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STARLIGHT EXCITATION OF PERMITTED LINES IN THE ORION NEBULA

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ABSTRACT

From an idealized model of the Orion Nebula and from an analysis of line ratios it is shown that direct starlight excitation of the permitted O I lines dominates over recombination and Lyman line fluorescence. The line strengths predicted by this mechanism agree reasonably well with those observed in the Orion Nebula. The application of direct starlight excitation to other ions is also discussed.

Subject headings: line formation — Orion Nebula

I. INTRODUCTION

Permitted lines of O I (primarily λ8446) have been seen in the Orion Nebula and in several planetary nebulae (Morgan 1971; Andrillat and Houziaux 1968; Danziger and Aaronson 1974). In this paper we will investigate possible excitation mechanisms for these lines. The observed triplet lines (from Morgan 1971) are shown on the energy level diagram in figure 1 with the observed line strengths (corrected for reddening and normalized to Hβ). The line at λ5555 is an uncertain identification, according to Morgan, while the line at λ5958 is assumed to be part of a blend with Si II $4p\ ^2P_{1/2}$–$5s\ ^2S$. The λ4368 line was not actually observed by Morgan, but she included it from the work of Kaler, Aller, and Bowen (1965). This line was also observed by Chopinet and Fehrenbach (1961), where it was identified as a line of C II. λ7254 and λ6046 were also listed (but not identified) by Flather and Osterbrock (1960).

The usual explanation for permitted lines in the spectra of nebulae is recombination from higher ionization states. However, the recombination process is not sufficient to explain the strength of the λ8446 line, as we will show in § II. Two other possible excitation mechanisms, Lyman line fluorescence and direct excitation by starlight, have been suggested (Morgan 1971), and will be discussed in §§ III and IV, respectively.

To explicitly calculate the strength of the λ8446 and other permitted lines of O I arising from each of these three mechanisms, we have constructed a very idealized model of the Orion Nebula consisting of an O7 V star (Conti 1973) surrounded by a spherical, uniform density nebula containing 4000 hydrogen atoms per cubic centimeter. The star is modeled by a 37,500° K, $\log g = 4.0$, non-LTE stellar atmosphere (Mihalas 1972). Immediately beyond the edge of the H II region, the density drops to the normal interstellar value. In figure 2, we show the oxygen ionization structure of this model where we have utilized an $N_{\rm O}/N_{\rm H}$ number ratio of 6×10^{-4}. This idealized Orion Nebula model is based on work by S. Grandi, E. Jensen, J. Scott, J. Stocke, and R. Williams which will be reported on elsewhere. Although the actual physical conditions in the Orion Nebula are quite a bit more complicated than described in this model (Simpson 1973), the normalized line strengths of the prominent forbidden and recombination lines predicted by this model are in order-of-magnitude agreement with the observations (from Johnson 1968) as listed in table 1. While we do not pretend that this model adequately represents the Orion Nebula, it should be sufficient to delineate the relative effects of the physical processes under consideration. Since the other parameters needed for our calculations—the atomic constants for O I and Morgan's (1971) visually determined line ratios—are also somewhat uncertain, a detailed model is not truly justified. However, we shall also note the model-independent O I line ratios in our discussion of each process.

II. RECOMBINATION

We first predict the ratio of O I λ8446 flux to Hβ flux assuming that all of the λ8446 flux is due to recombination from O II. Since only the total recombination coefficient and the coefficient to the ground state have been determined for O I, we will follow Andrillat and Houziaux (1968) and assume that all recombinations not to the ground state go to the $3p\ ^3P$ term and decay via λ8446. Using the recombination coefficients given by Aldrovandi and Pequignot (1973), we obtain the following for the volume emission coefficients for λ8446:

$$j_{8446} = N_e N_{\rm O\,II} \frac{h\nu_{8446}}{4\pi} 2.1 \times 10^{-13} t_e^{-0.68}\,, \qquad (1)$$

where N_e and $N_{\rm O\,II}$ are the electron and O II densities, respectively, and t_e is the electron temperature in units of 10^4 ° K. Similarly, the volume emission coefficient for Hβ is

$$j_{\rm H\beta} = N_e N_{\rm H\,II} \frac{h\nu_{\rm H\beta}}{4\pi} 3.07 \times 10^{-14} t_e^{-0.90} \qquad (2)$$

using the recombination coefficient from Seaton

TABLE 1

LINE STRENGTHS FROM IDEALIZED ORION NEBULA MODEL

Line	Observed Strength	Predicted Strength
Hβ...............	1.0	1.0
He I 5876.........	0.25	0.14
He I 4471.........	0.051	0.048
[O III] 5007........	3.32	9.0
[O II] 3727........	1.83	0.84
[O I] 6300.........	0.046	0.010
[N II] 6584........	0.36	0.66
[N I] 5199.........	0.007	0.021
[Ne III] 3869.......	0.27	0.35

