram illustrating a Fe II self-fluorescence process in which 2 separate lines pump the same level of Fe II to produce 2 fluorescent lines.

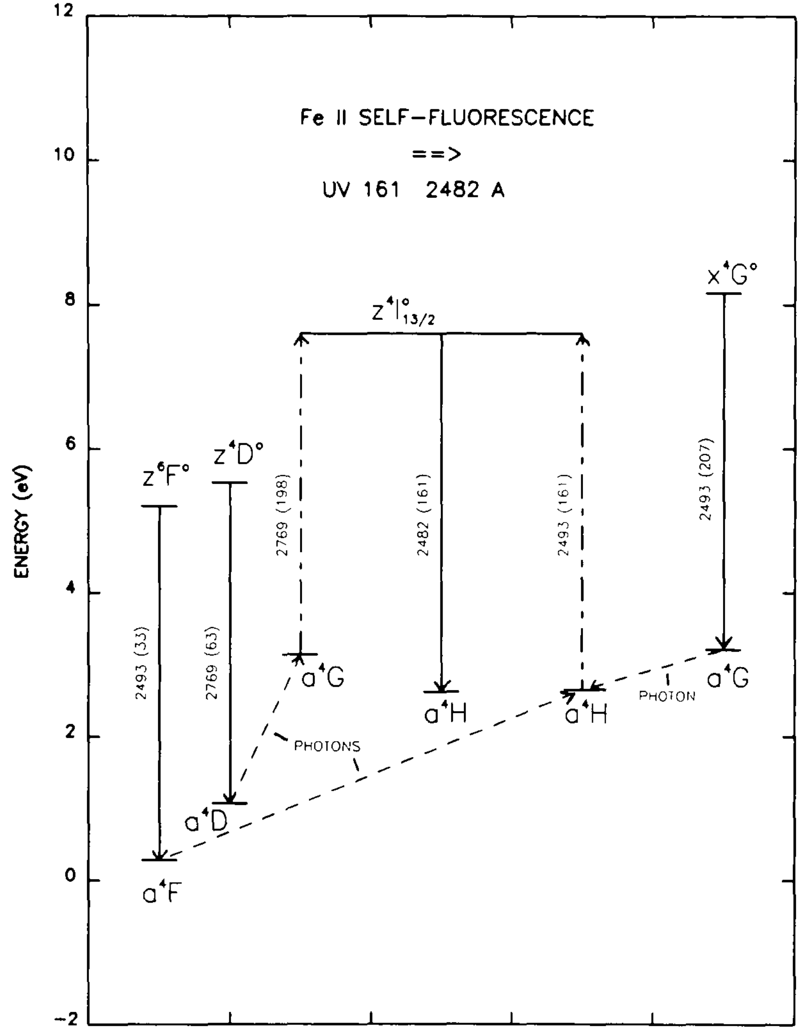

Figure 3. Partial Grotrian diagram illustrating a possible Fe II self-fluorescence process which requires 3 separate pumps to excite one Fe II level and produces a single fluorescent feature near 2482 Å.

Table 3

Fe II FLUORESCENT LINES PUMPED BY LYMAN ALPHA

Fluorescent Features	Pumped Transitions	Pumps	Reference for Process
	DIRECT DECAYS FROM PUMPED LEVEL		
Fe II (#) 1289.1 Å 1299.3 1299.4	Fe II (#) 1216.5 1215.85 1216.0	H I (UV 1) 1215.7 Å	Johansson & Jordan 1984 (Ref. 7) all weak in Gamma Cru
Fe II (#) 1360.2	Fe II (#) 1215.5	H I (UV 1) 1215.7	Carpenter et al. 1988 (Ref. 2)
Fe II (#) 1366.4 1368.8	Fe II (#) 1214.7 1214.7	H I (UV 1) 1215.7	Jordan 1988 (Ref. 8); Carpenter et al. 1988 (Ref. 2) (1368.8 weak in Gamma Cru)
Fe II (#) 1869.5 1872.7	Fe II (#) 1215.2 1215.87	H I (UV 1) 1215.7	Johansson & Jordan 1984 (Ref. 7)
Fe II (#) 2407.2, 2431.0	Fe II (#) 1216.0	H I (UV 1) 1215.7	Johansson & Jordan 1984 (Ref. 7)
Fe II (#) 2415.19, 2457.10	Fe II (#) 1216.3	H I (UV 1) 1215.7	Carpenter et al. 1988 (Ref. 2)
Fe II (#) 2430.4, 2438.5	Fe II (#) 1214.1	H I (UV 1) 1215.7	Carpenter et al. 1988 (Ref. 2)
Fe II (#) 2448.1	Fe II (#) 1216.5	H I (UV 1) 1215.7	Carpenter et al. 1988 (Ref. 2)
Fe II (#) 2457.0	Fe II (#) 1216.2	H I (UV 1) 1215.7	Carpenter et al. 1988 (Ref. 2)
Fe II (#) 2504.9, 2506.8 2506.4, 2508.3	Fe II (#) 1217.8 1218.2	H I (UV 1) 1215.7	Johansson & Jordan 1984 (Ref. 7) 2504.9 blended with UV 33
	SECONDARY CASCADES FROM PUMPED LEVELS		
Fe II (363) 2537.1	Fe II (#) 1215.7 +/-2	H I (UV 1) 1215.7	Carpenter et al. 1988 (Ref. 2)
Fe II (UV 380) 2817-2856	Fe II (#) 1215.7 +/-2	H I (UV 1) 1215.7	Brown,Ferraz,&Jordan 1981 (Ref. 6) Johansson & Jordan 1984 (Ref. 7)
Fe II (UV 399) 2824-2859	Fe II (#) 1215.7 +/-2	H I (UV 1) 1215.7	"
Fe II (UV 391) 2839-2852	Fe II (#) 1215.7 +/-2	H I (UV 1) 1215.7	"

