The $\text{N} \text{II}$ spectrum of the Orion nebula

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Accepted 2005 May 13. Received 2005 May 9; in original form 2004 December 7

ABSTRACT

The predicted emission spectrum of $\text{N} \text{II}$ is compared with observations of permitted lines in the Orion nebula. Conventional nebular models show that the intensities of the more intense lines can be explained by fluorescence of starlight absorption with a $\text{N}$ abundance that is consistent with forbidden lines. Lines excited mostly by recombination, on the other hand, predict high $\text{N}$ abundances. The effects of stellar and nebular parameters and of the atomic data on the predicted intensities are examined.

Key words: line: formation – ISM: individual: Orion nebula.

1 INTRODUCTION

Recent deep spectroscopic surveys of the Orion nebula (Esteban et al. 1998; Baldwin et al. 2000, hereafter BVV; Esteban et al. 2004, hereafter EPG) show that $\text{N}^{+2,+1,+0}$ recombination cannot explain the intensities of the $\text{N} \text{II}$ permitted lines with a nitrogen abundance that is consistent with the $\text{N} \text{II}$ forbidden line intensities. Seaton (1968) first suggested the possibility that permitted lines of $\text{C}$ and $\text{O}$ ions in nebulae may be excited by continuum fluorescence of starlight, and Grandi (1976) noted that this also must be an important mechanism for exciting the $\text{N} \text{II}$ lines in Orion. Grandi suggested that additional absorption of photons of the HeI $1s^21S_0–1s8p3P_1$ line at $\lambda 508.643$ Å from the diffuse field of the nebula by the $\text{N} \text{II}$ $2p^23P_1–2p4s3P_1$ transition at $\lambda 508.668$ Å followed by decay to $3p$ terms would enhance the observed intensity of some lines. There is little direct evidence of the plausibility of this mechanism. BVV and EPG observed lines at $\lambda \lambda 3829.92$, 3838.47 and 3856.27 that could be produced by the $3p3P_1–4s3P_1$, $3p3P_2–4s3P_1$ and $3p3P_2–4s3P_1$ transitions, respectively. Unfortunately those lines are probably blended with lines from other elements, and their identification and intensity are uncertain. Sharpee et al. (2003) have detected those and other lines of the $3p3P–4s4P$ multiplet in a planetary nebula (IC 418), where the $\text{N} \text{II}$ spectrum is probably excited by recombination. The $4s3P_1$ level requires pumping of the $\text{N} \text{II}$ $2p^23P_1–2p4s3P_1$ $\lambda 508.697$–Å transition, which lies $32$ km s$^{-1}$ from the HeI line. Other lines from the $4s3P_1$ term like those of the $3p3D–4s3P$ multiplet in the $\lambda\lambda 3311.42–3331.31$ interval, which should be as intense as the $3p3P–4s3P$ multiplet, were not detected by EPG. The efficiency of this Bowen-type line fluorescence depends heavily on uncertain nebular parameters that are needed in the theory of line radiative transfer, and modelling can become quite arbitrary. Therefore we will not consider it in this work (for further discussion see, Escalante 2002; Liu et al. 2001).

The critical parameters that determine the intensities of the lines and the relative importance of the fluorescence mechanism over the recombination process are the $\text{N}^{+2}$ and $\text{N}^{+1}$ column densities in the gas and the stellar UV radiation field. Absorption of a UV photon by a resonant transition between a ground configuration state and an excited state has a higher probability of subsequent re-emission in the same transition. Decay to an intermediate state will be favoured when the optical depth of the resonant transition is large, and the resonant photon is scattered a few times until it is converted into a lower-energy photon producing a subordinate line. However, the optical depth of the resonant transition must not become too large or it will not allow enough resonant photons to penetrate into the $\text{N}^+$ zone. The efficiency of the continuum fluorescence excitation in $\text{N}^+$ depends on the transfer of resonant photons between the lowest resonant transition that can produce a subordinate line, $2p^23P–3d^3D$, $\lambda \lambda 533.51–533.88$ Å, and the ionization limit at 419 Å. We have also included transitions from the $2p^21D_2$ and $1S_0$ metastable states – populated mostly by collisions – to other singlets in order to consider the observation of singlet lines in Orion. In the singlet system the lowest transition that produces a subordinate line is $2s^22p^21S_0–2s2p^21P_1\lambda 745.84$ Å. Fig. 1 shows the observed transitions in Orion of the singlet and triplet $\text{N} \text{II}$ systems. Possible observations of quintet lines and higher excitation states are discussed in Section 4.4, below.

The observed intensities of permitted lines in planetary nebulae are often higher than their intensities as predicted by recombination rates with CNO abundances measured from forbidden lines (Liu et al. 1995, 2001; Luo, Liu & Barlow 2001, and references therein). Some of the $\text{N} \text{II}$ lines observed in PNe have $4f$ upper levels, which are excited mainly by recombination. In Orion there exists a similar situation and we will show that fluorescence cannot account for the excess intensity of lines from $4f$ levels. The accuracy of the recombination theory can be more easily tested by comparing line ratios from $4f$ decays because all the transitions involved are optically...
The important processes that can produce excited states with low principal quantum numbers in N II are absorption, fluorescence, and recombinations of N II states and recombinations of N II excited states and recombinations of N II. The fluorescence theory is more difficult to test because it depends, often non-linearly, on several model parameters. We will use the ratio of predicted over observed intensities, averaged over all N II lines with reasonably accurate identifications and measurements, hereafter referred to as \( R = (I_{\text{obs}}/I_{\text{mod}}) \), to test the model parameters. The scatter around \( R \) will be used as a test of the atomic data and the details of the transferred stellar continuum.