(1968*a*). The λ8446/Hβ flux ratio is

$$\frac{F_{8446}}{F_{\mathrm{H}\beta}} = \int_0^R j_{8446} r^2 dr \Big/ \int_0^R j_{\mathrm{H}\beta} r^2 dr\,, \tag{3}$$

where R is the radius of the nebula. Using the idealized Orion Nebula model, we obtain from these expressions a flux ratio of 1.7×10^{-4}, which is over two orders of magnitude below the observed ratio of 0.015.

Also, the lack of quintet lines of comparable strength to the triplet lines would seem to rule out recombination as an excitation mechanism. One would expect, if recombination were exciting the O I lines, that the quintet lines and triplet lines should be present

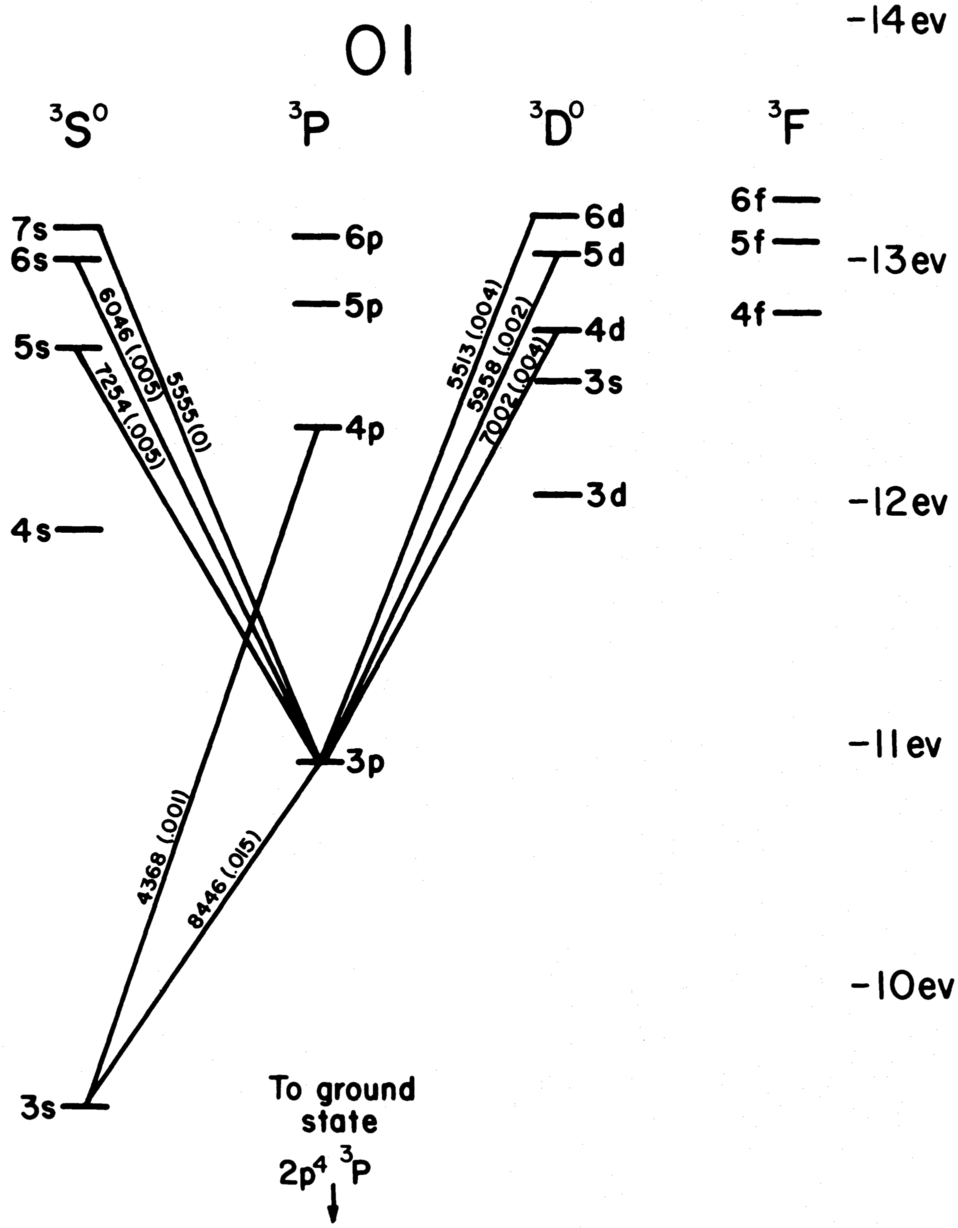

FIG. 1.—Energy level diagram of the triplets of O I showing transitions seen in the Orion Nebula. Line strengths (normalized to Hβ = 1) are shown in parentheses.