= the transition has not been assigned a multiplet number in C. Moore's tabulations (Ref. 9); see Carpenter *et al.* (Ref. 2) for transition information.

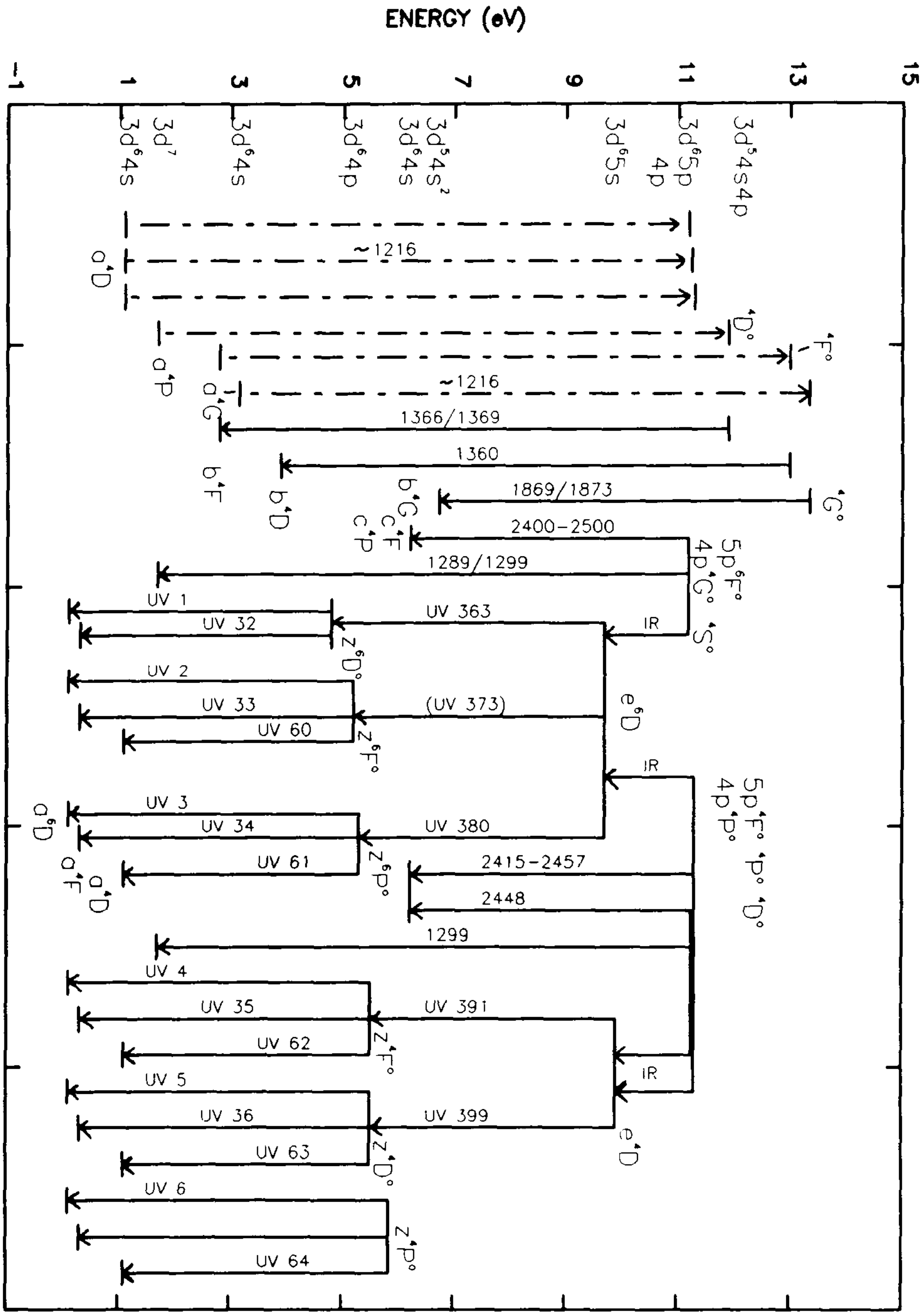

Figure 4. Partial Grotrian diagram for Fe II showing the transitions which produce lines seen in the UV spectra of non-coronal stars. The transitions pumped by Lyman-alpha are shown by dot-dashed lines, while downward transitions (*i.e.* observed emission lines) are indicated by solid lines. See the text for further details.