Realistic nebular models and hot star model atmospheres, along with available atomic data bases, can explain successfully the intensities of a majority of the forbidden lines in Orion as well as general observed trends of ion abundances in Galactic H II regions (see for example Baldwin et al. 1991; Stasińska & Schaerer 1997). This paper demonstrates that the intensity of most of the N II permitted lines in the Orion nebula can be predicted by fluorescence of the starlight continuum and some contribution of recombination by these models with currently accepted physical conditions and abundances of the nebula.

2 CALCULATION OF POPULATION DENSITIES

2.1 Atomic processes

The important processes that can produce excited states with low principal quantum numbers in N II at nebular temperatures are absorption of UV photons by transitions from ground and metastable states and recombinations of N II. Subsequent decays of these states produce the optical N II spectrum. UV radiation is provided mostly by the star \( \theta^1 \) C Ori. The contribution of the diffuse continuum to the absorption is negligible.

The number density of a N II excited state \( j \) at a certain point in the nebula in steady state, \( n_j \), is given by

\[
A_j n_j = \alpha_j n_e n(N^+) + \sum_{g} \beta_{gj} n_g + \sum_{k > j} A_{kj} n_k,
\]

where \( A_j = \sum_i A_{ji} \) is the spontaneous decay rate, \( \alpha_j \) is the recombination (radiative plus dielectronic) coefficient to state \( j \), \( n_e \) is the electron density, \( n(N^+) \) is the population density of one of the five \( N^+ \) ground and metastable states, \( 2p^2 \text{^3}P_{0,1,2}, \text{^1}D_2, \text{^1}S_0 \), and \( \beta_{gj} \) is the radiation absorption rate. If \( J_j \) is the local starlight mean intensity averaged over the absorption profile,

\[
\beta_{gj} = \sigma_{gj} \left( \frac{4\pi}{\hbar} \frac{J_j}{\nu} \right) Y_{gj},
\]

where \( \sigma_{gj} = 0.02654 f_{gj} \) cm\(^2\) Hz is the absorption cross-section and \( f_{gj} \) is the f-value of transition \( g \to j \). \( J_j \) is attenuated by continuum opacity and geometry. The 'pumping probability' to account for the attenuation due to the transition \( g \to j \) as defined by Ferland (1992) is

\[
Y_{gj} = \int e^{-\tau_\nu(\nu)} \phi(\nu) d\nu,
\]

where \( \phi(\nu) \) is the normalized Voigt profile for a displacement \( \chi = (\nu - \nu_0)/\Delta\nu \), and \( \tau_\nu = e^{-\phi(\nu)} \Delta n_\nu \) is the mean optical depth for a column density \( n_\nu \) integrated along a ray from the star.

An actual stellar spectrum shows absorption lines superposed on the continuum and the P-Cygni profiles of the wind. If the structure of the stellar absorption spectrum varies in scales comparable to the width of \( \Delta \lambda \sim 0.01 \) Å of the UV resonant lines in the nebular gas, equation (3) should be changed to

\[
Y_{gj} = \int \psi(\chi)e^{-\tau_\nu(\nu)} \phi(\nu) d\nu,
\]

where \( \psi(\chi) = J_j/J_\nu \) is the continuum stellar profile around the resonant line. Grids with that resolution are available in the optical (Murphy & Meiksin 2004). In the UV, Smith, Norris & Crowther (2002) and Sternberg, Hoffmann & Pauldrach (2003) have published models with a lower resolution.

The populations of the metastable states at nebular temperatures are controlled by electron collisions, and are nearly independent of other excited states. The system of equations (1) is triangular, and can be solved in terms of the cascade matrix, \( C_{kj} \) (Seaton 1959). \( C_{kj} \) is the probability that a state \( k \) is produced by the excitation of state \( j \) followed by radiative decays by all possible routes ending in \( j \).

Equation (1) thus becomes

\[
A_j n_j = \alpha_j n_e n(N^+) + \sum_{g} \beta_{gj} n_g + \sum_{k > j} A_{kj} n_k,
\]

where

\[
\alpha_{gj} = \sum_{k > j} \alpha_{kj} C_{kj},
\]

\[
\beta_{gj} = \sum_{k > j} \beta_{kj} C_{kj},
\]

are the effective recombination coefficient and the effective fluorescence rate in equation (7) is less sensitive to that type of correction because the absorption rate \( \beta_{gj} \) is non-zero only for states connected to the ground and metastable states by dipole-allowed transitions, and decreases more rapidly with the principal quantum number \( N \) than \( \alpha_{gj} \).
quantum number \( n \) of the upper state. The contribution of levels with \( 4 \leq n \leq 12 \) and orbital angular momentum \( 0 \leq l \leq 2 \) in equation (7) is less than 5 per cent for the N II lines observed in Orion. The contribution of f states to the fluorescence rate is even less important because they are not connected by resonant transitions to the ground term, and the transitions \( nd \rightarrow mf \) have a low relative probability. By eliminating states with \( n > 9 \) and \( l > 2 \) in equation (7), the CPU time decreases by a factor of 10. However, the f states (and higher \( l \) states) must be included in the cascade due to recombinations, which tend to favour high-angular momentum states.

Most of the observed N II transitions in Orion come from decays of the 3p and 3d triplet terms. Practically all the excitations of the 3d terms are produced by direct absorptions in the multiplets 2s22p23 P–2p3d 3 P, which produce negligible contributions to the populations of the 3d terms. The 3p terms, not being connected by direct transitions to the ground term, have more varied excitation channels. Between half and 80 per cent of excitations of 3p terms come from decays of 3d terms. The rest comes mostly from absorptions in the multiplet 2s22p23 P–3p3d 3 P, which produces negligible contributions to the populations of the 3d terms. The 3p terms, not being connected by direct transitions to the ground term, have more varied excitation channels.

