Fluorescence of [Fe II] in H II regions[*]

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Abstract. A study of [Fe II] lines at various positions within the H II regions M42 and M43 is presented. The relative intensities of selected optical [Fe II] lines are shown to be correlated with the intensity of the apparent nebular continuous spectrum. Since the continuum of H II regions is known to be mostly stellar radiation scattered by dust intermixed with the emitting gas, these correlations provide direct evidence for the existence of fluorescent excitation in the formation process of the [Fe II] lines, irrespective of the prevailing physical state.

Key words: ISM: H II regions – line: formation – ISM: individual objects: M42 – ISM: individual objects: M43

1. Introduction

Recent studies of the [Fe II] lines observed in M42 have shown that some relative intensities between them cannot be accounted for by assuming that the line excitation is produced only by electron collisions, at the densities ($N_e \lesssim 10^4 \text{cm}^{-3}$) indicated by the ground state transitions $^2D - {}^4S$ of [S II] and [O II] (e.g. Bautista et al. 1996; Baldwin et al. 1996). In order to solve the ensuing problem, Bautista et al. (1994) postulate that the lines in question have their origin in a high-density partially ionized layer with $N_e \sim 10^6 \text{cm}^{-3}$ (see also Bautista & Pradhan 1995; Bautista et al. 1996; Bautista & Pradhan 1998, BP98 hereafter). But, alternatively, Lucy (1995) has shown that the line ratios can be explained by considering the fluorescent excitation of the Fe^+ levels by UV nebular radiation, which is diluted and reprocessed stellar light, an interpretation further supported by Baldwin et al. (1996) and Rodríguez (1996). The main arguments presented in all these papers for and against either interpretation, rest on the comparison of measured [Fe II] line intensity ratios with calculations involving the collision strengths of the relevant Fe^+ levels and the spectral distribution of the radiation field. Consequently, the reliability of the arguments cannot be readily assessed, and since not all the calculations use the

same set of collision strengths, it is also difficult to carry out a meaningful comparison of their results.

This paper presents direct observational evidence for the important role played by fluorescence in the formation of the optical [Fe II] lines in M42 and M43. On the basis of this new evidence, the aforementioned interpretations of the [Fe II] line intensities, either in terms of fluorescent excitation or as a diagnostic for the existence of a high-density partially ionized layer, will be critically discussed.

2. The data

The intensities of line and continuum radiation emitted by various areas within seven Galactic H II regions, measured by Rodríguez (1996), provide the basic data for this discussion. Because the optical [Fe II] lines are intrinsically weak and the contamination of the true nebular continuum by night-sky light is minimal, this paper is restricted to the apparently brightest H II regions M42 and M43.

The present discussion opens with a comparison between the line and continuum intensities used in this paper and those available in the literature. In Table 1 are shown the reddening-corrected intensity ratios, $I(\lambda)/I(H\beta)$, of four of the stronger optical [Fe II] lines: $\lambda4287$ ($a\,^6D_{9/2} - a\,^6S_{5/2}$), $\lambda5158+9$ ($a\,^4F_{9/2} - a\,^4H_{13/2}$, $a\,^4F_{7/2} - b\,^4P_{3/2}$), $\lambda5262$ ($a\,^4F_{7/2} - a\,^4H_{11/2}$) and $\lambda8617$ ($a\,^4F_{9/2} - a\,^4P_{5/2}$). Besides the uncertainties inherent in the measurement of individual line intensities (particularly in the fixing of the continuum level), the ratio $I(8617)/I(H\beta)$ may be affected by the intensity calibration between the two different spectral ranges involved, with no lines in common. This latter uncertainty is estimated to be $\sim 15\%$, the degree of disagreement between the reddening-corrected ratios $I(\text{Pa}12)/I(H\beta)$ and $I(\text{Pa}13)/I(H\beta)$ and their recombination values (Hummer & Storey 1987), since Pa12 and Pa13 are in the same spectral range as $\lambda8617$. For comparison with some of the values given in Table 1, the relative [Fe II] line intensities obtained by Osterbrock et al. (1992) and Esteban et al. (1998) at various positions in M42 are listed in Table 2. It can thus be seen that the ratios of Osterbrock et al. (1992) are quite close to the values for the positions M42 A–4 and M42 A–5 in Table 1. The values for M42–1 and M42–2 in Table 2 are also almost equal to those for M42 A–3 and M42 A–5 in Table 1.