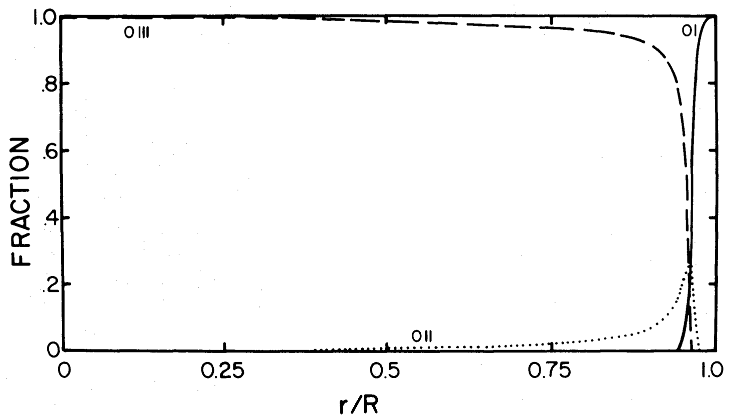

FIG. 2.—Oxygen ionization structure of the idealized Orion Nebula model. The fractional ionization is plotted versus the fractional radius.

in ratios corresponding to the ratio of their statistical weights. However, instead of being slightly stronger the only observed quintet line (λ7774, $3s\ ^5S$–$3p\ ^5P$) is a full order of magnitude weaker than its triplet equivalent (λ8446).

III. FLUORESCENCE

Since the ionization potential of O I and H I are almost exactly the same, their upper energy levels are quite similar. Many of the transitions from the ground state of O I are within a few angstroms of a Lyman line, and some are virtually coincident. It happens that the strongest component of the ground-state transition to $3d\ ^3D$ in O I is λ1025.77, while Lβ is at 1025.72 Å. This close coincidence in line frequency makes the fluorescence mechanism an attractive candidate to explain the strength of the λ8446 line (Swings 1955).

To calculate the ratio $F_{8446}/F_{\mathrm{H}\beta}$ expected from this process, we will follow Morgan (1971) and provisionally assume that Lβ fluorescence of the $3d\ ^3D$ term accounts for all the λ8446 line emission. We obtain for the volume emission coefficient of λ8446 from fluorescence:

$$j_{8446} = N_{\mathrm{O\,I}}\langle J_{\mathrm{L}\beta}\rangle B_{1027}\frac{A_{11287}}{A_{11287}+A_{1027}}\frac{h\nu_{8446}}{4\pi}\,, \quad (4)$$

where the subscript 1027 refers to the $2p^4\ ^3P$–$3d\ ^3D$ transition and the subscript 11287 refers to the $3p\ ^3P$–$3d\ ^4D$ transition. $\langle J\rangle$ is an appropriate average over frequency of the mean intensity of radiation, and A and B are the Einstein coefficients.

If we now assume that all of the Hα photons we see from the nebula are generated by the degradation of Lβ, we obtain

$$j_{\mathrm{H}\alpha} = N_{\mathrm{H\,I}}\langle J_{\mathrm{L}\beta}\rangle B_{\mathrm{L}\beta}\frac{A_{\mathrm{H}\alpha}}{A_{\mathrm{H}\alpha}+A_{\mathrm{L}\beta}}\frac{h\nu_{\mathrm{H}\alpha}}{4\pi}\,, \quad (5)$$