### Table 1. f absorption values for some N II resonant multiplets.

| Multiplet            | \( \lambda (\text{Å}) \) | \( f \) |
|----------------------|--------------------------|--------|
| 2p22 3P–3s 3p6       | 508.74                   | 0.00987|
| 2p22 3P–3p3 3p6      | 529.68                   | 0.102  |
| 2p22 3P–3p3 3D0      | 533.67                   | 0.294  |

The model potential data of Victor & Escalante (1988) do not include transitions to levels with principal quantum numbers greater than 5 and produces lower fluorescence rates of lines with upper \( p \) levels, because those levels have cascade contributions from higher levels. The model potential data of Victor & Escalante (1988) do not have transitions to doubly excited configurations and consequently give higher rates as shown in the fourth column of Table 2. Transitions between states with the 2s2p3 configuration and the singly

### Table 2. Effective fluorescence rates for some N II lines.

| Line                  | \( \lambda (\text{Å}) \) | \( P_{ji} \sum_g \beta_{gji}^{\text{eff}}(10^{-8} \text{ s}^{-1}) \) |
|-----------------------|--------------------------|-------------------------------------------------|
| i – j                 | (1)                      | (2)                              | (3)                      | (4)                      |
| 3s 2P2–3p 3P2         | 4630.5                   | 10.8                             | 25.7                     | 16.1                     | 13.7                     |
| 3p 2D3–3d 3D3         | 4803.3                   | 4.6                              | 4.5                      | 4.5                      | 4.6                      |
| 3s 2P2–3p 3D3         | 5679.6                   | 7.1                              | 16.3                     | 10.3                     | 8.9                      |
| 3p 2P2–3d 3D0         | 5941.7                   | 8.0                              | 8.6                      | 8.6                      | 8.0                      |

b = \( k_e/k_i \) is the continuum-to-mean line opacity ratio. The term

\[
b F(b) = \int_{-\infty}^{\infty} \frac{k_e}{k_i} \phi(x) \, \text{d}x,
\]

is the probability that the resonant photon will be lost by continuum absorption. The effect of \( P_e \) is to increase considerably the probability that a resonant absorption will decay into the subordinate line rather than re-emitting the resonant photon. The average ratio, \( R = \langle |I_{\text{obs}}|/I_{\text{calc}} \rangle \), increases by a factor of 20 between the two limits \( P_e = 1 \) (case A) and \( P_e = 0 \) (case B) respectively. A spectrum dominated by fluorescence, however, must be in an intermediate regime in order to allow the penetration of UV stellar photons through a large column density of absorbers at the same time that the resonant photons are scattered repeatedly.

All the resonant photons that produce the N II optical spectrum have a high probability of being lost by conversion into other lines besides being absorbed by the continuum, and the probability of a large number of scatterings is small. Consequently we used a Doppler core in the calculation of \( K(x, b) \) and \( F(b) \).

### 2.3 Atomic data

The main source of A- and f-values for this work is the compilation of Wiese, Fuhr & Deters (1996), which is based primarily on the Opacity Project data (Seaton et al. 1994) and configuration-interaction calculations, but also includes intermediate coupling calculations and experimental measurements. That compilation has data for most lines of the series 2s22p(2P)nl with \( n \leq 5 \) and \( l \leq 2 \), and 2s2p(4P)nl with \( n \leq 2 \) and \( l \leq 1 \), including spin-forbidden transitions between quintet and triplet terms. The model potential calculations from Victor & Escalante (1988) were used for the rest of the transitions needed in the cascade matrix of the effective fluorescence rate in equation (7). Transition probabilities between fine structure levels were obtained by applying LS fractions to the multiplet data (Allen 1973).

Table 2 shows the effect of different atomic data bases on the effective fluorescence rate (7) summed over the ground and metastable states times the branching ratio of the subordinate line. The continuum is a blackbody spectrum at \( T = 37 \text{ kK} \) with a photon flux of 9.24 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \) at \( \lambda 533.7 \text{ Å} \) and \( \tau_0 = 0 \) for all lines, i.e. \( \gamma_{ji} = 1 \), \( P_e = 1 \). The compilation of Wiese et al. (1996) does not include transitions to levels with principal quantum numbers greater than 5 and produces lower fluorescence rates of lines with upper \( p \) levels, because those levels have cascade contributions from higher levels. The model potential data of Victor & Escalante (1988) do not have transitions to doubly excited configurations and consequently give higher rates as shown in the fourth column of Table 2. Transitions between states with the 2s2p3 configuration and the singly

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excited configurations $2s^22p3p$ can change the branching ratios significantly. The entries in the fifth column have been complemented with transitions to states with the $2s2p^3$ core configuration and spin-forbidden transitions taken from Wiese et al. (1996). The last column combines both data sets. The cascade matrix elements tend to be similar for different data sets because systematic differences in the atomic parameters between different data sets cancel out in the branching ratios $P_j = A_j/A_i$.

A recent calculation of effective recombination coefficients by Kisielius & Storey (2002) shows a general agreement with the model potential calculations of Escalante & Victor (1990) (hereafter EV) and the calculations of Péquignot, Petitjean & Boisson (1991) for the $2s^22p(^2P)_3d$ and $4f$ configurations. The most important differences between the three calculations are in the branching ratios of multiplets from the $2s^22p(^2P)_3p$ $^3D$ term. The accuracy of the model potential in this case was limited by the lack of observed energies in the $2s^22p(^2P)_nnp$ series. The best agreement between the three data sets is in the $4f$ terms, where most of the contribution to the recombination comes from levels with small non-hydrogenic effects. The main uncertainty is in the line fractions involving $4f$ terms, where LS-coupling is not a good approximation. EV used LK coupling for these terms, and line fractions for other couplings are available (Escalante & Gongora 1990), but general intermediate-coupling calculations for those states are clearly needed.