Table 1. Line and continuum intensities

Object[a]	$[I(\lambda)/I(\mathrm{H}\beta)] \times 10^3$				
	$\lambda4287$	$\lambda5158$	$\lambda5262$	$\lambda8617$	cont.[b]
M42 A–1	1.63	1.34	1.00	1.04	1.9
M42 A–2	1.3	1.04	0.77	0.95	1.7
M42 A–3	0.5	0.45	0.33	0.29	2.2
M42 A–4	0.79	0.85	0.59	0.59	2.0
M42 A–5	0.92	0.76	0.55	0.45	2.4
M42 A–6	0.9	0.54	0.47	0.37	3.3
M42 B–1	0.86	1.05	0.59	0.89	1.7
M42 B–2	0.61	0.63	0.39	0.48	2.3
M42 B–3	0.87	0.60	0.32	0.58	2.1
M42 B–4	1.27	1.94	0.90	1.60	2.2
M42 B–5	1.6	1.13	0.82	0.83	3.7
M42 B–6	1.3	1.01	0.54	1.06	1.9
M43–1	2.5	1.5	1.55	1.01	6.0
M43–2	3.4	2.7	2.47	1.73	5.4
M43–3	8.7	4.4	4.7	2.3	11.2
M43–4	2.3	1.50	1.28	0.92	6.5
M43–5	2.5	1.6	1.0	0.90	8.2

[a] Slit position A in M42 is centred $27''$ to the south of θ^1 Ori C and orientated east–west; slit position B is located on the bar. Further information on the areas studied is presented in Rodríguez (1996)
[b] In units of Å^{-1}. The continuum intensities have been measured near Hβ

On the whole, then, it would appear that the [Fe II] line ratios have a measurement accuracy of 15%.

Intensity measurements of the continuous nebular spectrum are not generally given in papers mainly concerned with the line spectrum, probably because they are intrinsically more difficult to carry out, requiring corrections due to the presence of night-sky light. The measurements presented here have been made after subtracting separate sky exposures, the intensities of which had to be scaled – by factors between 0.5 and 1.5 – in order to get the best cancellation of the sky lines, from the nebular exposures. In M42 and M43 the night-sky brightness contributes less than 5% to the continuum and the sky-subtraction process is thus inconsequential. The compilation by Schiffer & Mathis (1974) of intensity measurements in the continuous spectrum of M42, relative to Hβ, covers the range 1.6–5.5×10^{-3}Å^{-1}, in agreement with the measurements presented in Table 1.

3. Results

According to Lucy (1995) and Baldwin et al. (1996), the line [Fe II] $\lambda8617$ is almost insensitive to the effects of optical pumping. The [Fe II] $\lambda4287$ line, on the contrary, is expected to be very sensitive to fluorescence, since it arises in the $a\,^6S$ term of the sextet system to which the $a\,^6D$ ground term also belongs and, therefore, $a\,^6S$ can be populated by allowed emissions from $z\,^6P^o$ and $z\,^6D^o$, terms, which in turn are connected to the ground term by allowed UV transitions. It follows that if fluorescence plays a role in the formation of $\lambda4287$, its intensity should

Table 2. Previous observations of [Fe II] lines

Object	$[I(\lambda)/I(\mathrm{H}\beta)] \times 10^3$				Ref.[a]
	$\lambda4287$	$\lambda5158$	$\lambda5262$	$\lambda8617$	
M42	0.86	0.87	0.54	0.67	(1)
M42–1	0.52	0.49	0.32	…	(2)
M42–2	0.96	0.71	0.47	…	(2)