where $A_{\mathrm{H}\alpha}$ refers to the $2s$–$3p$ transition only. We will assume that the value of $\langle J_{\mathrm{L}\beta}\rangle$ in equations (4) and (5) are equal even though $\langle J_{\mathrm{L}\beta}\rangle$ corresponding to the O I λ1027 line is likely to be smaller than the value in equation (5) due to the 0.05 Å offset between Lβ and O I λ1027. Also, some Hα photons will not be produced by Lβ degradation, hence equation (5) is a lower limit to $j_{\mathrm{H}\alpha}$. Therefore, because of these two effects, the λ8446/Hα flux ratio we will derive will be an upper limit. Finally, if we ignore any possible temperature dependence and if we assume that the mean intensity of Lβ as seen at a particular point in the nebula is representative only of the physical conditions at that point (i.e., a Lβ photon will not travel into regions of differing physical conditions before it is converted into Lα and Hα photons by collisions with neutral hydrogen), then the mean intensity of Lβ will be proportional to

$$\langle J_{\mathrm{L}\beta}\rangle \propto \frac{N_e N_{\mathrm{H\,II}}}{N_{\mathrm{H\,I}}}\,, \quad (6)$$

where the numerator represents the production and the denominator represents the loss of Lβ photons.

By combining equations (3), (4), (5), and (6) we obtain for the λ8446/Hα flux ratio:

$$\frac{F_{8446}}{F_{\mathrm{H}\alpha}} = \frac{\int_0^R (N_{\mathrm{O\,I}}N_e N_{\mathrm{H\,II}}/N_{\mathrm{H\,I}})r^2dr}{\int_0^R N_e N_{\mathrm{H\,II}}r^2dr} \times \left(\frac{B_{1027}A_{11287}h\nu_{8446}}{A_{11287}+A_{1027}}\right)\Bigg/\left(\frac{B_{\mathrm{L}\beta}A_{\mathrm{H}\alpha}h\nu_{\mathrm{H}\alpha}}{A_{\mathrm{H}\alpha}+A_{\mathrm{L}\beta}}\right). \quad (7)$$

We use a calculation of the Balmer decrement (Brocklehurst 1971) to obtain the ratio of Hα to Hβ flux, which leads to a value of 3.0×10^{-5} for the λ8446 to Hβ flux ratio for our model, as compared with the observed flux ratio of 1.5×10^{-2}. A nearly model independent result can be obtained from equation (7) by considering the fact that, due to charge exchange (Williams 1973), the number ratios $N_{\mathrm{O\,II}*}/N_{\mathrm{O\,I}}$ and $N_{\mathrm{H\,II}}/N_{\mathrm{H\,I}}$ are approximately equal throughout the nebula (O II* here refers to all the ionized forms of oxygen). Since in most of the nebular region, all of the hydrogen and oxygen atoms are ionized, we can substitute $N_{\mathrm{O}}/N_{\mathrm{H}}$, the number ratio of oxygen to hydrogen nuclei, for $N_{\mathrm{O\,II^*}}/N_{\mathrm{H\,II}}$ which is equal to $N_{\mathrm{O\,I}}/N_{\mathrm{H\,I}}$ due to charge exchange throughout the nebula. Thus equation (7) becomes

$$\frac{F_{8446}}{F_{\mathrm{H}\alpha}} = \frac{N_{\mathrm{O}}}{N_{\mathrm{H}}}\frac{B_{1027}A_{11287}h\nu_{8446}}{A_{11287}+A_{1027}}\bigg/\frac{B_{\mathrm{L}\beta}A_{\mathrm{H}\alpha}h\nu_{\mathrm{H}\alpha}}{A_{\mathrm{H}\alpha}+A_{\mathrm{L}\beta}}, \quad (7a)$$

which leads to a value of 5.5×10^{-4} for the λ8446 to Hβ flux ratio assuming a value for $N_{\mathrm{O}}/N_{\mathrm{H}}$ of 6×10^{-4}.

Even if Lβ fluorescence could account for the strength of the λ8446 line, the observed strengths of the other permitted O I lines must still be explained. Direct fluorescent excitation cannot account for most of the lines. For example, the resonance lines to $7s\,^3S$, which excite λ5555, are located at λλ976.45, 977.96, and 978.62 which are far outside the Lγ line at λ972.54. Morgan (1971) points out that there is a coincidence between Lε at λ937.80 and a component of the resonance multiplet to $7s\,^3S$ at λ937.84. Also, Lζ at λ930.75 corresponds to a component of the resonance multiplet to $7d\,^3D$ at λ930.90. However, cascades from these terms cannot explain the strengths of the other lines. For example, let us assume that a cascade from $7s\,^3S$ through $6p\,^3P$ accounts for Morgan's (1971) observed strength of λ6046. Using Einstein A values derived from Kelly (1964) we find that the observed λ6046/Hβ line ratio of 0.005 implies a λ5555/Hβ line ratio of 0.645 (43 times stronger than the observed strength of λ8446). In reality, Morgan (1971) calls her identification of λ5555 uncertain.

