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Ultraviolet fluorescence lines of Fe II observed in satellite spectra of the symbiotic star RR Telescopii⋆,⋆⋆

H. Hartman and S. Johansson

Department of Physics, Lund University, P.O. Box 118, 221 00 Lund, Sweden (henrik.hartman,sveneric.johansson@fysik.lu.se)

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Abstract. By examining all emission lines of Fe II in high resolution satellite spectra of the symbiotic star RR Tel we have made a systematic study of fluorescence lines in the ultraviolet wavelength region 1200–3000 Å. We list 33 energy levels of Fe II that are selectively excited in the stellar system by photons from strong lines of H, He II, Si III, O III, C IV, O V, Ne V, and O VI. All energy levels listed are accompanied by the most probable pumping line. The subsequent decay from the pumped levels results in about 120 fluorescence lines observed in spectra recorded with the International Ultraviolet Explorer and the Hubble Space Telescope. The tables include 9 energy levels and 17 emission lines of Fe II, which are for the first time attributed to fluorescence. In a finding list we also include potential fluorescence lines, which means additional transitions from the pumped energy levels observed in laboratory spectra but not in the stellar spectra.

Key words: atomic processes – line: identification – stars: binaries: symbiotic – stars: individual: RR Tel – ultraviolet: stars

1. Introduction

Satellite observations of nebular objects or stars with extended atmospheres yield often clean emission line spectra in the ultraviolet region. Depending on the plasma conditions (temperature, density, etc.) in the line forming regions the spectrum consists of a mixture of permitted lines, intercombination lines and forbidden lines of abundant elements at various ionization stages. In general, the lines are supposed to originate either from collisionally excited energy levels or from levels, populated through recombination processes. However, in many objects a great number of the prominent lines are generated through fluorescence processes, in which photons from a strong line of one element selectively excites an ion of another element, thereby producing a high population in a particular energy state. The subsequent decay of this overpopulated energy level results in fluorescence lines, the number of which depends on the number of fast decay channels.

The classical example of fluorescence is the "Bowen mechanism" (Bowen 1935), in which the permitted optical O III lines around 3300 Å in nebular spectra are explained by a selective excitation of highly excited O III levels by the He II Lyα line. An overview of fluorescence lines in ultraviolet spectra of stars by Johansson & Hamann (1993) includes later discoveries primarily based on spectra from the International Ultraviolet Explorer (IUE). One of the objects, for which the satellite UV spectrum is rich in fluorescence lines, is the symbiotic star RR Telescopii. RR Tel has been frequently observed in high resolution with IUE and later with the Hubble Space Telescope (HST), and detailed line lists have been published. The first line identifications in the IUE spectrum of RR Tel were done by Penston et al. (1983). Later and complementary line lists based on IUE spectra have been published by Aufdenberg (1993) and Doschek & Feibelman (1993).

Johansson (1983) identified and explained 10 lines in the IUE spectrum of RR Tel as fluorescent Fe II, pumped by the 1548 Å resonance line of C IV, by using the line list of Penston et al. (1983). In a later paper (Johansson 1988) another fluorescence case in Fe II was reported, where the identification of three Fe II lines between 1700 and 1900 Å implied an indirect observation of O VI in RR Tel. The resonance line of O VI at 1032 Å, which is outside the spectral region of IUE, pumps one particular Fe II level at high energy, and the subsequent decay is observed in fluorescence. A year later Schmid (1989) reported another indirect evidence of O VI in RR Tel by solving the long-standing problem with two emission lines at $\lambda\lambda$6825 and 7082 as being produced by Ramann scattering, a non-resonant fluorescence process involving pumping by O VI on hydrogen in the H Lyβ channel.

The major fluorescence pump of Fe II in RR Tel is H Lyα, which populates a number of odd-parity levels around 90 000 cm^{-1} (11.2 eV), as discussed in detail by Johansson & Jordan (1984). These levels decay primarily in near-infrared transitions but because of mixing with highly-excited 4p levels some of them decay with high transition probabilities to 4s states, giving strong lines in the 4s-4p resonance region 2300–2700 Å. Also, secondary cascades, following the near-

Send offprint requests to: H. Hartman

⋆ Based on observations by the International Ultraviolet Explorer (IUE) and the Goddard High Resolution Spectrograph (GHRS) onboard the Hubble Space Telescope (HST).

⋆⋆ Tables 1–5 are only available electronically with the On-Line publication at http://link.springer.de/link/service/00230/

infrared decay, appear in the 2800 Å region. These lines were identified by Penston et al. (1983) and further discussed by Johansson & Hamann (1993).