[a] (1) Osterbrock et al. (1992); (2) Esteban et al. (1998)

be related to that of the radiation field inducing the fluorescence, which is again in the UV range. Nevertheless, since the continuous spectrum of H II regions is primarily stellar light scattered by dust coexisting with the emitting gas, (O'Dell & Hubbard 1965; Peimbert & Goldsmith 1972), its observed intensity variations in the Hβ region should correspond to similar variations in the UV or any other range. Therefore, the clear correlation shown in Fig. 1a, between $I(4287)/I(8617)$ and the intensity of the continuum near Hβ, normalized to the Hβ intensity, shows indeed that fluorescence is taking place in the formation process of $\lambda4287$. The efficiency of fluorescence in enhancing the line intensities, over the value expected under pure collisional excitation, is shown for $\lambda4287$ in Fig. 1d, which exhibits the correlation between the intensity of the continuum near Hβ, in units of the Hβ intensity, and the $I(4287)/I(8617)$ ratio normalized to the value c_{col} that the same ratio would take if the line excitation were due to electron collisions, at densities $N_e[\mathrm{S\,II}]$ and temperatures $T_e[\mathrm{N\,II}]$ (see Rodríguez 1996 for the definitions of $N_e[\mathrm{S\,II}]$ and $T_e[\mathrm{N\,II}]$; the values of these parameters will be given elsewhere). The values of $I(4287)/I(8617)/c_{\mathrm{col}}$ shown in Fig. 1d imply that fluorescence enhances $\lambda4287$ by two orders of magnitude with respect to $\lambda8617$. In this context, it should be noted that the values of c_{col} appearing in Fig. 1 were calculated by Bautista & Pradhan (1996) using their own collision strengths, although the collision strengths of Pradhan & Zhang (1993) and Zhang & Pradhan (1995) are considered more accurate in BP98. The calculations of Pradhan & Zhang do not include the $a\,^6S$ term and hence cannot be used to calculate the collisional value of $I(4287)/I(8617)$. But, anyway, the correlation between $I(4287)/I(8617)$ and the intensity in the continuum is well established for the observed line ratios, i.e. uncorrected for collisional effects, and can only become tighter when the line ratios are normalized by c_{col} as calculated with correct values for the collision strengths.

As far as other [Fe II] lines are concerned, only the measured intensities of $\lambda5158$ and $\lambda5262$ exhibit clear correlations with the intensity in the continuum, similar although somewhat looser than that shown by $\lambda4287$, as can be seen in Figs. 1b, 1e, 1c and 1f. A fluorescent contribution to other lines, however, cannot be excluded, as for example, $\lambda4244+5$ ($a^4G_{7/2}-a^4F_{7/2}$, $a\,^4G_{11/2} - a\,^4F_{9/2}$), $\lambda4277$ ($a\,^4F_{7/2} - a\,^4G_{9/2}$) and $\lambda5334$ ($a\,^4F_{5/2} - a\,^4H_{9/2}$), are weaker than the transitions shown in Fig. 1, and therefore could be measured only in a few positions in M42, insufficient to provide sets of data with definite trends. The $\lambda4815$ ($a\,^4F_{9/2} - b\,^4F_{9/2}$) and $\lambda7155$ ($a\,^4F_{9/2} - a\,^2G_{9/2}$)