Column (3) of table 3 lists the O I/O I λ8446 line ratios predicted by a calculation of Lyman line fluorescence of the $3d\,^3D$, $7s\,^3S$, and $7d\,^3D$ levels in O I by Lβ, Lε, and Lζ, respectively. These line ratios are expected to be essentially model-independent, since they depend only on the relative strengths of these Lyman lines, which are given by the solution to the hydrogen capture-cascade equations (Pengelly 1964) which depend only weakly on temperature and density in the nebula.

IV. STARLIGHT EXCITATION

Seaton (1968*b*) has invoked the excitation of permitted lines by starlight to account for the presence of these lines in the spectra of planetary nebulae. Morgan (1971) has suggested that this mechanism might account for the O I line strengths in the Orion Nebula.

A difficulty in calculating line strengths due to this excitation mechanism occurs because of the nonuniformity of the spectral energy distribution of the central star due to the presence of absorption lines, which when combined with the absorption of these line photons by the nebular gas will prevent certain O I terms from being excited. For example, the coincidence of Lβ with the ground state to $3d\,^3D$ transition in O I mentioned in § III will prevent this term from being significantly excited by starlight. Also, the ground-state transition to the $3s\,^3D$ term corresponds to the N III resonance line at λ990 which is prominent in O star spectra (Smith 1970). N III is also present in large quantities in the nebula. Consequently, if direct starlight excitation is the principal excitation mechanism, lines resulting from cascades from these two terms should be practically nonexistent (except for contributions from cascades from still higher terms) compared with lines resulting from other cascades. Therefore, λ7990 ($3p\,^3P$–$3s\,^3D$) should be much weaker than corresponding lines such as λ7002; in fact, this line was not found by Morgan (1971) in her spectral survey. Also the line at λ11287 ($3p\,^3P$–$3d\,^3D$) should be much weaker than the corresponding line at λ13165 ($3p\,^3P$–$4s\,^3S$). If Lyman fluorescence were the dominant source of excitation, however, the reverse would be true: λ11287 should be much stronger than λ13165 since the ground-state transition to $4s\,^3S$ (at λ1040) does not correspond to a Lyman line; similarly, λ7990 should be of comparable strength with the other lines that would all presumably be cascades from $7s\,^3S$ and $7d\,^3D$.

Now let us assume that all the λ8446 photons produced come from the direct starlight excitation of the $4s\,^3S$, $5s\,^3S$, $6s\,^3S$, $7s\,^3S$, $4d\,^3D$, $5d\,^3D$, and $6d\,^3D$ terms followed by decays to $3p\,^3P$ and then a decay via λ8446. Consequently, the volume emission coefficient for λ8446 at a radial distance r from the central star becomes

$$j_{8446}{}^{(r)} = \frac{h\nu_{8446}}{4\pi} N_{\mathrm{O\,I}} \sum_i J_i{}^*(r) B_i \frac{A_i}{\sum A_i}, \quad (8)$$

where the first sum is over all the above mentioned terms, $J_i{}^*(r)$ is the mean intensity due to starlight at r at the proper excitation frequency, A_i is the Einstein A coefficient connecting this particular term to $3p\,^3P$, and $\sum A_i$ is the sum of the Einstein A's for all the downward transitions from this term.

When available, the transition probabilities were obtained from Wiese, Smith, and Glennon (1966); and, if necessary, the coefficients were derived from the line strengths of Kelly (1964). The mean intensity due to starlight is equal to

$$J^*(r) = H_{\mathrm{SURFACE}}{}^* R_*{}^2/r^2, \quad (9)$$

where R_* is the radius of the central star and $H_{\mathrm{SURFACE}}{}^*$ is the Eddington flux obtained from the stellar model (Mihalas 1972) used in the idealized Orion Nebula model. We have assumed that there is no opacity inside the nebula at these wavelengths, which are all longward of λ912. Extinction due to dust is also not considered. Over the wavelengths of interest, the stellar flux is approximately constant, so J^* has been taken outside the sum in equation (8).

