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FLUORESCENCE OF PERMITTED LINES IN THE ORION NEBULA

Vladimir Escalante

Instituto de Astronomía, UNAM, Morelia

RESUMEN

El espectro de emisión de N II se comparó con observaciones recientes de líneas permitidas en emisión en la nebulosa de Orión. Los ajustes de modelos nebulares a los datos muestran coincidencias cualitativas con un espectro excitado por fluorescencia de absorción de luz estelar, pero hay grandes discrepancias con las intensidades observadas en muchos casos.

ABSTRACT

The predicted emission spectrum of N II has been compared with recent observations of permitted emission lines in the Orion nebula. Fits of nebular models to the data show qualitative agreement with an spectrum excited by fluorescence of starlight absorption, but there are large quantitative discrepancies with the observed intensities in many cases.

Key Words: **ATOMIC PROCESSES — HII REGIONS — ISM: INDIVIDUAL (ORION NEBULA)**

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Excitation of permitted lines by fluorescence has been proposed by different authors to account for the intensities of some nebular emissions that have higher rates than those predicted by the recombination theory. Aller, Baker, & Menzel (1939) proposed this mechanism for the Balmer lines, naming it Case C. Fluorescence of H lines is unimportant in the general nebular situation with possible few exceptions (e.g., see Van Blerkom, Castor, & Auer 1973), but Seaton (1968) suggested its feasibility in the case of permitted lines of C and O ions. Grandi (1975; 1976) first proposed that the N II and O I lines in Orion were excited by fluorescence due to starlight absorption. He further proposed that absorption of the $\lambda\,508.643$ Å line of the He I $1s^2\ {}^1S$–$1s8p\ {}^1P^o$ multiplet was more important for the excitation of the N II $2p^2\ {}^3P_0$–$2p4s\ {}^3P^o_1$ $\lambda\,508.668$ Å line. To explain the observed spectrum, it is also necessary to pump the N II $2p^2\ {}^3P_0$–$2p4s\ {}^3P^o_1$ $\lambda\,508.697$ Å with this mechanism.

We calculated the N II and O I emission spectra to test this ideas with more recent atomic data and observations. The fact that planetary nebulae show a different N II emission spectrum that resembles more the recombination spectrum is indicative that the excitation mechanism depends on the excitation degree.

Reliable atomic data sets to calculate the recombination and fluorescence emission spectra have been published by different authors (Victor & Escalante 1988; Pequignot, Petitjean, & Boisson 1991; Seaton et al. 1994). We calculated Orion nebula models similar to the one described by Baldwin et al. 1991 using the Cloudy code (Ferland 1993), and varied the parameters to get reasonable approximations to the observed intensities of the forbidden and permitted lines. We found that the He I absorption line mechanism becomes almost ineffective if the turbulent FWHM of the lines is below $15\,\mathrm{km\,s^{-1}}$. Castañeda & O'Dell 1987 have observed a component with wider FWHM in Orion. However, the most uncertain factor in the calculations are the radiative transfer assumptions. We used the escape probability method of Lockett & Elitzur 1989. As they noted, the ease of implementation of this method comes at the expense of not accounting for the partial redistribution in the line wings. Both the He I and N II resonance lines are expected to be optically thick.

Here we compare our results with the extensive surveys of faint lines by Esteban et al. 1998 (position 1) and Baldwin et al. 2000. A more detailed comparison and discussion will be published elsewhere. The most intense permitted lines are given in the accompanying table for two limiting cases. In one (fourth column) the He I absorption line is the main excitation of the 4s ${}^3P^o$ term, and in the other (fifth column) there is no absorption of that line by N II. In both cases it was assumed that photons from N II resonant transitions are absorbed "on the spot" (case B of Aller et al. 1939). Although there is qualitative agreement with the observations, there are deviations among lines of the same multi-

TABLE 1

PERMITTED N II LINE INTENSITIES ($I(\mathrm{H}\beta) = 100$) BETWEEN 3500 AND 6000 Å.

λ (Å)	Multiplet	J–J'	$I(\lambda)^{\mathrm{a}}$	$I(\lambda)$	Esteban et al. 1998	Baldwin et al. 2000
3593.597	3p ^{3}S–4s ^{3}P$^{\mathrm{o}}$	1–2	0.030	0.001	···	···
3609.097		1–1	0.061	$<$ 0.001	···	···
3829.795	3p ^{3}P–4s ^{3}P$^{\mathrm{o}}$	1–2	0.029	$<$ 0.001	···	···
3838.374		2–2	0.087	0.004	···	0.068?[b]
3842.449		0–1	0.079	$<$ 0.001	···	···
3847.404		1–1	0.059	$<$ 0.001	···	···
3856.062		2–1	0.097	$<$ 0.001	0.165?	0.190?
3994.997	3s ^{1}P$^{\mathrm{o}}$–3p ^{1}D	1–2	0.006	0.006	···	···
4236.91						
4237.05	···		···	···	···	0.010?
4241.78	···		···	···	···	0.009?
4465.529	3p ^{3}D–3d ^{3}P$^{\mathrm{o}}$	1–1	$<$ 0.001	$<$ 0.001	···	0.015?
4477.682		2–1	0.001	0.003	···	···
4601.478	3s ^{3}P$^{\mathrm{o}}$–3p ^{3}P	1–2	0.019	0.013	0.020	0.015
4607.153		0–1	0.015	0.018	0.047?	0.057?
4613.848		1–1	0.011	0.013	0.007?	0.009?
4621.393		1–0	0.036	0.041	0.016	0.018?
4630.539		2–2	0.055	0.038	0.045	0.046
4643.086		2–1	0.018	0.021	0.009	0.022
4774.244	3p ^{3}D–3d ^{3}D$^{\mathrm{o}}$	1–2	0.001	0.003	···	···
4779.722		1–1	0.022	0.068	···	0.008
4781.190		2–3	0.003	0.007	···	···
4788.138		2–2	0.002	0.006	0.014	0.012
4793.648		2–1	0.007	0.022	···	0.011?
4803.287		3–3	0.008	0.019	0.010	0.013
4810.299		3–2	0.001	0.003	···	···
4895.117	2p^3 ^{1}D$^{\mathrm{o}}$–3p ^{1}P	2–1	0.001	$<$ 0.001	···	0.017?
4987.376	3p ^{3}S–3d ^{3}P$^{\mathrm{o}}$	1–0	0.001	0.003	0.055	0.076
4994.370		1–1	0.018	0.056	···	0.013?
5007.328		1–2	0.007	0.017	blended with [O III] λ 5006.8 Å	
5002.703	3s ^{3}P$^{\mathrm{o}}$–3p ^{3}S	0–1	0.003	0.002	···	···
5010.621		1–1	0.008	0.007	···	···
5045.099		2–1	0.012	0.011	0.013	···

plet that may indicate deviations from LS–coupling (Esteban et al. 1998). If there is a dominant excitation mechanism, it can be determined more easily by comparing intensity ratios of different multiplets, which are less sensitive to the details of the model because line intensities will be proportional to the ionic abundance. If the only excitation mechanism were fluorescence by starlight absorption, the components of the 3p ^{3}P–4s ^{3}P $\lambda\lambda$ 3830–3847 Å multiplet would be much weaker than other lines as shown in the fifth column of the table. Baldwin et al. 2000 may have observed components 3p ^{3}P$_2$–4s ^{3}P$_2$ λ 3838.374 Å and 3p ^{3}P$_2$–4s ^{3}P$_1$ λ 3856.057 Å, which according to our simplified model should be the most intense of the permitted N II lines if the Grandi mechanism were at work. However, a closer analysis of their data shows that these two lines can also be identified with Mg I and Si II lines, and it is likely

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TABLE 1

(CONTINUED)

$\lambda\,(\text{Å})$	Multiplet	J–J'	$I(\lambda)^{a}$	$I(\lambda)$	Esteban et al. 1998	Baldwin et al. 2000
5452.070	3p ^{3}P–3d ^{3}P^o	0–1	0.004	0.011	···	···
5462.581		1–1	0.003	0.008	···	···
5480.086		2–1	0.004	0.013	···	···
5495.655		2–2	0.003	0.007	0.007?	0.007
5535.347	3s′ ^{5}P–3p′ ^{5}D	3–4	···	···	···	0.006?
5551.992		3–3	···	···	0.009	0.007
5666.63	3s ^{3}P–3p ^{3}D	1–2	0.067	0.016	0.033	0.031
5676.02		0–1	0.020	0.015	0.012	0.012
5679.56		2–3	0.050	0.019	0.046	0.043
5686.21		1–1	0.015	0.011	0.008?	0.008
5710.77		2–2	0.022	0.005	0.011	0.009
5927.81	3p ^{3}P–3d ^{3}D^o	0–1	0.022	0.069	0.012	0.007?
5931.78		1–2	0.008	0.020	0.017	0.014
5940.24		1–1	0.016	0.051	0.008	···
5941.65		2–3	0.012	0.030	0.018	0.012
5952.39		2–2	0.003	0.006	···	0.006?

[a]Predicted intensity with He I $\lambda\,508.643$ Å line absorption.

[b]Uncertain intensities due to blends, low signal/noise or dubious identifications are marked with '?'

that they have little or none N II contribution. Furthermore, there are several lines at the blue end of the optical spectrum produced by the decay of the 4s ^{3}P term that have not been observed, which suggests that fluorescence by the He I line absorption is not the main excitation mechanism.

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Vladimir Escalante: Instituto de Astronomía, UNAM Campus Morelia, Apdo. Postal 72–3 (Xangari), C. P. 58089 Morelia, Michoacán, México (v.escalante@astrosmo.unam.mx).