This work uses the recombination coefficients of EV with branching ratios given by the $A$-values of Victor & Escalante (1988) and Wiese et al. (1996). Effective recombination coefficients for the levels of a term were obtained by assuming that the coefficients are proportional to the statistical weights of the levels.

3 MODEL CALCULATIONS

3.1 Nebular models

In order to determine the electron, $N^+$, and $N^+$ densities in equation (5), as well as the temperature and opacity at each point in the nebula, we used the codes CLOUDY (Ferland 1996, version 90.05) and NEBU (Péquignot et al. 2001; Morisset et al. 2002). Models of the Orion nebula support the existence of a main emitting layer at the back of a cavity in the Orion Molecular Cloud–I (OMC–I). The thickness of the layer is highly variable across the nebula (Wen & O’Dell 1995). We approximated the layer by a plane-parallel model at constant pressure with CLOUDY and constant density with NEBU. CLOUDY allowed us to use the grain composition used by Baldwin et al. (1991) in their Orion model. Predicted line intensities by CLOUDY show some sensitivity when the radiation is included in the pressure law (Baldwin et al. 1996). Models with a constant gas pressure produce larger $N^+$ column densities than models with a constant gas plus radiation pressure. We have not tried to find a single model fit to the observed forbidden line intensities in Orion. Instead we have run a series of models to find the most important dependencies of the $N^+$ lines excited by fluorescence on model parameters.

3.2 Model atmospheres

The Orion nebula is mostly excited by $\theta^1$ C Ori. The other Trapezium stars increase the fluorescence of the $N$ II lines by less than 2 per cent and will not be considered in this calculation. $\theta^1$ C Ori is a class V star with variable wind features that produce uncertainties in the determination of its spectral classification and effective temperature. Different authors give values close to $T_{\text{eff}} = 39$ kK and log $(g) = 4$ for this star (Howarth & Prinja 1989; Hillenbrand 1997, and references therein). However, comparisons of the intensities of forbidden lines with nebular model predictions suggest temperatures as low as $36$ kK (BVV). Metallicity measurements by Cunha & Lambert (1994) show that the Trapezium stars are slightly underabundant with respect to the Sun.

The calculation of the fluorescence of the gas needs a high-resolution stellar spectrum. This is important with hot massive stars, which have expanding atmospheres with a dense forest of absorption lines and broad overlapping P Cygni profiles. The emission peaks and absorption troughs of the overlapping P Cygni profiles can increase or decrease the absorption rate in equation (3) by large factors and change the fluorescence excitation rate significantly. On the other hand, nebular models usually smooth the spectrum of the exciting star to calculate the ionization structure. In order to take into account the detailed spectral structure of the model atmosphere, we input the unattenuated stellar spectrum into the nebular model and extracted the predicted attenuated local continuum at each point in the nebula. To calculate the pumping rate in equation (3), the full resolution spectrum was read and interpolated at the absorption frequency and was scaled by the ratio of the attenuated to the unattenuated stellar continuum predicted by the nebular model.

The motion of the star with respect to the gas introduces a Doppler shift that can change the intensity of the continuum at the absorbing frequencies. The proper motion velocity of $\theta^1$ C Ori is uncertain (Wen & O’Dell 1995). Doppler shifts of up to $\pm30$ km s$^{-1}$ did not change predicted line intensities by more than a few per cent with the resolution of about $\Delta \lambda \sim 1$ Å in the far UV of the model atmospheres that we used. Therefore we assumed a static star with respect to the gas.

Recent model atmospheres of O stars include the effects of line blanketing and line blocking of the stellar wind. We used model atmospheres calculated with the wmbasic code (Pauldrach, Hoffmann & Lennon 2001; Sternberg et al. 2003) to account for these effects. We also used the local thermodynamic equilibrium, line-blanketed atmospheres of Kurucz (1991) for comparison purposes.

4 BASIC MODEL

All transitions of the observed permitted lines in Orion end in excited states and are optically thin. Their intensities can thus be obtained by integration of the emissivity along the line of sight:

$$I = \frac{h \nu}{4\pi} \int A_{ji} n_j \, dr$$

We now examine the dependence of the fluorescence excitation on the stellar spectrum and the density and compare them with the observations of BVV and EPG.

We have adopted a set of central values for the parameters of the models that are given in Table 3. These values are close to the ones recommended by Baldwin et al. (1991), and we will refer to them as the basic model (BM). We discuss below a few features of this model.

4.1 Gas abundances and density

The $N^+$ abundance in the nebula can be estimated from the measurements of lines with upper $4f$ levels, which are populated mostly by recombination. Table 4 lists the observed intensities of these lines in Orion and their predicted recombination emission rates normalized to the observed intensities and recombination rate of the $3s^2P_{1,2} - 3p^3D_2,3$ $\lambda 5679.56$ Å line. BVV and EPG measured the lines...
Table 4. Intensities of lines from 4f levels in Orion and PNe [I(N II) / 5679.56 = 1]. Numbers in column headings represent: (1) line fraction in LK coupling; (2) values calculated from recombination rates at $T = 10^4 K$ in case A, EV; (3) BVV; (4) EPG; (5) NGC 6153; Liu et al. (2000), intensities from scanned spectrum; (6) M 1–2; Liu et al. (2001); (7) M 2–36; Liu et al. (2001).

