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[Fe IV] EMISSION IN IONIZED NEBULAE

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RESUMEN

Se presentan los resultados de un análisis de la emisión en [Fe IV] en varias nebulosas ionizadas, basado en nuevas identificaciones y medidas anteriores de líneas de [Fe IV]. Las abundancias de Fe obtenidas al sumar las abundancias de los iones relevantes (principalmente Fe^{++} y Fe^{3+}) resultan ser menores, por factores en el rango 2.6–5.9, que las abundancias implicadas por las líneas de [Fe III] y un factor de corrección por la ionización obtenido con modelos de ionización. Se discuten las posibles razones de esta discrepancia así como las implicaciones que tiene para nuestro entendimiento tanto de la evolución del polvo en nebulosas ionizadas como de la historia química de galaxias de baja metalicidad.

ABSTRACT

I present the results of an analysis of [Fe IV] emission in several ionized nebulae, which is based on new identifications and previous measurements of [Fe IV] lines. The Fe abundances obtained by adding the abundances of the relevant Fe ions (mainly Fe^{++} and Fe^{3+}) are found to be lower, by factors in the range 2.6–5.9, than the Fe abundances implied by [Fe III] emission and an ionization correction factor derived from ionization models. The possible reasons behind this discrepancy are discussed, as well as the implications it has for our understanding of both the evolution of dust in ionized nebulae and the chemical history of low metallicity galaxies.

Key Words: **H II REGIONS — LINE: IDENTIFICATION — ISM: ABUNDANCES**

1. INTRODUCTION

The first detection of an [Fe IV] line in an H II region is due to Rubin et al. (1997), who measure [Fe IV] λ2837 in the Orion nebula (M42). From this line and two previous ionization models for Orion, Rubin et al. find Fe/H lower, by factors of 6.5 and 19, than the value the models need to reproduce [Fe II] and [Fe III] emission in M42. The large difference between the results obtained from the two models is due mostly to the different average electron temperatures predicted by each model. Another uncertainty in the value of this discrepancy arises from the lack of measurements of [Fe III] and diagnostic lines at exactly the same position in the nebula, since Rubin et al. just measured the UV spectrum at their selected position.

Since Fe^{3+} is an important or dominant ionization state in most H II regions, the reality of this underabundance implied by [Fe IV] emission, and the reasons behind it, are critical issues in our understanding of both the evolution of dust in H II regions (Rodríguez 2002a) and the chemical evolution at low metallicities (Izotov & Thuan 1999).

2. RESULTS

Further results on [Fe IV] emission are presented in Rodríguez (2002b). These results are based on new identifications and previous measurements of [Fe IV] lines in several ionized nebulae: 30 Doradus (Peimbert 2002), IC 4846 (Hyung at al. 2001), M42 (Baldwin et al. 2000), SMC N88A (Kurt et al. 1999), and SBS 0335-052 (Izotov et al. 2001). The available spectra, which include measurements of [Fe III] and diagnostic lines obtained at the same positions, were analyzed in the standard way to derive physical conditions and the ionic and total abundances of the O and Fe ions. The list of objects, their O abundances, the [Fe IV] lines used in the analysis and the final Fe/O abundance ratios are presented in Table 1. Two values for the Fe/O abundance ratio are shown in this table. The first one is based on the Fe^{++} abundance and an ionization correction factor derived from grids of ionization models: $\mathrm{Fe/O} = [x(\mathrm{O}^+)/x(\mathrm{Fe}^{++})]\,[(\mathrm{Fe}^+ + \mathrm{Fe}^{++})/\mathrm{O}^+] = 1.1\,[(\mathrm{Fe}^+ + \mathrm{Fe}^{++})/\mathrm{O}^+]$, where $x(X)$ is the ionization fraction of the X ion, and $[x(\mathrm{O}^+)/x(\mathrm{Fe}^{++})] \simeq 1.1$ is the ionization correction factor. (The contribution of Fe^+ to the total abundance was considered to be negligible in all objects except M42.) The second value of Fe/O is that implied by the sum of the ionic abundances. These last values can be seen to be systematically lower, by factors in the range 2.6–5.9, than the first ones. The Fe^{3+} abundances are