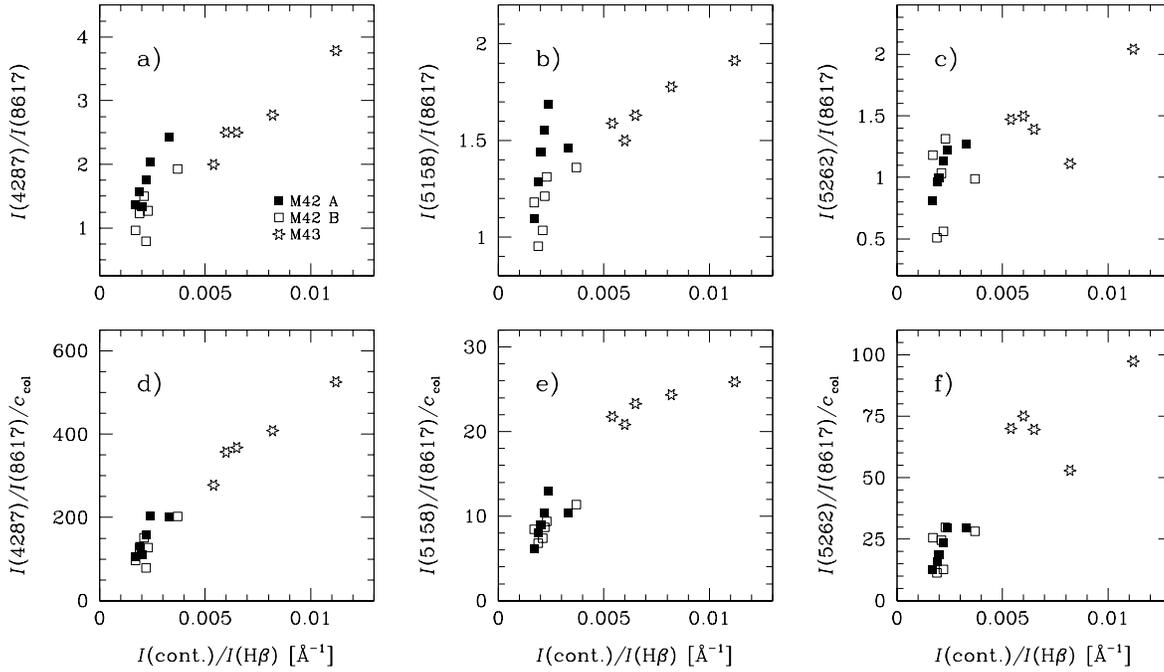**Fig. 1a–d.** The $I(4287)/I(8617)$, $I(5158)/I(8617)$ and $I(5262)/I(8617)$ ratios by themselves (**a, b, c**), and normalized to their predicted values c_{col} (Bautista & Pradhan 1996) for N_e[S II] and T_e[N II] (**d, e, f**), as a function of the nebular continuum intensities near Hβ in units of Hβ intensity

lines are as strong as those of Fig. 1, but $\lambda4815$ is blended with Si III $\lambda4813$ and S II $\lambda4815$ (Esteban et al. 1998), and $\lambda7155$ is insensitive to fluorescence, since it arises in the doublet system.

The fluorescence effects clearly illustrated in Fig. 1, especially for the lines $\lambda4287$ and $\lambda5158$, give grounds for considering that most [Fe II] lines may be significantly affected by radiative excitation, depending in a very complicated fashion on the structure of the Fe^+ ion. The observed strength of the [Fe II] lines can therefore be explained in terms of a line formation process based on physical principles applicable under the conditions characteristic of conventional nebular models (density, temperature and state of ionization). Since fluorescent excitation of [Fe II] is not important for densities greater than $10^5 cm^{-3}$ (BP98), it would appear that the use of the [Fe II] lines as a diagnostic for the existence of a high-density layer is completely inappropriate. The proponents of this high-density model have attempted to use the intensity ratio $I(\lambda6300+\lambda6363)/I(\lambda5577)$ of nebular [O I] lines as independent evidence for the high-density layer in their model (Bautista & Pradhan 1995; BP98), but the nebular [O I] lines are difficult to measure accurately because of their contamination by the strong night-sky emission in the same [O I] lines, especially the auroral feature at $\lambda5577$. The ratios obtained from recent and reliable measurements of the nebular component of this line in M42 (Esteban et al. 1999; see also Baldwin et al. 1996), have shown that the [O I] line ratio is in fact quite consistent with the line formation taking place at moderate densities. Besides, recent measurements of [Fe II] lines insensitive to fluorescence in the 1–2 μm spectrum of the "bar" in M42 (Marconi et al. 1998; Luhman et al. 1998)

indicate that the densities at their levels of formation are in the range 10^3–$10^4 cm^{-3}$.

Independently of their argument based on the nebular [O I] lines, BP98 also suggest that several measured [Fe II] line ratios, when compared with model predictions, imply the existence of a high-density emitting layer, even allowing for the contribution of lower density layers to the line intensities. However, when comparing the predictions of the two [Fe II] line formation models under discussion, it should be kept in mind that both rely on calculated collision strengths for the lines, which must be used with caution. An example of the uncertainties affecting the collisions strengths well illustrates the problem. The calculations of Pradhan & Zhang (1993) and Zhang & Pradhan (1995) are considered in BP98 to have relatively low uncertainties, but they do not consider the $\lambda4287$ and $\lambda7155$ transitions. The two available sets of collision strengths dealing with $\lambda4287$ (Bautista & Pradhan 1996; BP98) lead to predicted values for the $I(4287)/I(8617)$ ratio that differ by a factor of 10 for any density value. Therefore the values derived for $I(4287)/I(8617)$ and $I(7155)/I(8617)$ may be quite uncertain, and these ratios are precisely those implying more clearly the existence of high-density emitting regions according to BP98.

In conclusion, it can be said that there is no compelling evidence for the presence of high-density regions to explain the origin of the [Fe II] lines. Those in the near infrared must arise in regions of moderate density, while the optical lines have been clearly shown here to be affected by fluorescence, of significance only at moderate densities.

3.1. On the efficiency of fluorescent excitation

It has been argued by BP98 that photoexcitation of [Fe II] lines is a relatively inefficient mechanism, since the ground state of the Fe$^+$ ion is $a\,^6D_{9/2}$ whereas most of the observed lines arise in the quartet system. According to BP98, photoexcitation of these quartet levels must occur through intercombination transitions, with transition probabilities much lower than those of permitted transitions. However, even at moderate densities ($N_e \sim 10^3\,\mathrm{cm}^{-3}$) the lowest level of the $a\,^4F_{9/2}$ quartets has an appreciable population (Osterbrock et al. 1992), and, therefore, higher quartet levels can be populated through permitted transitions from this level.

The absence of some Fe II lines in the spectra of M42 has been considered by BP98 as further evidence against fluorescent excitation. In particular, Fe II $\lambda5169$ ($z\,^6P^o_{7/2} - a\,^6S_{5/2}$) is mentioned as the main transition that would contribute to populate $a\,^6S_{5/2}$ radiatively. The intensity of $\lambda5169$ should then be about 70% that of $\lambda4287$, according to BP98. Since the upper limit of the relative intensities of these lines has been estimated to be 0.1 for M42, BP98 conclude that less than 20% of the [Fe II] $\lambda4287$ intensity can be explained by fluorescent excitation.

The spectra available for M42 and M43 show a weak feature at $\lambda \sim 5169$ Å whose intensity is about 10% that of $\lambda4287$, in accord with the upper limit mentioned by BP98. In view of the clear demonstration in Fig. 1 of the importance of fluorescence effects in the formation of $\lambda4287$, this result is puzzling and difficult to explain, as it is also the extremely low contribution of fluorescence to the ratio $I(4287)/I(8616)$ estimated by BP98 (see their Fig. 4.6d). One way out of this difficulty would be to consider as alternative radiative excitation mechanisms of the level $a\,^6S_{5/2}$, transitions to levels $y\,^6P^o$ or $x\,^6P^o$ (with energies 0.57 and 0.72 Ry, respectively), implying the absorption of photons with $\lambda = 1608$ or 1261 Å. These sextets are comparable in energy with some of the quartets that BP98 consider when calculating the fluorescence effects on [Fe II] emission, but they are not included in the set of collision strengths used by BP98, and therefore, these sextets are not considered in their calculations.

The effects of fluorescent excitation on the [Fe II] line intensities in M42 have also been calculated by Baldwin et al. (1996). Unfortunately, neither the $a\,^6S$ nor the $a\,^2G$ terms are included in the set of collision strengths they use (Pradhan & Zhang 1993; Zhang & Pradhan 1995), and lines like $\lambda4287$ and $\lambda7155$ are not considered in their calculations. The same collision strengths are used by BP98 for the lines in common, but their predicted line ratios are somewhat different from those calculated by Baldwin et al. (1996). Nevertheless, the latter authors conclude that fluorescent excitation in a region of moderate density can explain the [Fe II] spectrum observed by Osterbrock et al. (1992), while opposite conclusions are advanced by BP98. The different approaches to the problem of both papers make it difficult to find the reasons for the discrepancies. The differences in the contribution of fluorescence to the line ratios presented by Baldwin et al. (1996) and BP98 can thus be considered to reflect the un-certainties involved in the calculation of fluorescence effects in a complex ion like Fe$^+$.

In summary, none of the available calculations faithfully reproduces the observed [Fe II] spectra, but it should be borne in mind that the effects of UV pumping on the [Fe II] line ratios can be quite different from those calculated so far, since the contribution to the pumping of the dust-scattered light – whose relative intensity increases with frequency – has not yet been taken into account. The change in the spectral distribution of the diffuse radiation field would imply that terms like $z\,^4G^o$ (located 0.55 Ry above the ground level) and the sextets mentioned above ($y\,^6P^o$ and $x\,^6P^o$) would have greater contributions to the pumping, thereby increasing the fluorescence effects on lines like $\lambda4287$, $\lambda4815$, $\lambda5158$, $\lambda5262$ or $\lambda5334$.

4. Conclusions

The relative intensities of the [Fe II] lines in the infrared spectra of M42 imply densities in the range 10^3–$10^4\,\mathrm{cm}^{-3}$ (Marconi et al. 1998; Luhman et al. 1998), but the optical [Fe II] spectrum cannot be reproduced assuming pure collisional excitation at these low densities, independently of the set of collision strengths used in the calculations. Two additional agents for the excitation of the upper levels of the optical lines have been proposed: UV pumping (Lucy 1995) and emission at very high densities $N_e \sim 10^6\,\mathrm{cm}^{-3}$ (Bautista et al. 1994). The available calculations based on these two processes (Baldwin et al. 1996; BP98) encounter certain difficulties when trying to reproduce faithfully the observed [Fe II] line ratios. However, these calculations depend on the values used for the collision strengths, which have an accuracy that it is difficult to estimate, on the completeness of the set of levels considered in the pumping processes and on the spectral intensity distribution of the radiation field involved. Consequently, the overall reliability of the results is difficult to assess.

The observations presented here have been shown to imply the importance of fluorescence processes on the formation of the optical [Fe II] emission. This conclusion is independent of any calculation and renders the assumption of a high-density emitting layer unnecessary. Further implications are the unreliability of the available collision strengths for Fe$^+$ (at least for some sextets and the doublets), and the need for further calculations on fluorescence that take into account the contribution of dust-scattered light to the radiation field.

References

Baldwin J.A., Crotts A., Dufour R.J., et al., 1996, ApJ 468, L115
Bautista M.A., Pradhan A.K., 1995, ApJ 442, L65
Bautista M.A., Pradhan A.K., 1996, A&AS 115, 551
Bautista M.A., Pradhan A.K., 1998, ApJ 492, 650 (BP98)
Bautista M.A., Pradhan A.K., Osterbrock D.E., 1994, ApJ 432, L135

Bautista M.A., Peng J., Pradhan A.K., 1996, ApJ 460, 372

Esteban C., Peimbert M., Torres-Peimbert S., Escalante V., 1998, MN-
    RAS 295, 401

Esteban C., Peimbert M., Torres-Peimbert S., 1999, A&A 342, L37

Hummer D.G., Storey P.J., 1987, MNRAS 224, 801

Lucy L.B., 1995, A&A 295, 555

Luhman K.L., Engelbracht C.W., Luhman M.L., 1998, ApJ 499, 799

Marconi A., Testi L., Natta A., Walmsley C.M., 1998, A&A 330, 696

O'Dell C.R., Hubbard W.D., 1965, ApJ 142, 591

Osterbrock D.E., Tran H.D., Veilleux S., 1992, ApJ 389, 305

Peimbert M., Goldsmith D.W., 1972, A&A 19, 398

Pradhan A.K., Zhang H.L., 1993, ApJ 409, L77

Rodríguez M., 1996, A&A 313, L5

Schiffer III F.H., Mathis J.S., 1974, ApJ 194, 597

Zhang H.L., Pradhan A.K., 1995, A&A 293, 953