| LK Multiplet | Line J-[KJ] | $\lambda$ (Å) | per cent | Theory (2) | Orion (3) | PNe (6) |
|--------------|-------------|---------------|----------|------------|----------|---------|
| $^{3}D^{0}$–$^{4}F[K/J]$ | 3–[9/2]J | 4026.08 | 13.9 | 0.24 | * | * |
| | 2–[7/2]J | 4035.08 | 23.8 | 0.41 | – | – |
| | 4–[9/2]J | 4041.31 | 40.7 | 0.70 | – | 0.30 |
| | 3–[7/2]J | 4043.53 | 17.4 | 0.30 | – | – |
| $^{3}D^{0}$–$^{4}F[K/J]$ | 3–[9/2]J | 4201.35 | – | – | 0.14 | – |
| $^{3}D^{0}$–$^{4}F[K/J]$ | 1–[5/2]J | 4236.93 | 20.0 | 0.20 | 0.23 | 0.17 |
| | 2–[7/2]J | 4237.05 | 12.7 | 0.13 | 0.16 | 0.26 |
| | 2–[5/2]J | 4241.24 | 3.7 | 0.04 | – | 0.04 |
| | 3–[7/2]J | 4241.76 | 16.9 | 0.17 | 0.20 | 0.28 |
| | 3–[7/2]J | 4242.79 | 42.9 | 0.42 | 0.49 | 0.54 |
| | 3–[7/2]J | 4242.49 | 1.6 | 0.02 | – | 0.28 |

*Blended with He I.

4.2 Stellar continuum and geometry

The blister model, in which $\theta^1$ C Ori is near the wall of the OMC–1 (Zuckerman 1973; Balick, Gammon & Hjellming 1974), gives the most likely geometry for the nebula. The Lyman photon flux of the star at a distance $r_\odot$ from the illuminated face of the nebula is $\phi_0 = Q_{\beta}\pi r_\odot^2$, and can be constrained by the Hβ brightness observed up to a geometrical factor that depends on the angle of illumination $\theta$ of the slab of gas as described by Wen & O’Dell (1995). The value $\phi = 10^{12} cm^{-2} s^{-1}$ and $\theta = 0$, fixes the Hβ intensity around 4$\pi r_\odot^2 = 2.6 erg cm^{-2} s^{-1}$ observed by Baldwin et al. (1991) if corrections are considered to account for reflected optical and absorbed UV radiations (Ferland 2001). The $T_{eff} = 37 K$ is too low for the probable spectral type of $\theta^1$ C Ori, but was chosen because it reproduces the absolute intensities of the fluorescence lines with respect to the Hβ flux and the N abundance measured from forbidden lines as discussed in Section 5.1.

4.3 The recombination spectrum

The 4f levels in N$^+$ are in an intermediate coupling between LK and jK couplings (Cowan & Andrew 1965). In both couplings the total angular momentum is $J = K \pm 1/2$. The line fractions for either coupling can be obtained from Escalante & Gongora (1990).
favors the excitation of NII lines by fluorescence over recombination (2003). This nebula has a lower ionization level than most PNe that and 3d levels with respect to lines from the 4f levels (Sharpee et al. PN IC 418, which shows a strong enhancement of lines from 3p 4f F\[7\]2 term (Cowan & Andrew 1965), and strong mixing with the 4f F term (Cowan & Andrew 1965), and E\(\lambda\) = 4861 \(\alpha\) \(\lambda\) E(\(\lambda\)H\(\beta\)) \(\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} n(H^+) n_e d\ell\), E = \(\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} n(N^{+2}) n_e d\ell\) and P(\(\lambda\)) is the branching ratio of the 3d–4f line with \(\lambda\) given in Å. To account for the excess abundance of 0.6 obtained from the effective recombination rate of multiplet 3d 3\(D^0\)–4f F\(\lambda\lambda\) 4236.91–4247.20, we need B(5d) = 0.6E / P(5d, 4f), which means a rate of population of the 3p \(^3P\) term of B(5d)P(5d, 3p \(^3P\)) = 10.5E. The contribution to the intensity of a multiplet like 3s \(^3P\)–3p \(^3P\)\(\lambda\lambda\) 4601.48–4643.08 due to this additional excitation with N\(^{-2}\)/H\(^+\) \(\approx\) 6 \(\times\) 10\(^{-3}\) would be B(5d)P(5d, 3p \(^3P\))P(3p \(^3P\), 3s \(^3P\)) / E(\(\lambda\)H\(\beta\)) = 7.7 \(\times\) 10\(^{-4}\) where we took P(3p \(^3P\), 3s \(^3P\)) = 0.36 and an effective recombination coefficient of the 4F term \(\alpha_{\text{eff}}^{4F}\) = 10\(^{-15}\) cm\(^3\) s\(^{-1}\) at 10\(^4\) K (EV). The strongest line of the multiplet, 3s \(^3P\)–3p \(^3P\)\(\lambda\lambda\) 4630.54, has an LS line fraction of 11.25/27 (Allen 1973) and the corresponding increase in intensity would be at least 0.034 (\(\lambda\)H\(\beta\)) = 100, which is comparable to the observed intensity of 0.048 (EPG) produced by more direct cascade routes following absorption of photons at \(\lambda\lambda\) 530 and 534 Å by 3d states. Thus the excitation of 4f states by fluorescence would produce lines from 3p and 3d states with intensities much higher than the observed values unless the stellar continuum had an unusual shape that selectively excited states above the 4f states. Our calculations show a negligible contribution of fluorescence to the excitation of the 4f levels because the absorption rate is much less for higher resonant levels than for the 3d levels, and point to other mechanisms to excite them (Tsamis et al. 2004). EPG also observed the lines at \(\lambda\) 5001.14 and 5001.48 with upper levels 3d \(^3P\)\(\omega\) 2. The most intense component of the multiplet at \(\lambda\) 5005.15 is blended with the [O III] line. As with the lines with upper 4f levels, the \(\lambda\) 5005.15 line is mostly excited by recombination because its upper level 3d \(^3P\)\(\omega\) can receive only indirect contributions from the fluorescence excitation of higher levels. The other lines, 3d \(^3P\)\(\omega\) 2.3, are connected to the ground state through weak dipole-allowed transitions (Bell, Hibbert & Stafford 1995), and have a substantial fluorescence contribution. Our model calculations show that fluorescence contributes less than 5 per cent to the intensity of the lines produced by the 3d \(^3P\)\(\omega\) and 4f levels in Orion, and it is not sufficient to explain the discrepancy between the abundances determined from recombination and collisionally excited lines.

