Chapter 11

Fluorescence in Astrophysical Plasmas

Henrik Hartman

Abstract Following the initial detection by Bowen in 1934 of the strong O III lines being due to accidental resonance with strong He II radiation, many strong spectral emission lines are explained as produced by fluorescence. Many of these are Fe II lines pumped by H Ly α , as a consequence of strong radiation from hydrogen and a favorable energy level structure for Fe II. The lines are observed in many types of objects with low density plasma components. The Weigelt condensations in the vicinity of the massive star Eta Carinae is one location where these lines are observed and can be studied in detail, as well as been used for diagnostics.

These gas condensations do not only show a spectrum indicating a non-equilibrium excitation but also non-equilibrium ionization, where the strong hydrogen radiation plays a key role. Early studies identified certain strong lines being the result of Resonance Enhanced Two-Photon Ionization (RETPI). Further investigations suggest that RETPI can be the responsible mechanism for the ionization structure of gas condensation.

We will review the resonance processes, with emphasis on the Eta Carinae spectrum. Large spectral, spatial and temporal coverage is available for this fascinating object, allowing for detailed analysis.

11.1 Fluorescence in Astrophysical Plasma

Many emission lines observed in spectra of nebulae and other low-density plasmas are thought to be formed either by collisions with electrons or by recombination. However, some levels can also be photoexcited, either by absorption of continuous radiation from a nearby star or by monochromatic light from strong emission lines present in the environment. The atom is then excited from a ground state or low excitation state. The subsequent decay occurs in one or more fluorescence channels producing emission lines.

H. Hartman (✉)

Faculty of Technology, Group of Material Science and Applied Math, Malmö University and
Lund Observatory, 20506 Malmö, Sweden
e-mail: henrik.hartman@astro.lu.se

Thus, in the presence of strong radiation fields a non-LTE level population can be obtained in a low-density plasma due to selective photoexcitation. In this chapter we will consider two cases: Photoexcitation by continuum radiation (PCR) and photoexcitation by an accidental resonance (PAR). There will be a special emphasis on a PAR process where Fe II is selectively photoexcited by H Ly α .

Fluorescence appears in many fields and in many different scientific areas. Here we limit the discussion to fluorescence processes observed in low-density astrophysical plasmas.

Parity forbidden lines are, by definition, lines from levels with same parity, and the upper level long-lived metastable levels. Due to the low transition rates, metastable levels are not pumped from lower levels. The forbidden lines are thus widely used as probes of plasma density and temperature. We also discuss the possibility of populating levels through selective two-photon ionization from a lower ion, so-called Resonance Enhanced Two-Photon Ionization (RETPI).

11.2 Photoexcitation by Continuous Radiation, PCR

Some stellar spectra contain numerous permitted emission lines, where the corresponding upper level is pumped by continuum radiation from a nearby star. This is often referred to as photoexcitation by continuous radiation (PCR). Such lines are observed e.g. in satellite spectra of the symbiotic star KQ Puppis [28, 32], where high-lying excited levels in Fe II are populated by absorption of UV continuum radiation from one of the stars in the symbiotic system. A large number of levels are observed having an enhanced population and all of them are photoexcited from a low level, which is verified by observed absorption lines. And, inversely, all levels having strong channels down to the lowest levels in this wavelength region show an enhanced population. The population enhancement is determined by the excitation energy of the absorbing level and the oscillator strength of the absorption line. Some radiative energy is in this way transferred from the UV continuum to optically thin fluorescent lines at longer wavelength through the line absorption.

In analyses of the abundance pattern in Active Galactic Nuclei (AGN) it has been shown that it is important to consider PCR [31]. In low resolution spectra of AGN the iron abundance is measured as integrated flux in large UV bands of the Fe II resonance region. However, this is the region where also the PCR pumped fluorescence lines appear. It is thus important to include fluorescence in the modeling of AGN since it affects the total flux in the UV region.