Recently, Jordan & Harper (1998) extended the list of fluorescent Fe II lines in RR Tel on the basis of new identifications in spectra recorded with the Goddard High Resolution Spectrograph (GHRS) onboard the Hubble Space Telescope (HST). These new findings include pumping by the He II 1084 Å line, and either Ne V] or Si III for a highly excited energy level.

In this paper we summarize all those Fe II lines in the satellite UV spectrum of RR Tel, that can be explained by various fluorescence processes. We include 9 new cases of selectively excited energy levels of Fe II, resulting in the explanation of 17 previously unidentified emission lines.

2. Observational and laboratory data

Spectra of RR Tel obtained with the International Ultraviolet Explorer (IUE), labelled SWP20246 and LWR16187 and recorded on June 17 and 18, 1983, respectively, have been used for the line identifications in the present work. These spectra cover the wavelength range 1200–3000 Å. Penston et al. (1983) based their line list on early IUE observations from 1979. The line lists by Aufdenberg (1993) and by Doschek & Feibelman (1993) include later IUE observations with longer exposure times, which explains the new lines present in these lists but absent in the work by Penston et al.

Spectra obtained with GHRS onboard HST have also been used. The spectra were recorded in the GO-05863 programme (see e.g. Jordan & Harper, 1998). These medium resolution spectra cover parts of the wavelength range 1200 to 2700 Å, each spectrum being approximately 50 Å wide. They were calibrated using the CALHRS routine. For observations where a calibration lamp spectrum was obtained in connection with the stellar spectrum the calibration procedure WAVECAL was used to further improve the wavelength scale. The observed wavelengths have been adjusted to heliocentric wavelengths by correcting for the generally adopted heliocentric radial velocity of RR Tel, –62.3 km s^{-1}, as given by Thackeray (1977).

The atomic data used are taken from the Kurucz database (1993) for which Fe II wavelengths are based on energy levels from laboratory work by Johansson (1978, and unpublished work). In addition, papers and articles concerning line identification in RR Tel and similar objects as well as additional laboratory data are used. The multiplet numbers given in Tables 2–4 are from Moore's Multiplet tables 1950, 1959).

3. The fluorescence mechanism

The fluorescence lines we discuss in this paper have general characteristics, which are also valid for the original case, the Bowen resonance fluorescence lines, and other fluorescence lines:

a) One observes a set of emission lines coming from a particular energy level A, where there are no indications of emission from the other fine structure levels of the upper term in the same multiplet.
b) One of the decay branches from level A coincides in wavelength with a prominent line, in general from another species, and in few cases from the same species.
c) The decay of level A may occur in more than one step resulting in primary and secondary cascades.

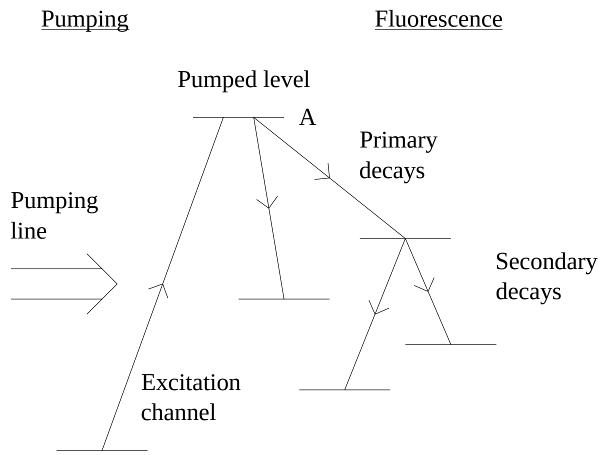

Fig. 1. Schematic picture showing the pumping and fluorescence processes (see text Sect. 3).

The first characteristic implies that level A is selectively populated, and an enhanced population is created. The relative population is not given by a Boltzmann distribution, as no emission lines are observed from energy levels of similar excitation energy. It is obvious that we observe a non-LTE population in level A. The second characteristic implies that level A is radiatively excited by photons from a strong line with a large flux, simply because of an accidental coincidence in wavelength. This strong line acts as a pump. In most cases it's not clear whether the source of the pump is located in the same plasma or cloud as the source of the fluorescence lines. In Fig. 1 we show a schematic picture of the fluorescence process with the pumping line acting on an excitation channel of an atom or ion, thereby producing an enhanced population in the pumped level A. The decay of the pumped level produces the fluorescence lines, which might result from primary and/or secondary cascades.