The resulting λ8446 to Hβ flux ratio calculated due to this mechanism for the idealized Orion Nebula model is 0.009, while the observed value is 0.015. Cascades from the $4s\,^3S$ term generate 47 percent of the line strength, and cascades from $4d\,^3D$ supply 35 percent of the line strength. Similarly, we can derive line strengths for the other observed O I lines, and these are listed in table 2 (normalized to Hβ), along with predictions for some lines that have not been investigated. (The observed line strengths are from Morgan 1971 and Johnson 1968.) The λ5555 and λ5513

TABLE 2

NORMALIZED LINE STRENGTHS FROM STARLIGHT EXCITATION OF O I

Wavelength of O I Line (1)	Observed (2)	Predicted (3)	Normalized (4)
3692	...*	0.002	0.009
4368	0.001	0.001	0.006
5513	0.004	0.00002*	0.0001
5555	0*	0.0002*	0.0008
5958	0.002	0.0004	0.002
6046	0.005	0.0005	0.002
7002	0.004	0.004*	0.02
7254	0.005	0.001	0.005
7774	0.001	...*	...
8446	0.015	0.009	0.032
11287	...	0.0002*	0.001
13150	...	0.003	0.01

* See text.

lines come from terms whose excitation wavelengths are close to Lϵ, so the line strengths predicted here may be overestimated because of absorption lines and nebular opacity (λ5555 is called an uncertain identification by Morgan). The line at λ7002 is a similar case in that its excitation wavelength is close to Cl IV λ973 and Lγ so that the stellar flux exciting this line will be depressed. The coincidence is not exact enough for nebular opacity to be important, however. The line at λ7774 ($3s\,^5S$–$3p\,^5P$) is the quintet counterpart of λ8446 and is presumably due to intercombination transitions among the excitations or the cascades. The presence of λ3692 ($3s\,^3S$–$5p\,^3P$) is masked by H16 which is 10 times stronger and only 1 Å away. As can be seen, the predictions are in order-of-magnitude agreement with the observations except for λ5513. The predicted line strengths are in general smaller than the observed line strengths, but the predicted [O I] λ6300 line strength is also smaller than observed (see table 1). Column (4) of table 2, therefore, contains the O I/Hβ line ratios normalized so that the observed and predicted line strengths of [O I] λ6300 agree. It should be noted, however, that the regions emitting O I radiation are not in general the same regions emitting [O I] radiation due to the requirement of free electrons to excite the forbidden lines.

TABLE 3

O I LINE RATIOS

Line Ratio (1)	Observed (2)	Lyman Fluorescence (3)	Direct Starlight Excitation (4)
4368/8446.....	0.07	1×10^{-4}	0.2
7254/8446.....	0.3	1×10^{-5}	0.1
6046/8446.....	0.3	6×10^{-6}	0.06
5555/8446.....	0*	6×10^{-4}	0.02
7002/8446.....	0.3	1×10^{-6}	0.4
5958/8446.....	0.1	8×10^{-8}	0.06
5513/8446.....	0.3†	2×10^{-9}	0.003

* Uncertain identification.

† See text.

Table 3 contains the O I/O I λ8446 line ratios predicted by direct starlight excitation, which should be almost entirely model independent, since the ratios depend only on the spectrum of the exciting star.

V. CONCLUSIONS

Comparing the results of the previous three sections, we find that, based on our model, direct starlight excitation dominates the excitation of λ8446 over recombination and Lyman line fluorescence by several orders of magnitude. The line strengths (when normalized so that the observed and predicted strength of [O I] λ6300 agree) predicted by direct starlight excitation are in reasonable agreement with observations (see table 2). Also, the lack of quintet lines as predicted by recombination and the large disagreements between the line ratios predicted by Lyman fluorescence and the observed ratios provide model-independent reasons for discounting these processes in favor of direct starlight excitation, which predicts O I line ratios in fair agreement with observation (see table 3). Therefore, we conclude that direct starlight excitation is the correct mechanism for exciting the permitted O I lines in the Orion Nebula.

The large discrepancy between the observed and the predicted line strength of λ5513 leads us to believe that Morgan's (1971) identification of the line observed at λ5513 as O I $3p\,^3P$–$6d\,^3D$ is incorrect. If, however, the calculations of Kelly (1964) which lead to an Einstein A for the λ5513 line of 1.9×10^4 (the smallest of any downward permitted transition from $6d\,^3D$) are in error and the Einstein A for this transition is actually greater than Kelly's value, then the predicted strength of the line would accordingly be larger, perhaps enough larger to account for the discrepancy with the observed λ5513 strength. Assuming that Kelly's results are correct, however, a line strength for O I λ5513 as large as reported by Morgan would result in an even stronger line at λ14114 ($4p\,^3P$–$6d\,^3D$) because the Einstein A for this line is 18 times larger than that for λ5513. This would, in turn, result in an enhanced λ4368 line ($3s\,^3S$–$4p\,^3P$). If we assume that all levels are excited by direct starlight excitation except for $6d\,^3D$ which somehow is excited 50 times more strongly than by the starlight in order to produce the observed λ5513 strength, we obtain a λ4368/λ8446 line ratio of 0.7, which is an order of magnitude larger than the observed ratio of 0.07. In other words, if the Einstein A for λ5513 transition taken from Kelly is correct, there is no mechanism that can produce the observed λ5513 line strength without also producing a λ4368 line strength 10 times that which is observed. Therefore, we conclude that the observed line at λ5513 is not the O I λ5513 line.