11.3 Photoexcitation due to an Accidental Resonance, PAR

In spectra of some astrophysical plasmas one can observe some of the individual transitions in an *LS* multiplet as strong lines, whereas other components of the same multiplet are absent in spite of a similar excitation energy. The observations

Fig. 11.1 Principle for the Bowen mechanism in O III and a similar fluorescence case in Fe II

clearly imply a large non-LTE distribution of the population of the energy levels. The excitation mechanism behind this observation has to be selective with sharp resonances in the excitation cross sections. The most probable mechanism is a photoexcitation due to an accidental resonance (PAR) [26], i.e. the wavelength of an intense line coincides with the wavelength of a transition in the pumped ion. Photons from the pumping line of an abundant element in the plasma (e.g. H, He, C, etc.) excite the pumped ion in the same plasma from a very low state, in general, to a higher state. When the photoexcited level in the pumped ion decays, the radiation is distributed in a number of decay channels (fluorescence lines) according to their transition probabilities. The fluorescence lines are often optically thin and can therefore easily escape from the plasma and act as a cooling agent for the gas.

The PAR process described above is often referred to as the Bowen mechanism since Bowen was not only first to identify forbidden [O III] lines in nebulae but also first to explain strong nebular lines as fluorescent O III lines [2]. All these identifications were based on Bowen's own laboratory analysis of O III. The strength of the [O III] lines in nebulae had been a puzzle and seemed to be correlated with the strength of optical He II lines [1]. Lines from high excitation levels in O III were also observed in nebular spectra, but only from certain energy levels. Bowen noted the coincidence in wavelength between the He II line at 303.780 Å and the O III transition from the ground state $2p^2\ ^3P_2$ to the excited state $2p3d\ ^3P_2$ at 303.799 Å. Radiative energy can thus be transferred from He II to O III, which is excited to the $2p3d\ ^3P_2$ state. The most probable decay branch for this level is back to the $2p^2$ ground state with a new 303 Å photon as a result. But, there is a probability of a few percent that O III decays to $2p3p$ and subsequently to $2p3s$ resulting in emission of fluorescence lines in the 3000–4000 Å region [2, 3]. A simplified level diagram is given in Fig. 11.1. Since the fluorescence lines are high excitation lines,

and their lower states are efficiently depleted by a prompt decay down to the ground states, they are optically thin. The radiative energy can thus be transferred from the optically thick He II line to the O III lines and thereby more easily escape from the nebula.

For the fluorescence process to work efficiently a number of requirements must be fulfilled. The pumping line must be strong, i.e. have an intense radiation field. The absorption line with the coincident wavelength in the pumped ion must have a large transition probability, and the lower state a sufficiently large population. The latter is normally achieved by collisional excitation for low states in abundant ions. A complex spectrum with many energy levels is also very line rich, and there is a high probability for a wavelength coincidence to occur.

An example is the prominent UV 34 multiplet in Fe III, where one level is pumped and yields fluorescence in the 1914 Å line [22]. The level z^7P_3 is pumped by H Ly α from the ground state a^5D_4 , but the other levels, z^7P_2 and z^7P_4 , do not show any sign of enhanced population. The pumping channels for the z^7P_2 are too far from H Ly α , the closest being at 1226 Å. The z^7P_4 has a transition at 1213 Å which is often within the line profile of H Ly α . However, the transition probability is too low for efficient pumping, a few orders of magnitude less than for the transitions to z^7P_3 . The reason for this difference is a level mixing with the close z^5P term, which does not have a $J = 4$ level but can transfer some quintet character to the $J = 3$ level. Thus, the z^7P_4 level has a pure septet character resulting in a low transition probability for the intercombination transitions to a^5D .

Since the first explanation by Bowen of the nature of fluorescence lines, a number of similar processes with other elements involved have been detected. A compilation of known PAR processes, including pumping lines and pumped levels are given in Table 11.1.

Fe II line emission from a number of levels at 11 eV is observed strong in a number of stars [6, 13, 18, 19, 23]. Other levels, with similar or lower energy, do not show any emission at all. The populated levels, with configuration (5D)5p, do all have strong channels down to the ground configuration (5D)4s with wavelengths all within a few Ångströms from H Ly α at 1215 Å and are thought to be pumped by the PAR process. They are discussed in more detail in the section below in connection with the identification of fluorescence lines in the symbiotic nova RR Tel.