Various alternatives to name the fluorescence mechanism have been suggested, and there is no special notation for fluorescence lines, as there is for forbidden lines and intercombination lines. The "Bowen mechanism" is an established concept associated with the O III lines, but Bowen (1935) himself described the process as "excitation by secondary radiation". Osterbrock (1989) describes it as the "Bowen resonance-fluorescence mechanism" in his textbook. In a later paper Bowen (1947) uses the words "exciting line" for the pumping line in Fig. 1, "coincident line" for the excitation channel, and "excited lines" for the fluorescence lines. Kastner & Bhatia (1986) introduced the acronym PAR for "Photoexcitation by accidental resonance", and later Johansson & Hamann (1993) distinguished between PAR and PCR, the latter meaning "Photoexcitation by continuum radiation". The name "PAR fluorescence" would cover both the observed emission and the excitation mechanism behind it. In a recently submitted paper (Johansson et al., 2000) the notation ⟨Fe II⟩ followed by a wavelength has been suggested to indicate emission lines, which are generated by fluorescence.

4. Observed fluorescence lines of Fe II in the UV spectrum of RR Tel

As mentioned in the introduction numerous emission lines have been identified as fluorescent Fe II in the IUE spectrum of RR Tel in a number of papers. Recently, there have been additions based on HST spectra. In Table 1 we have summarized all the energy levels of Fe II that are found to be radiatively excited in different PAR processes, giving observed fluorescence lines in the satellite UV spectrum of RR Tel. For each level we have identified the excitation channel and the pumping line. For the pumped levels we have inserted the configuration and level labels using the LS coupling notation and also the excitation energy above the ground state in cm^{-1}. For the excitation channels we give the wavelength, the level notation and energy for the lower level. The level notation for the lower level is shortened by using Moore's notation in the Multiplet Tables and the Atomic Energy Levels. The table also contains levels that are populated through the primary cascade, and are thus the upper levels in the secondary cascade. These levels are marked "primary cascade" in the columns for the excitation channel. The second last column gives information about the pumping line, spectrum and wavelength, e.g. Si III] 1892, and the last column gives the reference where the fluorescence from that particular level was first identified.

The Fe II levels that are pumped by PAR processes in RR Tel range in energy from 60 000 cm^{-1} (7.5 eV) to 109 000 cm^{-1} (13.5 eV). Nearly half of them are pumped by H Lyα, and the rest of them by prominent lines in various ionization stages of He, C, N, O, Ne and Si. For the highly excited levels above 90 000 cm^{-1} there are, in general, both primary and secondary cascades. This will be discussed more in detail in the following subsections, where we place the fluorescence lines in different categories, based on the pumping lines.

The initial levels, from where the atoms are pumped, have energies in the range from zero to about 25 000 cm^{-1} ($\sim$3 eV). This indicates that the population for states with energies up to 3 eV is sufficiently high for fluorescence to occur with respect to the monochromatic flux present in the pumping line. All the initial levels are metastable states with radiative lifetimes of the order of milliseconds to seconds. A substantial population of these metastable states is further verified by the presence of forbidden [Fe II] lines in the optical spectrum of RR Tel (see e.g. Crawford et al., 1999), even though it is not possible to tell whether the fluorescence lines and the forbidden lines are formed in the same plasma. However, in spatially resolved HST spectra of Eta Carinae (T. Zethson, private communication) it is clear that fluorescence lines and forbidden lines of Fe II appear in the same nebular clouds. We find no indication of a strange population distribution among the metastable levels in general, as forbidden lines are observed in RR Tel from most of these states. There could be a slight population redistribution among levels involved in the fluorescence processes.

5. Energy levels at 11.2 eV pumped by H Lyα and the corresponding fluorescence lines

Due to the large flux in H Lyα, the high cosmic abundance of iron, and the line rich spectrum of Fe II, the selective photoexcitation of Fe II to high-lying levels is especially efficient. The Lyα pumping of Fe II may occur when the line profile of H Lyα (λ_{lab}=1215.67 Å) overlaps the line profile of Fe II transitions, that originate from levels having a sufficiently low excitation energy to be thermally populated. There is a large group of energy levels belonging to the $3d^6(^5D)5p$ configuration around 90 000 cm^{-1} (11.2 eV) that can be photoexcited by Lyα from the a^4D term at about 1 eV, giving numerous fluorescence lines in the satellite UV and near-IR wavelength regions. This was thoroughly discussed by Johansson & Jordan (1984) with applications to IUE spectra of cool stars and RR Tel. Brown et al. (1981) noted that the observed emission around 2800 Å from the 5s levels results from an enhanced population of the 5s levels, which is created by primary decays from pumped 5p levels. Later Carpenter et al. (1988) made a systematic study of the fluorescence lines seen in IUE spectra of a specific cool star, γ Gru.

In order to relate the Lyα pumping and fluorescence channels to the atomic structure of Fe II we have constructed a partial term diagram in Fig. 2. The pump photoexcites Fe II from a^4D to some 5p levels, and all levels involved are built on the same parent term, ^5D, which is also the ground term of Fe III. Therefore, we expect to find the strongest decay channels within the particular set of subconfigurations which are built on the ^5D parent term. However, the high level density in Fe II often results in configuration interaction and level mixing, and there are 4p levels (marked 4p* in Fig. 2) that mix strongly with some of the 5p levels. The result of this mixing is that some of the pumped levels at 90 000 cm^{-1} behave as they had both 5p character and 4p character, simultaneously. Since 4p and 5p levels have two different sets of decay channels, a mixed level can decay either as a 4p level or as a 5p level. Below we discuss these two cases.