4.4 The fluorescence spectrum

Table 5 gives the predicted intensities for the observed upper terms in Orion by BVV and EPG that are excited mostly by fluorescence. Although the two data sets are from different parts of the nebula, it is important to notice that both sets give similar measurements of the N II permitted line intensities with respect to H\(\beta\). Uncertain observed intensities due to blends, low signal-to-noise ratio (S/N) or dubious identifications are marked with '?' in the table as indicated by those authors. We also added a question mark to the line at 4987.4 Å, which is probably blended with the [Fe III] 4987.20 line, and thus has an observed intensity much higher than our prediction. The line at 4994.4 Å belonging to the same multiplet should be theoretically more intense, contrary to the observations.

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### Table 5. Predicted intensities of the basic model (BM) and observations ($I(H\beta) = 10^4$) for lines excited by fluorescence. Numbers in column headings represent: (1) recombination contribution to total intensity; (2) predicted intensities with an H$\beta$ flux of 2.51 erg cm$^{-2}$ s$^{-1}$; (3) BVV; (4) EPGR.

| Transition | $\lambda$(Å) | $I(I/\beta)$ (1) | $I(I/H\beta)$ (2) | $I(I/H\beta)$ (3) | $I(I/H\beta)$ (4) |
|------------|--------------|------------------|-------------------|-------------------|-------------------|
| $2p^3 3p^4 3s^1$ | 1060.2 | 0.362 | 0.38 | – | – |
| $2p^3 3p^4 3s^1$ | 1060.2 | 0.362 | 0.37 | – | – |
| $2p^3 3p^4 3s^1$ | 1060.3 | 0.362 | 0.15 | – | – |
| $3p^3 3p^1 3p^2$ | 1275.0 | 0.118 | 17.31 | – | – |
| $3p^3 3p^1 3p^2$ | 1275.3 | 0.118 | 11.62 | – | – |
| $3p^3 3p^1 3p^2$ | 1275.3 | 0.118 | 0.21 | – | – |
| $3p^3 3p^1 3p^2$ | 1276.2 | 0.094 | 3.92 | – | – |
| $3p^3 3p^1 3p^2$ | 1275.6 | 0.094 | 11.62 | – | – |
| $2p^3 3p^1 3p^0$ | 1276.8 | 0.079 | 6.01 | – | – |
| $2p^3 3p^1 3p^0$ | 1343.3 | 0.257 | 3.30 | – | – |
| $2p^3 3p^1 3p^0$ | 1343.6 | 0.257 | 0.39 | – | – |
| $2p^3 3p^1 3p^0$ | 1345.1 | 0.176 | 0.68 | – | – |
| $2p^3 3p^1 3p^0$ | 1345.3 | 0.176 | 0.55 | – | – |
| $2p^3 3p^1 3p^0$ | 1345.3 | 0.176 | 2.63 | – | – |
| $2p^3 3p^1 3p^0$ | 1346.4 | 0.167 | 1.80 | – | – |
| $2p^3 3p^1 3p^0$ | 1346.4 | 0.167 | 0.66 | – | – |
| $2p^3 3p^1 3p^0$ | 1627.3 | 0.118 | 0.13 | – | – |
| $2p^3 3p^1 3p^0$ | 1627.4 | 0.094 | 0.46 | – | – |
| $2p^3 3p^1 3p^0$ | 1628.9 | 0.094 | 0.30 | – | – |
| $2p^3 3p^1 3p^0$ | 1628.9 | 0.094 | 0.07 | – | – |
| $2p^3 3p^1 3p^0$ | 1629.1 | 0.094 | 0.11 | – | – |
| $2p^3 3p^1 3p^0$ | 1629.8 | 0.079 | 0.18 | – | – |
| $2p^3 3p^1 3p^0$ | 1675.7 | 0.084 | 5.43 | – | – |
| $2p^3 3p^1 3p^0$ | 1675.8 | 0.084 | 8.87 | – | – |
| $2p^3 3p^1 3p^0$ | 1675.8 | 0.084 | 1.83 | – | – |
| $2p^3 3p^1 3p^0$ | 1740.3 | 0.257 | 9.39 | – | – |
| $2p^3 3p^1 3p^0$ | 1743.2 | 0.176 | 2.39 | – | – |
| $2p^3 3p^1 3p^0$ | 1743.2 | 0.176 | 7.32 | – | – |
| $2p^3 3p^1 3p^0$ | 1745.0 | 0.167 | 2.54 | – | – |
| $2p^3 3p^1 3p^0$ | 1745.1 | 0.167 | 0.17 | – | – |
| $2p^3 3p^1 3p^0$ | 1745.3 | 0.167 | 3.45 | – | – |
| $2p^3 3p^1 3p^0$ | 1831.6 | 0.362 | 0.02 | – | – |
| $2p^3 3p^1 3p^0$ | 1836.2 | 0.362 | 0.06 | – | – |
| $2p^3 3p^1 3p^0$ | 3329.7 | 0.454 | 0.01 | – | – |
| $2p^3 3p^1 3p^0$ | 3955.8 | 0.454 | 0.06 | – | – |
| $2p^3 3p^1 3p^0$ | 3990.0 | 0.454 | 0.60 | – | 1.07 |
| $2p^3 3p^1 3p^0$ | 4114.3 | 0.014 | 0.01 | – | – |
| $2p^3 3p^1 3p^0$ | 4375.0 | 0.035 | 0.03 | – | – |
| $2p^3 3p^1 3p^0$ | 4379.6 | 0.016 | 0.01 | – | – |
| $2p^3 3p^1 3p^0$ | 4459.9 | 0.014 | 0.15 | – | – |
| $2p^3 3p^1 3p^0$ | 4465.5 | 0.014 | 0.09 | 1.57 | – |
| $2p^3 3p^1 3p^0$ | 4477.7 | 0.014 | 0.34 | – | – |
| $2p^3 3p^1 3p^0$ | 4488.1 | 0.033 | 0.06 | – | – |
| $2p^3 3p^1 3p^0$ | 4507.6 | 0.033 | 0.45 | – | – |