VI. DISCUSSION

The fact that the presence of O I is confined to the transition region of the nebula is a crucial one in the dominance of starlight excitation over excitation by Lyman line fluorescence. It turns out that over the whole nebula, about 100 times more Lβ photons are

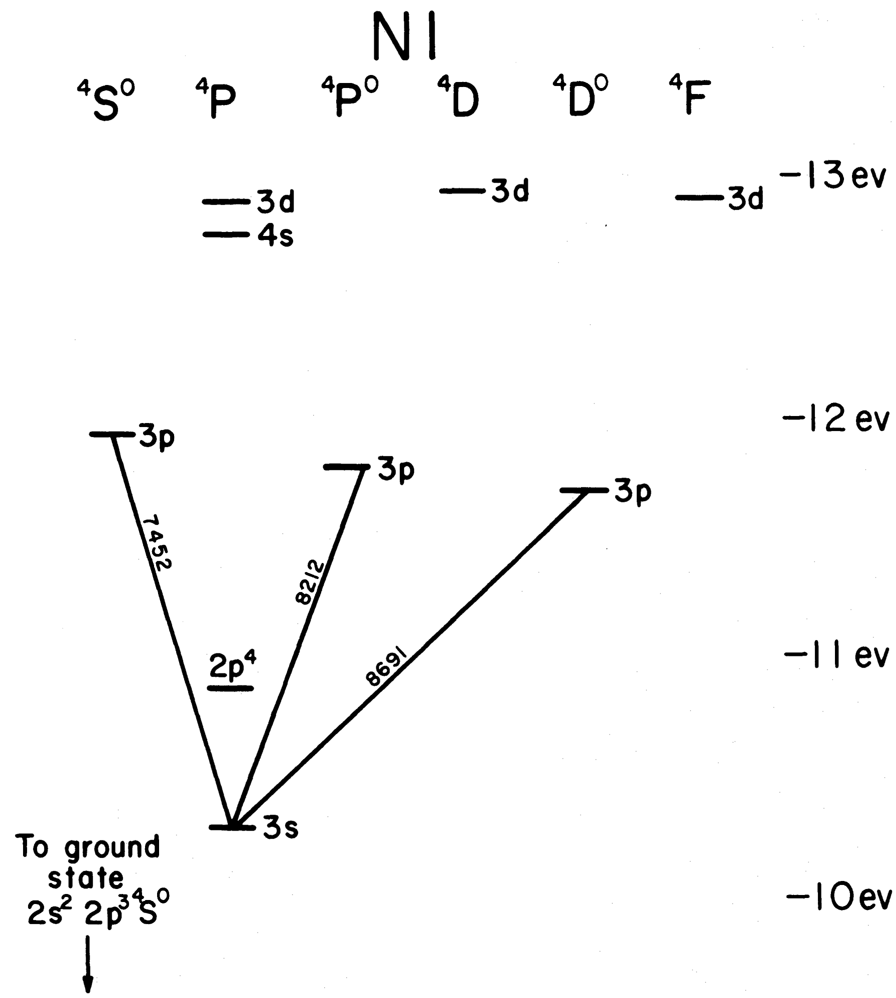

FIG. 3.—Energy level diagram of the quartets of N I showing the three transitions discussed in the text

generated per second than stellar photons capable of exciting the O I lines. However, the vast majority of the Lβ photons exist in the inner parts of the nebula where $(N_{\rm H\,II}/N_{\rm H\,I})N_e$ is large. Since these Lβ photons cannot travel into the outer regions of the nebula without being degraded by scatterings with neutral hydrogen, the Lβ density in the regions where O I exists will reflect the low $(N_{\rm H\,II}/N_{\rm H\,I})N_e$ ratio present there. Consequently, since the Lβ photons are confined to the interior while the O I is confined to the exterior, Lβ fluorescence is not important. One way to circumvent this difficulty would be to postulate a sufficient optical depth in the Balmer lines in the transition region of the nebula which might allow enough Lβ photons to be generated in the O I region to account for the observed λ8446 strength by fluorescence. However, the fact that the other observed O I lines could not be produced by Lβ fluorescence would seem to exclude this possibility.