Case 1: The 5p levels can decay in one step or three consequtive steps to the ground, as schematically illustrated in Fig. 2. (For simplicity the 3d and 4d states are omitted in the Figure.)
a) One step: There is a direct decay back to the ground through 5p-4s (or 5p-3d) transitions around 1000–1200 Å.
b) Three steps: The primary decay is to 5s (or 4d), the second step to 4p, and the third step from 4p down to 4s (or 3d).

Case 2: The 4p* quartet levels can also decay in one or three steps:
a) One step: A direct decay down to low quartet levels of 4s or 3d in the far UV region (not indicated in the Figure).
b) Three steps: The primary decay is an intraparent 4p-4s transition at about 2500 Å, the secondary is a 4s-4p transition in the infrared. This can occur since the high 4s states (marked 4s*) are located above the low 4p states as a consequence of

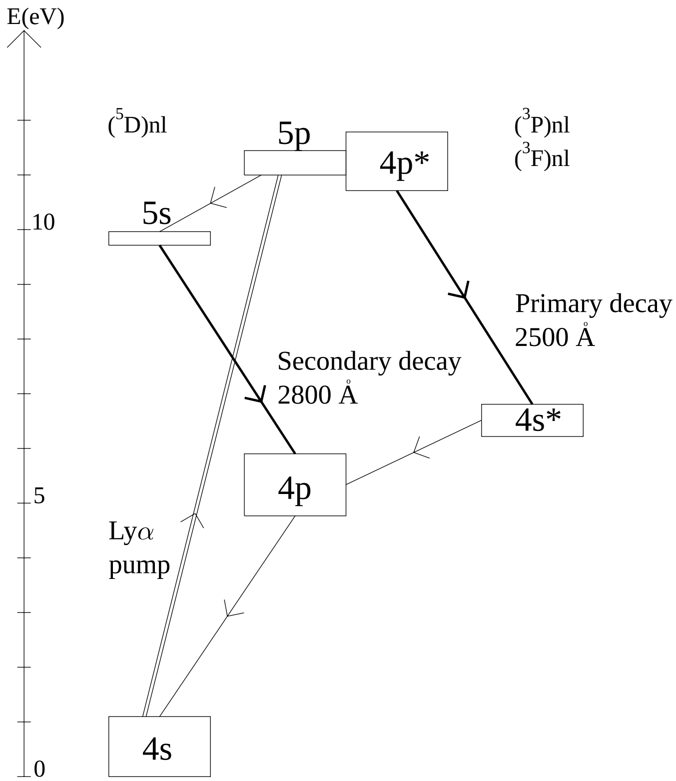

Fig. 2. Partial term diagram of Fe II. The fluorescence lines observed in the ultraviolet spectrum of RR Tel are marked with thicker lines. The 5p levels decay within the (^{5}D)nl system (to the left in the figure), and the 4p* levels decay within the (b^{3}F)nl and (b^{3}P)nl systems (to the right). The asterisk (*) marks subconfigurations of 4s and 4p that are based on the highly-excited (6 eV) parent terms b^{3}P and b^{3}F of Fe III.

an extended parent structure. The final step is the same 4p-4s transition as in the 5p case above.

The fluorescence lines that we can detect in the satellite UV region can be placed in four categories:

1) The secondary step (5s-4p, 4d-4p) in case 1b with wavelengths typically at 2800 and 2300 Å, respectively.
2) The first step in 2b, where the wavelength is around 2500 Å.
3) One possible decay route in 2a at about 1300 Å.
4) The last (common) step in 1b and 2b - the strong ultraviolet 4s-4p lines of Fe II.

In the discussion we will disregard category 4, as these lines involve the very lowest levels of Fe II and are therefore, in general, optically thick. We have not observed any 4d-4p transitions in category 1), which means that the 5p-4d transitions have low branching fractions compared to 5p-5s and 5p-4s transitions. Jordan & Harper (1998) have identified some lines as 4d-4p transitions. We cannot confirm these identifications since a number of them are blended or have alternative identifications. For example, the feature at 2482.86 Å is identified as [Fe III], see Sect. 7 below. Thus, the 4d levels are probably not sufficiently populated in the primary cascade in case 1b.

We see in Table 1 that nine of the 5p and 4p levels around 90 000 cm^{-1} are pumped by Lyα in RR Tel, as derived from the observed fluorescence lines in the satellite ultraviolet region. In the primary cascade from 5p (Case 1b above) the 5s levels are populated, and we find secondary fluorescence lines from eight of the nine 5s levels tabulated in Table 1 (excitation channel marked primary cascade). It should be noted that some of these 5s levels could be populated through decays of pumped 5p levels, that are not listed in Table 1, since the table only includes levels that have primary cascades in the ultraviolet region. The pumped transitions have wavelengths between 1213.7 and 1218.2 Å about $\pm$2 Å from the rest wavelength of H Lyα, and the corresponding excitation channels originate from the a^{4}D term. The resulting ultraviolet fluorescence lines are given in Table 2. Below we discuss some of the H Lyα pumped levels and their fluorescence lines, and we distinguish between primary and secondary cascades.

5.1. Primary ultraviolet cascades

5.1.1. 90042 and 90067

These levels are of particular interest. Since they belong to two different configurations and have the LS labels ^{6}F and ^{4}G, respectively, they are not expected to interact, but as they are close in energy and have the same parity and J-value they are strongly mixed. This mixing results in a doubling of the number of transitions, as each line from either of the two levels is accompanied by a line from the other level. The separation of the lines is determined by the difference in energy of 25 cm^{-1} between the two levels. As the pumping transitions appear at about 1218 Å the levels might be pumped by O V as suggested by Johansson & Hamann (1993).

5.1.2. 90629 and 90839

The most probable decay of these (b^{3}P)4p levels, $^4S_{3/2}$ and $^4P_{1/2}$, yields the intraparent 4p-4s transition down to c^{4}P. From $^4S_{3/2}$, the 3/2–1/2 and 3/2–3/2 transitions are observed, and there is an indication in the spectrum of the 3/2–5/2 transition. For $^4P_{1/2}$, the 1/2–3/2 transition at 2418 Å is observed, which is expected to be the strongest transition according to laboratory intensities. This stellar feature is, as described below, blended with the Fe III transition a$^5S_2$-z$^7P_3$ but the contribution from Fe III is small. The more clear indication of fluorescence from $^4S_{3/2}$ can be explained in two independent ways. The transition pumping the $^4S_{3/2}$ level differs 0.3 Å in wavelength from Lyα, whereas the transition pumping the $^4P_{1/2}$ level is 1.5 Å away. Also, the $^4P_{1/2}$ level has more of 5p character than $^4S_{3/2}$. The 4p-3d transitions from these two levels down to a^{4}P are not as strong as predicted from theoretical and laboratory intensities. It is difficult to measure or estimate their strengths in the stellar spectrum, as most of them appear as blends.

5.1.3. 90898 and 90901

These levels are very close in energy but have different J-values. 90898 is identified as the (b^{3}P)4p $^4P_{3/2}$ level, whereas 90901 is the (^{5}D)5p $^4P_{5/2}$ level. Due to the small energy difference between these levels, both can be pumped by Lyα from the same lower level. They also decay to the same lower level, $c^4P_{5/2}$, resulting in the stellar fluorescence feature at 2456.98 Å. Another common transition to $c^4P_{3/2}$ is also observed in the stellar spectrum. The wavelength difference of 0.18 Å between the two decay channels is too small to resolve in the IUE spectrum. The stellar wavelengths of the lines that are common for both levels seem to favour the $^4P_{5/2}$ level (Table 2). This is confirmed by the stellar feature at 1683.01 Å, for which the lower level has J=7/2 and can only combine with the J=5/2 level at 90901 cm^{-1}.

5.1.4. 90638 and 91048

The levels at 90638 and 91048 belong to 5p ^{4}D and have J=5/2 and J=3/2, respectively. The pumped transition for the 5/2 level is strong and is very close in wavelength to Lyα. The fluorescence that results from the decay of these levels to c^4P is substantial in RR Tel, and is further verified in the near-IR by the 5p-5s decay at 8296 Å (McKenna et al., 1997).

5.2. Secondary ultraviolet cascades

In the satellite ultraviolet spectrum of RR Tel we observe strong emission lines around 2800 Å originating from 5s levels at 10 eV. In contrast to 5p, the 5s levels are of even parity and can therefore not be explained by direct radiative pumping from the lowest levels in Fe II, as they have the same parity. The most probable explanation is that they are populated when the 5p levels decay, i.e. they belong to category 1 above. Emission lines are observed from all levels of the e^6D and e^4D terms of the (^{5}D)5s subconfiguration, except for $e^6D_{1/2}$, and they are presented in Table 4. About twenty of these 5s-4p lines were identified by Penston et al. (1983) in the IUE spectrum of RR Tel.

In Table 4 we give all (^{5}D)5s levels and list the predicted wavelengths and calculated A-values of all strong intraparent 5s-4p transitions. The lines that have been observed in IUE and GHRS spectra are indicated, as well as references to previous identification work. We can see that for some levels all or most transitions are observed in RR Tel, which implies that these levels are strongly populated through the primary cascade from 5p. In other cases, e.g. the J=1/2 and 3/2 levels of e^6D, we see no or very few lines. For details, see Table 4.

6. Energy levels above 12 eV pumped by H Lyα and the corresponding fluorescence lines

The emission feature at 1360 Å is identified as a transition from the $3d^5(^2D)4s4p(^3P)\,^4F_{7/2}$ level (Johansson & Carpenter 1988). The transitions from this particular level, that are calculated to be strong, involve the J=9/2 and 7/2 levels of b^4F and the $b^4D_{5/2}$ level. The first two transitions have wavelengths at 1218.067 and 1215.502 Å, respectively, and they act as excitation channels. It should be noted that the first wavelength coincides with a strong O V line in RR Tel at 1218.34 Å. Thus, the upper level can be photoexcited either by H I or by O V, and the only fluorescent decay observed is to $b^4D_{5/2}$ located at 1360 Å. This line has also been observed in the solar spectrum and in spectra of cool stars (Johansson & Carpenter, 1988; Carpenter et al., 1988).

The emission line at 1869,55 Å in IUE spectra of RR Tel was left unidentified by Penston et al. (1983). It was later identified by Johansson & Jordan (1984) as a transition from the level $(^2F)4s4p(^3P)\,^4G_{11/2}$ down to $b^4G_{11/2}$ in spectra of cool stars. The identification is verified by the presence of the companion transition to the $b^4G_{9/2}$ level at 1871.00 Å. The upper level can be pumped by Lyα from the $a^4G_{11/2}$ level at 3.2 eV.

7. Absence of H Lyα pumped Fe III, but presence of [Fe III]

In Fe III, the transition a^5D_4 - z^7P_3 at 1214.56 Å can be pumped by Lyα, which results in a strong Fe III fluorescence line at 1914 Å in multiplet UV 34 (Johansson et al. 2000). This process is efficiently operating in Eta Carinae, but that seems not to be the case in RR Tel. The potential fluorescence line at 1914 Å is weak in the RR Tel spectrum as well as the two other UV 34 lines at 1895 and 1926 Å. At the position of the Fe III spin-forbidden transition from the same upper level, a^5S_2-z^7P_3 at 2419 Å, there is an emission feature, but all the flux in this feature is probably due to Fe II (see Sect. 5.1.2). The transition probability of the intercombination line at 2419 Å is about two orders of magnitude smaller than the calculated transition probability for the LS allowed transition a^7S_3-z^7P_3 at 1914 Å.

Obviously the conditions for fluorescence in Fe III are not satisfied in RR Tel, either depending on a lack of Fe^{2+} ions in the region where Fe II fluorescence is significant, or a lack of Lyα flux in the region where Fe^{2+} are present in the plasma. There is a clear indication that Fe^{2+} ions are present somewhere in the symbiotic system, as the forbidden [Fe III] lines from a^5S_2 down to the ground term $a^5D_{4,3,2}$ are observed. These lines at $\lambda\lambda$2438, 2465 and 2483 do not appear in any database or compilation, but have recently been identified in the spectrum of Eta Car (Johansson et al., 2000). The 2438 Å feature was identified as UV47, $^5S_2$-z^7P_2, in Fe III by Penston et al. (1983). This seems unlikely since, as discussed above, the 1926 Å line from the same upper level is weak in the stellar spectrum, and it is predicted to be two orders of magnitude stronger than the 2438 Å line. The two other [Fe III] lines at 2465 and 2483 Å were observed but left unidentified by Penston et al. (1983).

8. Energy levels pumped by lines from other species than hydrogen.

In addition to the levels photoexcited by H Lyα, as discussed in the previous sections, there are indications of Fe II levels pumped by strong lines of highly ionized ions. In many of these cases the pumping occurs in transitions from metastable levels of $3d^7$ and $3d^64s$ to levels of the $3d^6$ 4p configuration around 8–10 eV. Fluorescence lines originating from levels pumped by O VI and C IV have previously been reported by Johansson (1983, 1988). Jordan and Harper have reported Fe II pumping by lines of He II and Si III (1998). In the present work we present new cases of Fe II fluorescence, due to pumping by He II, O III], C IV, N IV], [Ne V], Si III] and [Fe IV]. The Fe II levels pumped by these ions are included in Table 1, and the predicted lines and observed fluorescence lines in RR Tel are given in Table 3.

8.1. He II

Jordan & Harper (1998) identified three lines in the GHRS spectrum of RR Tel as originating from the $x^4H_{11/2}$ level at 92166 cm^{-1}. They identified the pumping line as the 1084 Å line in He II, which coincides in wavelength with the ground state transition $a^6D_{9/2}$-$x^4H_{11/2}$. The cause for this strange transition, having ΔS=1 and ΔL=3, is a mixing of the x^4H level with a ^6F level of the same configuration, $3d^5 4s4p$.

The transitions from $x^4H_{11/2}$ that are calculated to be strong are observed in RR Tel. Penston et al. (1983) identified one of them, the 2638 Å feature, as Al II, 3s3d $^3D_2$-3s5f $^3F_3$. However, the strongest Al II transitions from 3s3d $^3D_2$ are to 3s3p ^3P, and they are not observed in the spectrum. This makes it more probable, as pointed out by Jordan & Harper (1998), that the 2638 Å is fluorescent Fe II.

In addition to this previously reported $x^4H_{11/2}$ level, we have found another Fe II level that might be pumped by the He II line at 1084 Å, namely $u^2G_{9/2}$ at 92171 cm^{-1}. However, the intensity ratios observed in the stellar spectrum differ from those given by laboratory measurements and theory. The two strongest transitions, down to $d^2F_{7/2}$ and $c^4F_{9/2}$, are present, the latter being blended with $a^4F_{7/2}$-$z^4D_{7/2}$. There are also indications in the stellar spectrum of the two predicted lines around 1400 Å. According to theory, they should be stronger than observed.

8.2. C IV

Two levels, $y^4H_{11/2}$ and $w^2D_{3/2}$, are pumped by one of the resonance lines of C IV at 1548 Å. From $y^4H_{11/2}$, as reported by Johansson (1983), more than 10 strong fluorescence lines are seen.

From $w^2D_{3/2}$ the intra-parent transitions to c^2D levels are seen in IUE spectra, but they were unidentified in the line list by Penston et al. (1983). The transitions to $3d^7$ a^2P are calculated to be strong but they are faint in the stellar IUE spectrum. The transition at 2422 Å to (^1S)4s $a^2S_{1/2}$ is absent in the observed spectrum, but the fluorescence is observed in two other transitions. In total, four observed lines from $w^2D_{3/2}$ that have no other identification support the fluorescence from this C IV pumped level, and disagreements in the intensities may be due to problems with the calculated values.

8.3. N IV]

From the level $u^4F_{3/2}$, most certainly pumped by N IV] at 1486 Å, the strong intraparent transition to $c^4F_{3/2}$ is detected. There is also an indication of the transition to the $c^4F_{5/2}$ level.

8.4. O III]

Penston et al. (1983) identified five transitions from the $z^2G_{9/2}$ level, and more lines are observed in IUE and GHRS spectra. The wavelength coincidence between the $a^4F_{9/2}$ - $z^2G_{9/2}$ transition and O III] at 1660.803 Å is most probably responsible for the pumping. The difference between the rest wavelengths is only 36 mÅ. In addition, $a^2H_{9/2}$ - $z^2G_{9/2}$ coincides with [Ne IV] but since this line is weaker and the energy of the $a^2H_{9/2}$ is about 2.5 eV, this excitation channel is probably less efficient.

8.5. O VI, primary and secondary cascades

Transitions from the highly excited Fe II level (^3F)5p $^4D_{5/2}$ at 13.7 eV are really strong in RR Tel. They have been identified by Johansson (1988) as a result of pumping by O VI 1032 Å. These identifications implied the presence of strong O VI lines in RR Tel, which has later been confirmed in HUT-spectra studied by Espey et al. (1995). A further evidence of this pumping is the presence of strong 5s-4p transitions originating from the 5s level $f^4F_{5/2}$ at 99824 cm^{-1}, which can be populated via primary cascades from the O VI pumped 5p level at 13.7 eV (Jordan & Harper, 1998). The lines are due to secondary cascades to 4p levels around 2650 Å.

8.6. [Ne V]

According to calculations, the strongest ultraviolet lines from $x^4G_{7/2}$ are the intraparent transitions to $a^4G_{7/2,9/2}$. These lines are strong in the spectrum of RR Tel, and a pumping of the $x^4G_{7/2}$ level is verified by a few other lines. Fluorescence from this level, which is most probably pumped by [Ne V] at 1574 Å, has not been reported before. The transition to $a^4F_{5/2}$ is computed to be one of the strongest transitions, $A \sim 10^8$ s^{-1}, but it appears as a weak line in the laboratory as well as in the stellar spectrum.

8.7. Si III] and Si III

From the level $x^4F_{5/2}$ at 66522 cm^{-1} the strong lines to $b^2P_{3/2}$, $a^4G_{7/2}$ and $a^2F_{7/2}$ are observed in the RR Tel spectrum. The unexpected strength of the transitions to the doublet levels is explained by a mixing between $x^4F_{5/2}$ and $y^2D_{5/2}$. This illustrates that the concept "intercombination line" has no or little meaning in a complex spectrum like Fe II. The $a^4G_{5/2}$-$x^4F_{5/2}$ at 2470 Å is blended by a forbidden [O II] line. The $a^4P_{3/2}$-$x^4F_{5/2}$ line is masked by the strong stellar feature at 1892 Å identified as Si III], and this wavelength coincidence can probably explain the pumping of the $x^4F_{5/2}$ level. The transitions to a^4F are not detected in the observed spectrum despite high values of the calculated transition probabilities.

Three transitions from the $z^4G_{9/2}$ level of the $3d^6$(^3H)4p subconfiguration were identified by Penston et al. (1983). Six additional transitions have now been identified in the IUE and GHRS spectra. The transition $a^4D_{7/2}$-$z^4G_{9/2}$ coincides with the strong semiforbidden Si III], which apparently acts as the pump.

The transitions from $(^4G)4s4p(^1P)\ ^4H_{9/2}$ down to $b^4G_{7/2,9/2}$ were identified in IUE spectra by Aufdenberg (1993) and confirmed in GHRS spectra by Jordan & Harper (1998). The lines are close in wavelength and not resolved in IUE spectra, whereas the two lines are clearly resolved in the GHRS spectra. The intensity ratio of the two close lines is 6.9 in the laboratory source, 6.7 in the theoretical calculation (see Table 3), and is observed to be 6.8 in the GHRS spectrum. The transitions to $a^4H_{9/2}$ and $a^4G_{7/2}$ are blended with Ne V 1146 Å and Si III 1206 Å, respectively, which together may provide the pumping.

8.8. [Fe IV]

Penston et al. (1983) observed the transitions from $z^4G_{5/2}$ to $b^4F_{3/2,5/2}$ (the 5/2–3/2 transition being blended by another Fe II line), and the transition to $a^4H_{7/2}$ (blended by a weak Si III feature). The $b^2P_{3/2}$-$z^4G_{5/2}$ line at 2835 Å is blended by [Fe IV]. The level $b^2P_{3/2}$ has the energy 25787 cm^{-1} and has a smaller thermal population than lower lying levels.

8.9. ⟨Fe II⟩

The strongest transitions from $(^1G)4p\ x^2H_{9/2}$ are observed. The population process is somewhat uncertain, but the $3d^7\ a^2G_{9/2}$-$x^2H_{9/2}$ transition at 1776 Å differs only 20 mÅ in rest wavelength from the Fe II line, pumped by O VI (see Sect. 8.5). The transition to the ground term $a^6D_{7/2}$-$x^2H_{9/2}$ coincides with a strong Si IV feature, but the transition probability is small, $A\sim 10\ s^{-1}$.

9. Summary

The ultraviolet emission line spectrum of RR Tel as recorded by the spectrographs onboard the IUE and HST space telescopes contains lines from elements with a high solar abundance. Besides strong resonance lines, intercombination lines and forbidden lines of mildly ionized elements having $Z<20$, numerous permitted lines of singly ionized iron, Fe II, are observed. There is no correlation between the presence and the intensities of the stellar Fe II lines and the Fe II spectrum observed in a laboratory light source or a Fe II spectrum predicted from a plasma in thermal equilibrium. However, there is a consistency in the Fe II lines observed in RR Tel in the sense that they come from particular energy levels, which span in energy from 5 eV to 13.8 eV. In this energy regime there are about 900 energy levels known in Fe II, but we observe only transitions in RR Tel from about 50 of them. The common feature for about 30 of these energy levels is that they have transitions that coincide in wavelength with strong lines from other species in the stellar spectrum. The particular Fe II energy levels are thus selectively excited by photons from these strong lines of H, He, C, N, O, Ne, Si, etc. The only evidence for this conclusion at this stage is the coincidence in wavelength between a pumping line and an excitation channel in Fe II and the consistency in the presence of fluorescence lines expected to be observed when these photoexcited levels decay. This expectance is based on laboratory and theoretical intensities.

The radiation in the fluorescence lines that escapes the nebula is thus energy removed from the strong lines of the lighter elements, and one has to be careful when the intensity ratios of the latter lines are used for density and temperature diagnostics. It is not clear from this study where the fluorescence takes place, but the large variety in ionization stage for the pumping lines (H I to O VI) implies an interaction between radiation and matter from plasmas having a large difference in temperature. It is surprising that the newly found fluorescence case in Fe III (Johansson, 2000) where H Lyα is the pump is nearly absent in RR Tel, in spite of the large span in ionization for the lighter elements and the presence of [Fe III] lines. The Fe III fluorescence is prominent in gaseous ejecta of Eta Carinae, where the temperature is low.

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