### Table 5 – continued

| Transition | $\lambda$(Å) | $I(I/\beta)$ (1) | $I(I/H\beta)$ (2) | $I(I/H\beta)$ (3) | $I(I/H\beta)$ (4) |
|------------|--------------|------------------|-------------------|-------------------|-------------------|
| $2p^3 3p^1 3p^0$ | 3945.6 | 0.014 | 0.01 | – | – |
| $2p^3 3p^1 3p^0$ | 4036.3 | 0.035 | 0.03 | – | – |
| $2p^3 3p^1 3p^0$ | 4036.3 | 0.016 | 0.01 | – | – |
| $2p^3 3p^1 3p^0$ | 4036.3 | 0.014 | 0.15 | – | – |
| $2p^3 3p^1 3p^0$ | 4036.3 | 0.014 | 0.09 | 1.57 | – |
| $2p^3 3p^1 3p^0$ | 4036.3 | 0.014 | 0.34 | – | – |
| $2p^3 3p^1 3p^0$ | 4036.3 | 0.033 | 0.06 | – | – |
| $2p^3 3p^1 3p^0$ | 4036.3 | 0.033 | 0.45 | – | – |

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The most intense fluorescence lines are triplets connected by resonant transitions to the ground term, 2p$^2$ 3P. At temperatures characteristic of H II regions, the fine structure populations of the ground term are approximately proportional to their statistical weight, and consequently the relative intensities of all the other triplet levels are given by the LS line fractions (Allen 1973).

The lines at 5001.15 and 5001.48 Å arising from the 3d 5P term are blended. We split the total intensity according to the LS line fractions: 21.0:31.1, in order to compare them with our predictions. Most of the observed fractions: 21.0:31.1, are available from the authors upon request. The quintet lines 3p 3P–3d 3D, are blended. We split the total intensity according to the LS line configurations, spin-forbidden transitions from the triplets and recombinations. Intensities for other lines up to λλ3838.37–3856.06 Å with an intensity of $4 \times 10^4$ are normalized to $I_{\text{cal}}$ and $I_{\text{obs}}$ (marked with ‘?’ in Table 5). The broken horizontal line is the value of $R = (I_{\text{cal}}/I_{\text{obs}})$. The nebular model was calculated with N+(BM parameters, except for $T_{\text{eff}} = 39$ kK in the lower panels, giving column densities of N(N+) = 7.3 $\times 10^{16}$ cm$^{-2}$ and 2.6 $\times 10^{16}$ cm$^{-2}$ for the $T_{\text{eff}} = 37$ kK and 39 kK atmospheres respectively. Note that the observed intensities here and in Table 5 are normalized to $I(\text{H}\beta) = 10^4$.

### 5 VARIATION OF PARAMETERS

#### 5.1 Stellar temperature

Fig. 3 shows a comparison of observed and predicted intensities with two WMBASIC stellar atmospheres. The reduction in N$^+$ column density produced by the hotter star reduces the predicted intensities in general, but the intensities of the lines originating from d states suffer a much greater reduction than the ones from p states by an order of magnitude. We have traced this effect to an important decrease in the model atmosphere flux by a factor of $\sim$2 at 529.6 Å and a factor of $\sim$5 at 533.7 Å for $T_{\text{eff}} \gtrsim 38$ kK as shown in Fig. 4. As mentioned in Section 2.1, 3d states are pumped almost entirely by absorptions at those two wavelengths. At the same time there is an increase of a factor of $\sim$2 in the flux at 508.7 Å for $T_{\text{eff}} \gtrsim 37$ kK, which is important in the pumping of 3p states, and compensates for the decrease in the N$^+$ column density.

The difference in the pumping rates of d and p states for $T_{\text{eff}} \gtrsim 38$ kK depends only on the shape of the spectrum and the contribution of recombination to the population of those states. The disagreement between predicted and observed intensities of lines from d states with $T_{\text{eff}} = 39$ kK shown in Fig. 3 persists when the N abundance is increased to 1 $\times 10^{-4}$ or when the recombination contribution to the intensities is increased with the hypothesis of ultracold plasma proposed by Tsamis et al. (2004). A plasma temperature of 2000 K doubles the predicted intensities of lines from 3p states, but lines from 3d states increase their intensities in lower proportions because fluorescence is more important in the population of those states.
The NII spectrum of Orion

Figure 4. Surface Eddington flux of two WMBASIC atmospheres. Arrows show wavelengths of the resonant multiplets at 508.7, 529.6 and 533.7 Å.

The other critical parameter in the fluorescence line intensities is the column density. The N+ column density decreases with $T_{\text{eff}}$ at a much lower rate for $T_{\text{eff}} \gtrsim 38$ kK as reflected in Fig. 5. The N II fluorescence lines and the [N II] lines decrease little for harder spectra due to that persistent N+ concentration, but their different behaviour at lower $T_{\text{eff}}$ can be understood in terms of the N+ concentration and the escape probability concept. As shown in Fig. 2, the fluorescence N II lines form 50 per cent of their intensity in the inner layers of the nebula, much closer to the star than the [N II] lines, which are produced in the outer N+ zone. As $T_{\text{eff}}$ decreases, the N+ concentration and the optical depth of the resonant transitions increase, but the intensities of lines from p and d states behave differently as shown in Fig. 5 for the lines $3s\,^3P_2-3p\,^3P_2\lambda 4630.54$ and $3p\,^3P_2-3d\,^3D_2\lambda 5941.65$. Absorption transitions that populate the p states have a much lower optical depth than the ones pumping the d states. As a result the escape probability decreases more for d states than for p states with lower $T_{\text{eff}}$, and the pumping due to reabsorption of resonant photons for d states increases.

NEBU tends to give larger column densities than CLOUDY, and thus predicts higher intensities. Predicted line intensities by NEBU in the UV tend to be 30 per cent more intense than those given by CLOUDY because NEBU does not consider internal dust extinction, but predictions of the two codes are within 20 per cent of each other in the optical.

5.2 Kurucz atmospheres

CLOUDY contains a grid of low-resolution Kurucz atmospheres (Kurucz 1991) that can be readily used as continua in our calculations. A comparison of Figs 3 and 6 shows that the differences between the calculated intensities of p and d states with Kurucz atmospheres are much smaller than the differences with the WMBASIC atmospheres because the Kurucz atmospheres do not have the structure of the WMBASIC atmospheres that causes the different absorption rates between p and d states.

Modelling of Orion with CLOUDY (Baldwin et al. 1991, 1996, 2000) has favoured stellar temperatures that are lower than current spectrophotometric measurements. Our results with the WMBASIC atmospheres also favour a lower $T_{\text{eff}}$, but Kurucz atmospheres give...
a better agreement with observations because they are softer than other models and give a larger N\(^+\) column.

### 5.3 Stellar flux

Unlike most forbidden and recombination lines, fluorescence line intensities are more sensitive to changes in the stellar flux illuminating the nebula. Their intensities increase with \(\phi_0\) up to \(10^{12.5} \text{ cm}^{-2} \text{ s}^{-1}\) and remain nearly constant for higher \(\phi_0\). This behavior can be understood in similar terms to the curve of growth of the resonant lines. As the intensity of the ionizing flux grows, the N\(^+\) column density and the optical depth increase, and the cores of the resonant lines become saturated. Equations (2) and (9) show that the intensity of the fluorescence lines is approximately proportional to the integral along the line of sight of the pumping rate of equation (2) times the density of the absorbing state, \(n_c \beta_{gx}\). Changing the variable from \(r\) to \(\tau_0\), eliminating constant quantities and assuming a constant Doppler width, the intensity of a fluorescence line will be

\[
I \propto \int_{0}^{\infty} \int \epsilon_{-\phi(x)} \phi(x) \, dx \, d\tau_0
\]

\[
= J_c(0) \int_{0}^{\infty} \int e^{-\tau_c(0)} \epsilon_{-\phi(0)} \phi(x) \, dx \, d\tau_0,
\]

where \(J_c(0)\) is the stellar continuum at the illuminated face of the cloud, and \(\tau_c\) is the continuum opacity. The integration over \(\tau_0\) can be performed exactly if we assume a mean value for \(e^{-\tau_c}\). For fixed \(T_{\text{eff}}\) and \(v\), \(J_c(0)\) is proportional to \(\phi_0\), which in turn is proportional to the H\(\beta\) flux. Therefore the fluorescence line intensity normalized to H\(\beta\) must be proportional to

\[
\left(\epsilon_{-\phi(0)}\right) \left[1 - e^{-\tau_c(0)}\right] \, dx.
\]

The integral is proportional to the curve of growth \(W(\tau_0)\). Fig. 7 shows that the intensity of the lines follows closely a fit of the form

\[
I/I(\text{H} \beta) \propto e^{-2.5 \times 10^{-22} N(\text{H}^+)} W(\tau_0).
\]  

\[\text{Figure 7.} \quad \text{Same as Fig. 5, but with } T_{\text{eff}} = 37 \text{ kK and varying } \phi_0. \text{ The average } R = I(4630.54)/I_{\text{obs}} \text{ (not shown) is within } 3 \text{ per cent of the } 4630.54 \text{ Å line. The fit of equation (11) (dots) is normalized to the } 4630.54 \text{ Å line at } \log \phi_0 = 12.9. \]

where \(N(\text{H}^+)\) is the H\(^+\) column density in \(\text{cm}^{-2}\) and \(W(\tau_0)\) is the curve of growth of the \(2p^2 3P_2 - 4s 3P_2\) line, which pumps most of the 4630.54 line.

### 6 CONCLUSIONS

The intensity of the lines in the N\(\text{II}\) spectrum of the Orion nebula can be explained by fluorescence of the UV radiation of O\(^{4}\)C Ori in the ionized gas. Recombination of N\(^{+}\) contributes a minor part of the observed intensities of lines from 3p and 3d levels connected to the ground state. The effective temperature of the star must be below 38 000 K in order to reproduce the observed line intensities with typical ionization models that are consistent with the forbidden line intensities. An increased N\(^+\) abundance does not allow the use of a higher star temperature. The existence of intervening ionized material in the foreground (O’Dell et al. 1993) was not considered in our model and may help increase the predicted intensities of the N\(\text{II}\) lines. Fluorescence does not increase the intensity of the lines from 4f levels, and other mechanisms must be proposed to explain their strong intensities with respect to the collisionally excited and fluorescence lines in the Orion nebula.

### ACKNOWLEDGMENTS

The authors are very grateful to Katia Verner and Gary Ferland for valuable advice in running CLOUDY.

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