The spectrum of Cr II is also observed to show fluorescence lines pumped by H Ly α . The atomic structure of Cr II is similar to Fe II; the lowest configurations are $3d^5$ or $3d^4(^M L)n l$ in Cr II compared to $3d^7$ or $3d^6(^M L)n l$ in Fe II. The configurations $3d^6$ and $3d^4$ give rise to the same terms which means that $3d^6(^M L)n l$ and $3d^4(^M L)n l$ in Fe II and Cr II, respectively, have the same parent terms $^M L$. The energy separation in Cr II is similar to Fe II, and H Ly α matches therefore also the energy separation 4s–5p in Cr II. Infrared fluorescence lines of Cr II are seen from these levels in Eta Carinae [12, 34].

In the next chapter we will discuss the Fe II fluorescence in more detail, with the spectrum of RR Tel as a base.

Table 11.1 A number of fluorescence mechanisms have been identified since the first explanation by Bowen [1]. These are present in different plasmas, such as planetary nebulae, symbiotic stars and atmospheres of cool stars, showing emission lines. This table presents a compilation of known fluorescence processes

Ion	Pumped level	Energy (cm ⁻¹)	Pumping line	Ref.
O I	2p ³ (⁴ S)3d ³ D	97488	H Lyβ	B47
S I (UV9)	3p ³ 4s ³ P ₁	77150	O I 1304	BJ80
S I (UV9)	3p ³ 4s ³ P ₂	77181	O I 1304	BJ80
Ti I	v ¹ P ₁	42927	Mg II 2802	T37
V I	u ⁴ D _{7/2}	35379	Mg I 2852	T37
Cr I	s ⁵ F ₄	50210	Fe II 2373	T37
Cr II	4s4p x ⁶ D _{1/2}	93968	H Lyα	ZHJ01
Cr II	5p ⁴ P _{5/2}	93974	H Lyα	ZHJ01
Cr II	5p ⁶ P _{3/2}	94002	H Lyα	ZHJ01
Cr II	4s4p x ⁶ D _{3/2}	94098	H Lyα	ZHJ01
Cr II	5p ⁶ P _{5/2}	94144	H Lyα	ZHJ01
Cr II	5p ⁴ F _{3/2}	94256	H Lyα	ZHJ01
Cr II	4s4p x ⁶ D _{5/2}	94265	H Lyα	ZHJ01
Cr II	5p ⁶ P _{7/2}	94363	H Lyα	ZHJ01
Cr II	5p ⁴ F _{5/2}	94365	H Lyα	ZHJ01
Cr II	4s4p x ⁶ D _{7/2}	94452	H Lyα	ZHJ01
Cr II	5p ⁴ F _{7/2}	94522	H Lyα	ZHJ01
Cr II	4s4p x ⁶ D _{9/2}	94656	H Lyα	ZHJ01
Cr II	5p ⁴ F _{9/2}	94749	H Lyα	JC88
Mn I	y ⁶ P _{7/2}	35769	Mg II 2795	C70
Mn II	3d ⁵ (⁶ S)4f ⁵ F ₁	98461	Si II 1197.57	JWG95
Mn II	3d ⁵ (⁶ S)4f ⁵ F ₂	98462	Si II 1196.72	JWG95
Mn II	3d ⁵ (⁶ S)4f ⁵ F ₃	98463	Si II 1195.00	JWG95
Mn II	3d ⁵ (⁶ S)4f ⁵ F ₄	98464	Si II 1192.31	JWG95
Mn II	3d ⁵ (⁶ S)4f ⁵ F ₅	98465	Si II 1190.41	JWG95
Fe I	z ³ G ₄	35767	Mg II 2795	T37
Fe I	z ³ G ₃	36079	Mg II 2802	T37
Fe I	y ³ F ₃	37162	Ca II 3968	C70
Fe I	y ³ D ₂	38678	Hξ	C70
Fe I	y ³ D ₁	38995	Fe II 2611	WC90
Fe I	x ⁵ F ₁	41130	Fe II 2484	T37
Fe I	x ⁵ P ₃	42532	Fe II 2373	T37
Fe I	x ⁵ P ₂	42859	Fe II 2382	T37
Fe I	y ⁵ G ₃	43137	Mg II 2795	T37
Fe I	y ⁵ G ₂	43210	Mg I 2852	T37
Fe I	w ⁵ D ₄	43499	Mg II 2795	T37

Table 11.1 (Continued)

Ion	Pumped level	Energy (cm ⁻¹)	Pumping line	Ref.
Fe I	v ⁵ D ₃	44166	Fe II 2714	WC90
Fe I	w ⁵ D ₂	44183	Fe II 2761	T37
Fe I	x ⁵ G ₅	45726	Fe II 2607	T37
Fe I	w ³ P ₁	50043	Hξ, H16	C70
Fe II	(³ H)4p z ⁴ G _{9/2}	60807	[Si III] 1892	HJ00
Fe II	(³ H)4p z ⁴ G _{5/2}	61041	[Fe IV] 2835	HJ00
Fe II	z ⁴ I _{13/2}	61527	Fe II UV33, 207, 63	CP88
Fe II	(³ H)4p z ² G _{9/2}	62083	[O III] 1661	HJ00
Fe II	y ⁴ G _{5/2}	64087	Fe II 2628/2359	CP88
Fe II	(³ G)4p x ⁴ G _{7/2}	65931	[Ne V] 1575	HJ00
Fe II	x ⁴ G _{5/2}	66078	Fe II 2599	CP88
Fe II	(³ G)4p y ⁴ H _{11/2}	66463	C IV 1548	J83
Fe II	(³ G)4p x ⁴ F _{5/2}	66522	[Si III] 1892	HJ00
Fe II	(a ¹ G)4p x ² H _{9/2}	72130	(Fe II) 1776	HJ00
Fe II	(a ¹ D)4p w ² D _{3/2}	78487	C IV 1548	HJ00
Fe II	(b ³ F)4p ⁴ G _{9/2}	90042	H Lyα	JJ84
Fe II	(⁵ D)5p ⁶ F _{9/2}	90067	H Lyα	JJ84
Fe II	(⁵ D)5p ⁶ F _{7/2}	90300	H Lyα	MJC99
Fe II	(⁵ D)5p ⁴ F _{9/2}	90386	H Lyα	MJC99
Fe II	(⁵ D)5p ⁴ D _{7/2}	90397	H Lyα	MJC99
Fe II	(b ³ P)4p ⁴ S _{3/2}	90629	H Lyα	JJ84
Fe II	(⁵ D)5p ⁴ D _{5/2}	90638	H Lyα	JJ84
Fe II	(⁵ D)5p ⁴ F _{7/2}	90780	H Lyα	JJ84
Fe II	(b ³ P)4p ⁴ P _{1/2}	90839	H Lyα	JJ84
Fe II	(b ³ P)4p ⁴ P _{3/2}	90898	H Lyα	JJ84
Fe II	(⁵ D)5p ⁴ P _{5/2}	90901	H Lyα	JJ84
Fe II	(⁵ D)5p ⁴ D _{3/2}	91048	H Lyα	JJ84
Fe II	(⁵ D)5p ⁴ F _{5/2}	91070	H Lyα	JJ84
Fe II	(⁵ D)5p ⁴ D _{1/2}	91199	H Lyα	JJ84
Fe II	(⁵ D)5p ⁴ F _{3/2}	91208	H Lyα	JJ84
Fe II	(⁴ G)4s4p(³ P) x ⁴ H _{11/2}	92166	He II 1084	JH98
Fe II	(b ³ F)4p u ² G _{9/2}	92171	He II 1084	HJ00
Fe II	(b ³ F)4p u ⁴ F _{3/2}	93328	[N IV] 1487	HJ00
Fe II	(⁴ P)4s4p ⁴ D _{3/2}	95858	H Lyα	CP88
Fe II	(¹ G)4p ² H _{11/2}	98278	H Lyα	MJC99
Fe II	(⁴ P)4s4p(^x P) ² S _{1/2}	103967	H Lyα	MJC99
Fe II	(² D)4s4p(³ P) ⁴ F _{7/2}	104907	H Lyα/O V 1218	JC88
Fe II	(² F)4s4p(^x P) ⁴ G _{9/2}	107674	H Lyα	MJC99
Fe II	(² F)4s4p(³ P) ⁴ G _{11/2}	107720	H Lyα	JJ84

Table 11.1 (Continued)

Ion	Pumped level	Energy (cm ⁻¹)	Pumping line	Ref.
Fe II	(⁴ F)4s4p(^x P) ⁶ D _{5/2}	108130	H Ly α	MJC99
Fe II	(² F)4s4p(^x P) ⁴ F _{9/2}	108217	H Ly α	MJC99
Fe II	(⁴ F)4s4p(³ P) ⁶ D _{7/2}	108239	H Ly α	MJC99
Fe II	(⁴ G)4s4p(¹ P) ⁴ H _{9/2}	108868	Ne V 1146/Si III 1207	JH98
Fe II	(a ³ F)5p ⁴ D _{5/2}	110568	O VI 1032	J88
Fe III	3d ⁵ (⁶ S)4p z ⁷ P ₃	82333	H Ly α	JZH00
Zr I	x ¹ G ₄		Mg II 2795	B47
In I	d ² S _{1/2}		H γ	T37

B47 = [4], BFJ81 = [7], BJ80 = [5], C70 = [9], CP88 = [8], HJ00 = [13], HLW77 = [11], J83 = [15], J88 = [16], JC88 = [17], JH98 = [25], JJ84 = [19], JWG95 = [21], JZH00 = [22], MJC99 = [27], T37 = [30], WC90 = [33], ZHJ01 = [34]

11.4 Fluorescent Fe II Lines in RR Tel

Following the more general introduction, we will discuss the fluorescent Fe II lines in more detail using the beautiful spectrum of the symbiotic star RR Tel as an example.

The continuum radiation is often weak in the ultraviolet region of symbiotic stars since the Planck radiation from the hot and the cool stars in the symbiotic system dominates at shorter and longer wavelengths, respectively. Superimposed on the weak continuum is a rich emission line spectrum, dominated by Fe II lines from high-excitation levels in addition to lines of highly-ionized light elements (see spectrum in Fig. 11.2). Many of the Fe II lines are observed from specific odd levels with an energy of about 11 eV.

All levels which show an enhanced population and fluorescence lines have a strong transition connecting to a low state. As described above, many of these coincide in wavelength with H Ly α at 1215 Å. The flux is thus transferred from H Ly α , absorbed by Fe II and reemitted in the fluorescence lines. The levels observed to be pumped by H Ly α belong to the configurations (⁵D)5p, (b³P)4p and (b³F)4p. The small energy difference between them enhances the mixing between the levels and they share some properties. This mixing is responsible for enhancing the strength of the pumping channels for the latter two configurations. Strong lines are also seen from even parity levels. These cannot be pumped directly from any of the low even parity levels but are rather populated through cascades from the H Ly α pumped levels.

11.5 Identified Fluorescence Mechanisms

The natural way for the H Ly α pumped (⁵D)5p levels to decay is within the (⁵D)*nl* system either back to 4s or via the 3-photon route 5p → 5s → 4p → 4s where

Fig. 11.2 Part of the ultraviolet spectrum of RR Tel showing numerous fluorescent (Fe II) and high ionization lines (HST/GHRS)

the wavelength regions for the different steps are 9000 Å, 2800 Å and 2500 Å, respectively. The secondary decay is observed from almost all of the (^5D)5s levels, both from $e^4\text{D}$ and $e^6\text{D}$. When decaying, the flux is spread over many channels, and the flux per transition is thus also less from levels further down in the system. But some 5s levels are fed by cascades from many upper levels which might compensate for that. The ($b^3\text{P}$)4p and ($b^3\text{F}$)4p levels have their primary decay in the ultraviolet (see Fig. 11.4).

Fluorescence lines pumped by H Ly α are observed in a number of astrophysical objects. In RR Tel, strong lines from additional levels in Fe II are observed as well. In general they come from low excitation states compared to the H Ly α pumped levels. As reported in [13, 15, 16] other lines are responsible for this pumping, see Table 11.1.

The pumping channels for these levels differ in wavelength, since the different (^ML)4p states have different energies depending on parent term, from 60 kK for ($a^3\text{P}$)4p up to almost 100 kK for ($b^1\text{G}$)4p (see level diagram on Fe II in Fig. 11.3). The decay is, on the contrary, localized to the region 2500–2800 Å, since the difference between the (^ML)4p and the (^ML)4s states, which determines the wavelength of the fluorescence, is independent of parent term. The decay to the $3d^7$ levels falls in a wider wavelength region. This is an effect of the energy structure of the Fe II spectrum.

The strongest Fe II lines in the ultraviolet spectrum of RR Tel are the lines at 1776, 1881 and 1884 Å, all from the level ($a^3\text{F}$)5p $^4\text{D}_{5/2}$. This level is pumped due to a coincidence with the O VI line at 1032 Å [16]. The discovery of the fluorescence lines was the first indication of the presence of O VI in the RR Tel system.

Fig. 11.3 Energy level diagram on Fe II (by courtesy of Sveneric Johansson)

Fig. 11.4 Primary and secondary UV fluorescence channels (*bold lines*) from Fe II levels pumped by H Ly α (Notations: $nl = ({}^5D)nl$; $nl^* = (b^3F)nl$, $(b^3P)nl$)

Later Schmid [29] resolved the long-standing puzzle of two strong lines unidentified in spectra of many symbiotic stars. He suggested that the O VI lines at 1032 and 1038 Å were Raman scattered by hydrogen atoms. The energy difference between the oxygen lines and H Ly β was the same as the difference between the scattered

lines and H α . The presence of O VI lines has later been confirmed by direct far-UV observations of the λ 1032, 1038 lines. The fluorescence lines at 1776 Å might even work as a pumping line itself. This line coincides in wavelength with another Fe II line which connects a low state with a high-excitation state where the latter is seen to have an enhanced population [13].

The strong fluorescence lines pumped by C IV and O VI are not seen in Eta Carinae, although the H Ly α fluorescence is strong in this object [35] and apparently has favorable conditions for strong fluorescence. The reason is the lack of lines or ions responsible for the pumping. The mechanism producing the fluorescent Fe III in Eta Carinae mentioned in the previous section is on the contrary not working in RR Tel, although both H Ly α radiation and Fe²⁺ ions are present. One explanation can be the lack of spatial overlap for the radiation and atoms necessary for an efficient absorption.

11.6 Selective Ionization Through Resonance Enhanced Two-Photon Ionization (RETPI)

In low-density plasmas with strong radiation fields, the ionization structure is not determined by the LTE conditions and the SAHA equation, but rather by photo-ionization and recombination. A review of spectroscopy of photo-ionized plasmas is given by [10]. In analogy with the fluorescence discussed earlier, the radiation for the ionization emerge from either continuum or line emission. In general, broad continuum makes this more efficient. However, for a plasma where the emission lines such as the Lyman series of hydrogen gets very intense these lines can be as important for the ionization structure of certain elements. The intensity of the Lyman continuum radiation is converted to line radiation through photoionization of hydrogen and subsequent recombination producing the line radiation. The line radiation in turn photoionizes other elements and contribute to the ionization balance.

The RETPI process in low-density plasma was considered by [20], examining the possibilities for the process to work in C, N, O and Ar, Ne. An astrophysical plasma where this process may be important is the gas condensation close to the massive star Eta Carinae, the so-called Weigelt blobs (WBs). These are spatially resolved from the central stars using HST/STIS and the spectra indicated that the optical depth of hydrogen is sufficient to produce strong Ly line emission with the WBs. Eta Carinae exhibit a variation in the stellar radiation, where the radiation illuminating the WBs is cut off during several months each 5.5 years. These variations act as laboratory experiment with varying conditions, and allows for separating excitation processes with different time-scales. Excitation through recombination or collisions with electrons depend on the electron density, which changes on timescales of months. The radiation, on the contrary, drops on the time scale of days. Thus, data recorded during the months of less incident radiation allow for a discrimination between excitation mechanisms of the lines in the spectrum of the WBs [14]. From the recombination coefficients, the electron density can also be derive from

Fig. 11.5 RETPI pumping scheme for the production of strong Si III emission at 1892 Å. For energies involved, see [24]

the decay time of the recombination lines, allowing for additional probes of physical conditions in addition to the standard line ratios of forbidden lines.

One of the most striking examples of RETPI is the case of the [Si III] line at 1892 Å, being one of the strongest lines in the spectrum of Eta Carinae [35]. This line also shows the most prominent variations with time, as it disappears during the minimum state of Eta Carinae's 5.5 year cycle. The excitation routes are shown in Fig. 11.5.

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