TABLE 1

[Fe IV] LINES AND THE IRON ABUNDANCE

Object	$12+\log(\mathrm{O/H})$	[Fe IV]	$\log(\mathrm{Fe/O})^{\mathrm{a}}$	$\log(\mathrm{Fe/O})^{\mathrm{b}}$	$(\mathrm{Fe}^{3+}_{\mathrm{exp}}/\mathrm{Fe}^{3+})^{\mathrm{c}}$
30 Doradus	8.33 ± 0.03	$\lambda6740$	$-2.29^{+0.06}_{-0.07}$	≤ -2.62	≥ 2.7
IC 4846	$8.51^{+0.09}_{-0.12}$	$\lambda6740$	$-2.25^{+0.15}_{-0.20}$	$-2.73^{+0.20}_{-0.33}$	$3.2^{+2.3}_{-2.4}$
M42	$8.57^{+0.10}_{-0.13}$	$\lambda6740$	-2.30 ± 0.15	$-2.71^{+0.17}_{-0.25}$	$4.4^{+4.1}_{-3.9}$
N88A bar	8.01 ± 0.04	$\lambda2837$	$-1.69^{+0.17}_{-0.10}$	$-2.30^{+0.03}_{-0.04}$	$5.5^{+2.5}_{-1.3}$
N88A sq. A	$8.04^{+0.06}_{-0.08}$	$\lambda2837$	$-1.53^{+0.14}_{-0.25}$	$-2.30^{+0.08}_{-0.09}$	$7.5^{+3.2}_{-3.6}$
SBS 0335-052	7.26 ± 0.04	$\lambda4906$	-1.37 ± 0.13	$-2.07^{+0.15}_{-0.23}$	$6.1^{+3.7}_{-3.5}$

[a] $\mathrm{Fe/O} = 1.1\,[(\mathrm{Fe}^{+} + \mathrm{Fe}^{++})/\mathrm{O}^{+}]$.

[b] $\mathrm{Fe/O} = (\mathrm{Fe}^{+}/\mathrm{H}^{+} + \mathrm{Fe}^{++}/\mathrm{H}^{+} + \mathrm{Fe}^{3+}/\mathrm{H}^{+})/(\mathrm{O/H})$.

[c] The ratio between the expected and calculated values of $\mathrm{Fe}^{3+}/\mathrm{H}^{+}$, where $\mathrm{Fe}^{3+}_{\mathrm{exp}}/\mathrm{H}^{+}$ is derived from $\mathrm{Fe}^{+}/\mathrm{H}^{+} + \mathrm{Fe}^{++}/\mathrm{H}^{+} + \mathrm{Fe}^{3+}_{\mathrm{exp}}/\mathrm{H}^{+} = 1.1\,[(\mathrm{Fe}^{+} + \mathrm{Fe}^{++})/\mathrm{O}^{+}]\,\mathrm{O/H}$.

lower than expected by factors from 3.2 to 7.5 (see $\mathrm{Fe}^{3+}_{\mathrm{exp}}/\mathrm{Fe}^{3+}$ and footnote *c* in Table 1).

3. DISCUSSION AND CONCLUSIONS

The uncertainties in the results are too high to reach a definitive conclusion, but there are two hints as to the possible explanation of this discrepancy:

(i) The discrepancies obtained with [Fe IV] $\lambda6740$, on the one hand, and [Fe IV] $\lambda2837$ and the [Fe IV] blend at $\lambda4904$, on the other, might be different (see Table 1). The measurement of these lines in a single object would help to establish this issue. If confirmed, this result would imply that the collision strengths for Fe^{3+} are unreliable.

(ii) The values of $[x(\mathrm{O}^{+})/x(\mathrm{Fe}^{++})]$ derived for the objects in the sample might show a trend with the degree of ionization given by $\mathrm{O}^{+}/\mathrm{O}^{++}$ (see Fig. 1). Since the ionization models predict a constant value for this ionization correction factor, $[x(\mathrm{O}^{+})/x(\mathrm{Fe}^{++})] \simeq 1.1$, a deviation from this constant value that depends on the degree of ionization would suggest that the Fe ionization fractions predicted by models are seriously in error. The measurement of [Fe IV] lines in objects with different degrees of ionization, or at several positions in one object, would help to establish the reality of this trend.

There are other possible explanations, such as the existence of some kind of gradient in the Fe abundance within the ionized gas (as suggested by Bautista & Pradhan 1998), which cannot be ruled out at the moment.

Figure 2 shows the values of Fe/O given in Table 1 as a function of the O abundance and the degree of ionization. The values of Fe/O implied by both methods can be seen to decrease with metallicity. This trend, which should be confirmed for other low metallicity objects, probably reflects an increase of the Fe depletion factors in the different objects as their metallicity increases. The increment of Fe atoms in the gas of low metallicity H II regions could be due to the effect of the harder radiation fields typically found in these objects. This is suggested by the fact that if the planetary nebula IC 4846 is excluded, the Fe/O abundance ratios follow and extend to higher degrees of ionization the correlation with the degree of ionization found in Rodríguez (2002a) for Galactic H II regions in the solar neighborhood.