As we mentioned in § IV, the relative strengths of λ11287 and λ13150 will provide a test of the excitation mechanism present in the Orion Nebula. We predict, on the basis of direct starlight excitation, that λ13150 should have a normalized strength of 0.01 relative to Hβ (see table 2). Based on the hydrogen recombination-line calculations of Brocklehurst (1971), this line strength corresponds to a λ13150/Paschen β flux ratio of 0.06. Since λ11287 cannot be excited directly by starlight, we consider its excitation by cascades from the $4d\,^3D$, $5d\,^3D$, $5s\,^3S$, and $6s\,^3S$ terms via the $4p\,^3P$ and $5p\,^3P$ terms. Based on the idealized Orion Nebula model, this process results in a normalized λ11287/Hβ flux ratio of 0.001 which is an order of magnitude fainter than λ13150. The contribution to the λ11287 line strength from Lβ fluorescence as calculated in § III is more than an order of magnitude below the contribution of starlight excitation.

Danziger and Aaronson (1972) remark on the large spatial variation of λ8446 in the Orion Nebula, and they note that it increases in strength dramatically on the bright arc near θ^2 Ori. However, the spatial variations are different from those of the forbidden lines or recombination lines. One might expect such variations in starlight-excited lines in the actual Orion Nebula near another source of starlight excitation; and since the mechanisms involved are distinct, the mode of

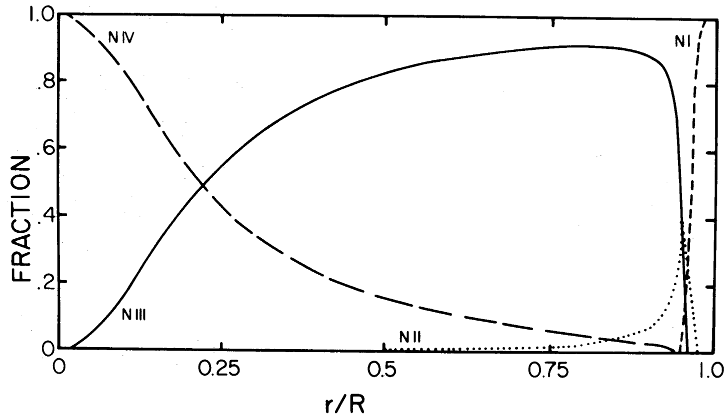

FIG. 4.—Nitrogen ionization structure of the idealized Orion Nebula model. The fractional ionization is plotted versus the fractional radius.

spatial variation should be different from that for recombination or collisionally excited lines.

VII. APPLICATION TO OTHER IONS

The effect of the starlight excitation mechanism on ions other than O I in H II regions is limited by several factors. First, for higher ionization states, the presence of absorption lines in the stellar spectrum (due to the same ionization states) will tend to eliminate any excitation. For example, the lines of the N III and N IV ions are prominent in O-star spectra (Smith 1970). This would presumably rule out starlight-excited lines from these ions. If the wavelengths needed to excite the ionic lines lie shortward of 912 Å, both the opacity inside the nebula and the dropoff of the stellar continuum flux will largely degrade the excitation. The O III ion is in this category since the wavelength of the resonance transition to the first excited term is λ374. Finally, in some cases recombination will clearly dominate all other processes (the permitted O II lines, for example). From these arguments, it appears that among the abundant ions besides O I, only the N I ion should be significantly excited by this mechanism.

Accordingly, we have considered the excitation of the $3d\,^4P$ and $4s\,^4P$ terms in N I by starlight and calculated the line strengths from the permitted decays leading to λ7468, λ8216, and λ8680 (the strongest members of their respective multiplets), following the techniques of § IV. In figure 3 we show the quartet energy levels of N I and the three transitions we have investigated. We present in figure 4 the nitrogen ionization structure of the idealized Orion Nebula as calculated from our model. We have assumed a N_N/N_H number ratio of 2×10^{-4}, and intercombination lines have been ignored. The resulting flux ratios to Hβ are 0.003, 0.003, and 0.004 for λ7468, λ8216, and λ8680, respectively. If we adjust these ratios to reflect the fact that our model overestimates the strength of the [N I] λ5199 line, we must reduce these ratios by a factor of 3. