Fluorescence Lines in Eta Carinae and Other Objects

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1. Introduction

The theme for this meeting is objects showing strange emission line spectra, such as η Carinae, and in this paper we discuss the influence of fluorescence lines. The occurrence of such lines is often associated with low density regions. The most famous fluorescence case is the Bowen mechanism, in which high-excitation O III lines in planetary nebulae were identified and explained by Bowen 65 years ago (Bowen, 1935) as being generated by selective pumping by the He II Lyα line at 303 Å. Between 1930 and 1980 a few new fluorescence cases were identified in the optical region, but from the observations with the International Ultraviolet Explorer (IUE) in the beginning of the 1980’s several objects showed ultraviolet fluorescence lines, as summarized by Johansson & Hamann (1993).

One of the earliest fluorescence cases in IUE spectra was the HLyα pumping of Fe II in cool star chromospheres (Brown et al. 1981), which was further studied by Johansson & Jordan (1984) and applied to γ Cru by Carpenter et al (1988). The lines become detectable in the ultraviolet when the continuous spectrum becomes weak on the blue side of the Planck curve. Secondary cascades of the HLyα pumping of Fe II appear around 2800 Å which were early observed in the IUE spectrum of RR Tel (Penston et al 1983), and some lines in this object could be explained as Fe II fluorescence generated by O VI and C IV. The UV spectrum of RR Tel is rich in permitted Fe II lines, and nearly all of the lines are selectively photoexcited by strong lines (Hartman & Johansson 2000; these proceedings).

In recent papers (cf. Sigut & Pradhan 1998) attempts have been made to model the fluorescence line spectrum generated by HLyα, in particular the Fe II lines. This is possible if experimental values of the energy levels are known to generate accurate wavelengths, and if there are reliable f-values available for the pumped channels and for the fluorescence lines. Since many fluorescence lines in the UV region are secondary channels in the decay routes of the pumped levels, reliable data are needed for all branches in the cascading decay scheme.

The IUE spectrum of η Carinae showed narrow, enhanced Fe II emission, and this was ascribed to fluorescence by Viotti et al. (1989). Due to the higher spatial resolution of HST spectra it became clear from HST/GHRS observations that these fluorescence lines could be associated with the narrow lines formed in the gaseous condensations outside the central star. The most striking case is the 2507 Å lines discussed in these proceedings by Johansson & Letokhov. The

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excitation channel for these lines was already discussed by Johansson & Jordan (1984) and Johansson & Hamann (1993).

In his book on planetary nebulae, Pottasch divides the line spectra of low density nebulae into two main classes:
A) Those lines formed by recombination of ions through the capture of an electron by a positively charged ion, and
B) Those lines formed by collisional excitation of an atom or ion (usually by an electron), followed by spontaneous radiation.

In the present paper we also discuss another class of lines, fluorescence lines, which are formed by photoexcitation by the continuous radiation (PCR) from a central star or by photoexcitation by an accidental resonance (PAR) in wavelength between a strong line (the pumping line) and a low-excitation transition (the pumped line) in an atom or ion in the low-density plasma. The pumping line is often a recombination line of hydrogen or helium, belonging to class A above, but it could also be a resonance line of some other spectrum (e.g. C IV, O VI etc). We discuss also the possibility that these higher ionization states might be generated by two-photon processes (RETPI) involving only hydrogen and helium lines. Hydrogen and helium ions are produced by blackbody radiation from a nearby star, and photons from the recombination lines from these elements produce the ions of the other elements inside the nebula. Thus, H and He can to a great part control the line radiation from low-density plasmas. Finally, we also discuss some collisionally excited Fe II lines around 1 \mu m in \eta Carinae, previously thought to be fluorescence lines.

2. Formation and location of fluorescence lines

The two types of fluorescence lines discussed in the introduction are distinguished by the pumping radiation, which is either monochromatic (single strong line, PAR) or broadband (blackbody radiation, PCR). Recent papers on Fe II fluorescence give good examples of the two different mechanisms: Nearly all UV line emission in RR Tel is explained by fluorescence formed in a great number of PAR processes (Jordan & Harper 1998, Hartman & Johansson 2000, and references therein), and nearly all UV emission in KQ Puppis is explained by fluorescence formed by photoexcitation by continuum radiation (PCR) (Redfors & Johansson 2000). However, it is not clear where the fluorescence takes place in these objects.

In \eta Carinae it is apparent from GHRS and STIS spectra that the fluorescence lines are formed in the gaseous condensations outside the central star, i.e. in the Weigelt blobs and other stellar ejecta. It is also generally understood that the origin of the fluorescence light is stellar radiative energy, either blackbody radiation or monochromatic UV line radiation or a combination of the two, transferred to the blobs and converted into photons with lower energy (in most cases) through PAR processes. The strongest fluorescence spectrum appears in the Weigelt blobs close to the star, and the intensities of the fluorescence lines decrease with distance from the star. However, anomalies occur. At one location, with a projected angular distance of 1.3 arcsec from the star, Zethson et al (1999) found three different radial velocities from tripled Cr II and Ni II lines, but the fluorescent Fe II lines appeared as single lines corresponding
to the lowest radial velocity of the Cr II lines (see Figs. 7 and 8 in the paper by Zethson et al.). The single-peaked fluorescence lines of Fe II originate from energy levels at 11 eV pumped by H Lyα, and the triple-peaked Cr II and Ni II lines are from low-excitation energy levels (5-6 eV). Also, low excitation Fe II lines appear with three components, consistent with the observations of Cr II and Ni II. The finding by Zethson et al. (1999) implies that the three peaks refer to three different "blobs having different velocities, and that the plasma conditions in one of these blobs are suitable for fluorescence to occur. There is no clear indication that possible differences in the distance between the star and the three blobs should cause the distinct differences in their spectra.

A comparison of the fluorescence spectra in RR Tel and η Carinae reveals remarkable differences. H Lyα pumping generates nearly all fluorescence lines in η Carinae, whereas there are many different pumping lines of various elements and ionization stages (e.g. H I, He II, C IV, O VI, Ne V) behind the fluorescence lines in RR Tel (Hartman & Johansson 2000 and references therein). In spite of the high temperature and luminosity associated with the central star of η Carinae, there is no sign of the pumping of Fe II by e.g. C IV and O VI, which causes strong and many fluorescence lines in RR Tel. On the other hand, we do not see the fluorescent Fe III UV 34 line pumped by H Lyα in RR Tel, which is very strong in η Carinae (Johansson et al 2000). The observational facts about the PAR processes in RR Tel and η Carinae can be summarized:

- In RR Tel the selective photoexcitation (pumping lines) is provided by radiation from most abundant elements and many different ionization stages, indicating a large spread in the excitation temperature. The pumped atoms (ions) that show fluorescence, predominantly Fe II, have low excitation temperature.

- In η Carinae the selective photoexcitation (pumping lines) is provided nearly exclusively by radiation from H Lyα. The pumped atoms (ions) showing fluorescence are Fe II, Fe III, Cr II and Mn II, indicating a somewhat higher excitation temperature than for RR Tel.

There is another observational fact that has bearing on the fluorescence lines in η Carinae. At the spectroscopic event, occurring with a period of 5.5 years, the intensity of the He I line λ6678 is reduced (Damineli et al 2000). Also, the intensities of lines from doubly ionized elements, e.g. Fe III, N III, Si III, Ne III, etc are substantially reduced, as well as all H Lyα pumped fluorescence lines of Fe II and Fe III. This is illustrated in Figure 1, where we show a region around 1900 AA with the Si III recombination line and the H Lyα pumped Fe III line, denoted <Fe III>. The two spectra are from the same spatial region, but recorded at two different dates, March 1998 and February 1999, i.e. 3 and 14 months after the latest spectroscopic event, respectively. The correlation between the intensity variation of the Si III] and <Fe III> lines raises the question whether H Lyα also has an influence on the production of doubly charged ions in the blob. Generally, both lines are supposed to result from recombination of the next higher ions, which are created by the blackbody radiation from the star. However, from the intensity ratios of the three components of the Fe III UV 34 multiplet, it is evident that the J=3 component at 1914 Å is selectively excited. In the next section we discuss the possibility that the Si^2+ ions are produced in a resonance-enhanced two photon ionization (RETPI) process.
3. Resonance-enhanced two photon ionization (RETPI).

Low-density plasmas outside bright stars, e.g. planetary nebulae or the blobs in η Carinae, are supposed to be ionized by blackbody radiation from the central star. For the production of multiply charged ions with high ionization energies that process requires a central star with a high temperature. A more efficient process is the resonance-enhanced two photon ionization (RETPI), where two photons from the same strong UV line or from two different UV lines, e.g. the Lyman series of H I or He II, can produce the next higher ion via a near-resonant intermediate excited state (Johansson & Letokhov 2001). We illustrate the process by showing a schematic picture to the right in Figure 2, where the energy difference between the real and the virtual state (2) is represented by the frequency detuning $\Delta \nu$. The second photon leaves the atom in an ionized (i) state. The hydrogen and helium ions generating the photons ($h\nu$) are produced by blackbody radiation from the central star, and the Lyman lines appear as a result of recombination in the plasma. The Lyman lines are supposed to be optically thick and trapped in the plasma. The lowest ionization stages can in general be formed in a RETPI process with Lyman lines of H I and may then undergo further RETPI to form higher ionization stages (+3, +4) with the inclusion of Lyman lines of He II.

This process offers a correlation between the internal H Lyα radiation field and the presence of lines from doubly ionized elements as well as H Lyα pumped fluorescence lines. Is there a possibility that the blackbody radiation from the
4. The 1 \( \mu \text{m} \) lines of Fe II in \( \eta \) Carinae and other objects

Quantitative analyses of Fe II lines in emission line objects assume in general that forbidden lines, i.e. parity-forbidden transitions between metastable states within the complex of the low even-parity configurations \( 3d^7, 3d^64s \) and \( 3d^54s^2 \), are collisionally excited. However, many of the metastable states are also populated by decays from odd-parity levels photoexcited through fluorescence processes (see Fig 2, left). The population of many metastable states is thus not de-
scribed by statistical distribution laws. This has recently been shown by Verner et al. (2000) to be the case in the Orion nebula, where continuum fluorescence plays an important role for the population of metastable Fe II states.

In light of this we have investigated some particular 3d$^6$4s states, located at higher excitation energy ($\approx 6$ eV) but still belonging to the low complex of even-parity configurations. The levels are represented by two quartet terms, c$^4$P and c$^4$F, shown to the left in a partial term diagram of Fe II in Figure 3. We see that c$^4$P and c$^4$F can decay by allowed electric-dipole (E1) transitions obeying the LS selection rules (!) to the odd z$^4$D$^0$, z$^4$F$^0$ and z$^4$P$^0$ terms of the 3d$^6$4p configuration at 2.2 and 1.6 $\mu$m, respectively. We thus face the situation where a 4s electron is less tightly bound than a 4p electron, i.e. the excitation energy of the 4p levels is smaller than the excitation energy of the 4s levels. It is like having the energy levels in the H and K lines of Ca II interchanged. How is that possible? In the complex structure of Fe II the parent configuration in Fe III, 3d$^6$, has 16 different LS terms, each of which can attach a 4s or a 4p electron. The spacing of the parent configuration is larger than the difference in binding energy between a 4s and a 4p electron. Hence, the 3d$^6$4s levels built on the highest parent term are located at higher energy than the 3d$^6$4p levels built on the lowest parent term (cf. Johansson 1978). In spite of the fact that LS-allowed electric-dipole channels are opened up for c$^4$P and c$^4$F, they still behave more like metastable states than ordinary excited states. It turns out that c$^4$P and c$^4$F have large radiative lifetimes, 16 ms and 1 ms, respectively, (see Figure 3, left), and only slightly shorter than the radiative lifetimes for purely metastable states ($\approx 10$ ms-1 s). We have therefore chosen to call them "pseudo-metastable states as they belong to the ground configuration but have allowed radiative decay channels.
To the right in Figure 3 we have included the quartet terms $d^4P$ and $b^4G$ of the $3d^54s^2$ configuration. These levels have shorter lifetimes than $c^4P$ and $c^4F$, of the order of 10 $\mu$s, even though their transitions "down to the $z^4P_o$ and $z^4F_o$ terms represent so called "two-electron jumps", which in general have low transition probabilities. The corresponding lines (called "the 1 $\mu$m lines (Rudy et al 1991)) appear in the region between 9000-10000 Å and the strongest one, $z^4F_{9/2}-b^4G_{11/2}$, is the 9997 Å line, observed to be strong in many emission line objects. As a matter of fact, when Thackeray (1969) first observed $\lambda 9997$ in $\eta$ Carinae, its identity was not known, but it initiated an extended laboratory analysis of Fe II (Johansson 1978). After the identification of the 9997 Å line (and other lines in the same multiplet at $\lambda \lambda 10501$, 10863, 11126) in $\eta$ Carinae (Johansson 1977), the line has been very much discussed, as its strength in astrophysical emission line spectra often has rivaled the strength of Pa$\delta$ (or Pa$\gamma$), located at 10049 Å.

Table 1. Relative intensities of the 1$\mu$m lines observed in spectra of LkH$\alpha$101, $\eta$ Car from ground and with STIS, and I Zw 1.

<table>
<thead>
<tr>
<th>$\lambda$ (Å)</th>
<th>LkH$\alpha$ 101</th>
<th>$\eta$ Car ground</th>
<th>$\eta$ Car STIS</th>
<th>I Zw 1</th>
</tr>
</thead>
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<tr>
<td>9997</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<td>9956</td>
<td></td>
<td></td>
<td>0.16</td>
<td></td>
</tr>
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<td>10174</td>
<td>0.27</td>
<td>0.4</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>10490</td>
<td>0.90</td>
<td>0.2</td>
<td></td>
<td>0.45</td>
</tr>
<tr>
<td>10501</td>
<td></td>
<td></td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>10863</td>
<td>0.79</td>
<td>0.7</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>11126</td>
<td>0.63</td>
<td>0.4</td>
<td>0.22</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Experimental, theoretical and observed relative intensities of the 1$\mu$m lines

<table>
<thead>
<tr>
<th>$\lambda$ (Å)</th>
<th>$J_{upper}$</th>
<th>Exp.</th>
<th>Theory/Exp.</th>
<th>LkH$\alpha$/Exp.</th>
<th>$\eta$ Car/Exp.</th>
<th>$\eta$(STIS)/Exp.</th>
<th>I Zw 1/Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>9997</td>
<td>11/2</td>
<td>1.00</td>
<td>1.00</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>9956</td>
<td>9/2</td>
<td>0.07</td>
<td>1.14</td>
<td></td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10174</td>
<td>9/2</td>
<td>0.11</td>
<td>1.18</td>
<td>2.4</td>
<td>3.6</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>10490</td>
<td>7/2</td>
<td>0.06</td>
<td>1.17</td>
<td>1.6</td>
<td>3.3</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>10501</td>
<td>9/2</td>
<td>0.49</td>
<td>1.10</td>
<td></td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10863</td>
<td>7/2</td>
<td>0.33</td>
<td>1.18</td>
<td>2.1</td>
<td>2.1</td>
<td></td>
<td>3.4a</td>
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<tr>
<td>11126</td>
<td>5/2</td>
<td>0.26</td>
<td>1.15</td>
<td>2.4</td>
<td>1.5</td>
<td></td>
<td>0.8</td>
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The seemingly anomalous strength of the 9997 Å line led to the suspicion that it is enhanced due to some selective excitation, e.g. a cascade in a fluorescence process. As a matter of fact, it is a secondary step in the cascade decay
from a H\(\text{Ly}\alpha\) pumped level of Fe II, discovered by means of strong fluorescence lines around 1850 Å in IUE spectra of cool stars (Johansson & Jordan 1984). Such a process could enhance one particular line compared to the other components of the multiplet. This secondary cascade has therefore been proposed as a possible explanation to the strength of the 9997 Å line (Johansson 1990). However, in the STIS spectra of the blobs of \(\eta\) Car the primary UV cascade of this process is very weak (Zethson 2001). This is also the situation in the narrowline, type 1 Seyfert galaxy I Zw1, where Rudy et al. (2000), draw the conclusion that the upper levels of the 1 \(\mu\)m lines probably are collisionally excited.

With modern near-infrared detectors it is now possible to get accurate intensities of nearly all the 7 components of the \(\text{z}^4\text{F}^o\) -\(\text{b}^4\text{G}\) multiplet. In Table 1, we present ground based data from the literature of the young stellar object LKH\(\alpha\) 101, \(\eta\) Carinae (Rudy et al. 1991), and I Zw1 (Rudy et al. 2000), as well as STIS data from \(\eta\) Car (Zethson 2001). In Table 2 we also present relative experimental and theoretical intensities of the lines in the multiplet, and compare them with the observed intensities. The intensities from each source are given relative to the strongest line at 9997 Å, whose intensity is set to one. The comparison between the sources is done by dividing the relative value for each source in Table 1 with the relative experimental value in Table 2. The resulting ratio shows if the stellar intensity of any line is enhanced relative to another line, i.e. if there is any selective excitation of any level. In most stellar spectra the two components at 10490 and 10501 Å are blended.