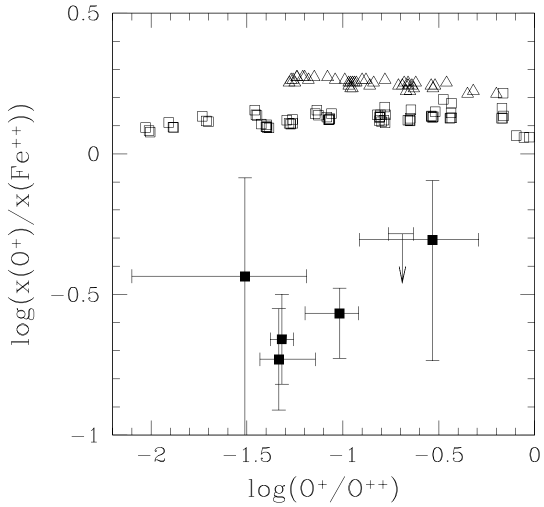

Fig. 1. Values of $x(\mathrm{O}^{+})/x(\mathrm{Fe}^{++})$ presented as a function of the degree of ionization given by $\mathrm{O}^{+}/\mathrm{O}^{++}$. The values calculated for IC 4846, M42, SMC N88A, and SBS 0335-052 are shown as filled squares; an upper limit is given for 30 Doradus. The empty squares are the results of the ionization models of Stasińska (1990); the triangles show the results of the models of Gruenwald & Viegas (1992). See Rodríguez (2002b) for further information.

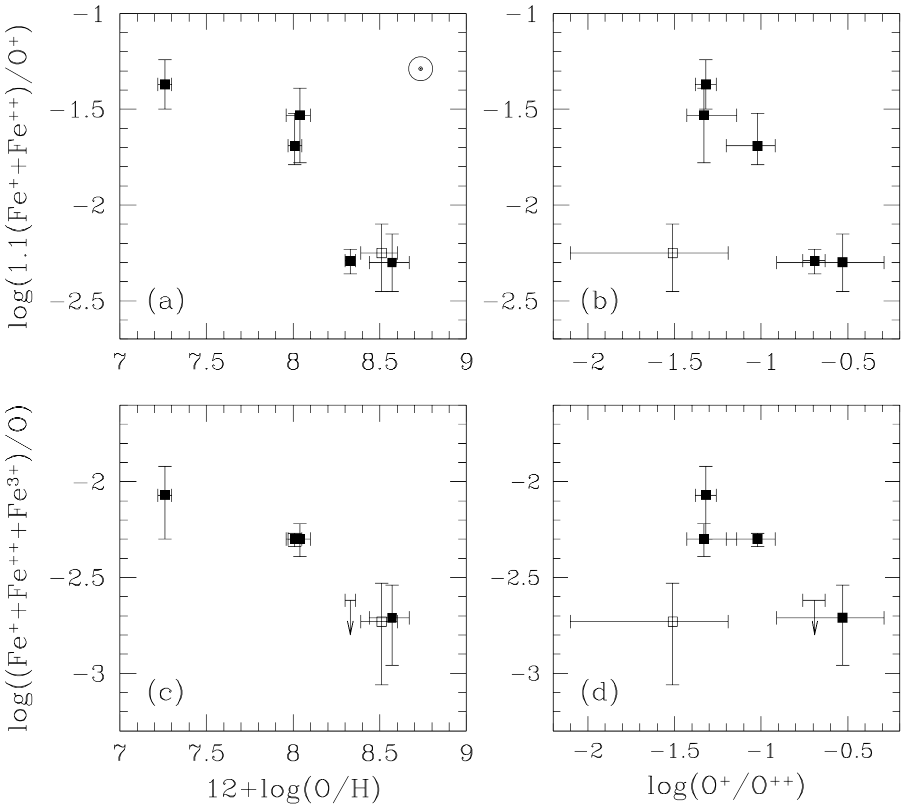

Fig. 2. Fe/O abundance ratio as a function of the O abundance and the degree of ionization for M42, 30 Doradus, IC 4846, two positions in SMC N88A, and SBS 0335-052. The values for the planetary nebula IC 4846 are represented by an empty square. In panels (*a*) and (*b*) it has been assumed that Fe/O = 1.1 $(Fe^{+} + Fe^{++})/O^{+}$; panels (*c*) and (*d*) show the values obtained from Fe/O = $(Fe^{+} + Fe^{++} + Fe^{3+})/O$. The contribution of Fe^{+} has been considered negligible for all objects except M42. The dotted circle in panel (*a*) shows the solar abundances (Holweger 2001); the size of this symbol represents approximately the associated uncertainties. See Rodríguez (2002b) for further information.

The deviation of IC 4846 from the relationship could be due to the large uncertainties in the abundances derived for this object or to the specific origin and characteristics of dust grains in planetary nebulae. Although the values of Fe/O for the other objects follow the correlation with the degree of ionization independently of whether [Fe IV] emission is considered or not, the shape of the correlation depends on which method is used in the abundance determination. Furthermore, the Fe/O abundance ratio in the low metallicity galaxy SBS 0335-052, which has important implications for our understanding of chemical evolution (see, for example, Recchi et al. 2002), remains uncertain by a factor of 5. All these implications emphasize the need for a correct understanding of the reasons behind the [Fe IV] discrepancy.

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