The result of this exercise is the opposite of what was expected - the 9997 Å line is relatively weaker than the other components, and there is no reason to search for a selective excitation of the \(J=11/2\) level of \(\text{b}^4\text{G}\). Rudy et al (2000) come to the same conclusion about the relative line intensities in I Zw 1, and discuss different possibilities how to excite the upper term \(\text{b}^4\text{G}\) of the 1\(\mu\)m lines. One possibility they consider is to feed \(\text{b}^4\text{G}\) from the H \(\text{Ly}\alpha\) pumped levels around 90000 cm\(^{-1}\), but such transitions are not seen in the laboratory source. The coupling of the electrons in the 3d\(^5\)4s\(^2\) configuration, to which \(\text{b}^4\text{G}\) belongs, suggests that it could be populated by cascades from levels around 110000 cm\(^{-1}\), as is the case in cool stars, but such lines are not seen in the spectra of \(\eta\) Car and I Zw 1, as pointed out above. This could support the conclusion the the levels are collisionally excited as was suggested by Hamann & Persson (1989). However, the evidence for collisional excitation of the 3d\(^5\)4s\(^2\) terms \(\text{b}^4\text{G}\) and \(\text{c}^4\text{P}\) is recently questioned by a new finding in the blob spectrum of \(\eta\) Car, where Zethson (2001) has found that lines from a third quartet term of the 3d\(^5\)4s\(^2\) configuration, \(\text{c}^4\text{D}\), located less than 0.7 eV above \(\text{b}^4\text{G}\), are a factor of 10 fainter than the 1 \(\mu\)m lines.

As we see from Table 2 there is a good correlation between the laboratory and calculated intensity ratios, plotted in Figure 4, which means that the calculated log \(gf\)-values are probably very reliable. (Figure 4 contains also a line from another multiplet but with an upper level from \(\text{b}^4\text{G}\).) It should be pointed out that it is extremely difficult to measure the oscillator strengths in the laboratory, due to the value of the radiative lifetimes. In a current project on Fe II, the FERRUM Project, we have measured lifetimes in the ns regime and in the ms regime, but have not found a way to measure lifetimes in the \(\mu\)s regime.
5. Conclusions

We present examples of emission lines enhanced in spectra of the blobs of η Carinae and other objects due to H Lyα induced fluorescence. The intensities of these lines change during the spectroscopic event in η Carinae. The intensity change is correlated with the intensity of emission lines from doubly ionized atoms, e.g. Si III. The presence of Si$^{2+}$ ions may also be controlled by hydrogen as the ions can be produced in resonance-enhanced two-photon ionization processes involving Lyman lines of hydrogen. Most doubly charged ions might be produced by trapped radiation in Lyman lines of hydrogen and helium. Near-infrared lines around 1μm, previously thought to be produced in fluorescence processes might be the only Fe II emission lines, solely produced by collisions, even though new findings imply some anomalies. The metastable states, thought to be collisionally excited, are probably also populated through primary or secondary decays from radiatively excited states.

References

Bowen, L.S., 1935, ApJ. 81, 1
Discussion

**Gull:** The comment about excitation by collisions leading to FeII UV 191 (via) H 2s metastable state is definitely relevant to Eta Car. Superimposed upon the scattered stellar Balmer lines in the northern lobe we see a nebular narrow absorption component of > 10 Balmer lines. Also the equivalent widths of the nebular Balmer absorption lines vary considerably between STIS observations and is independent of the stellar brightness. Likely this is caused by Lyman alpha trapping. A useful test would be to track the UV 191 emission across the nebula to determine if it correlates with the absorption component.

**Linsky:** One reason that pre-main sequence stars show many fluorescent lines is that the Lyman alpha line is very broad and therefore can pump many transitions.

**Davidson:** Here is a peculiar detail with a historical aspect. One of the stars that Nolan Walborn mentioned, He3-519, has rather strong Fe III λ 3011
emission. This is probably fluorescent but is not easy to explain. It was reported in only one other star: P Cygni, in 1940! (This was an amazingly short wavelength for ground-based observations.) But P Cyg does not have the line today. Such a variable fluorescent feature must be trying to tell us something.
A Virtuoso in Fe and Music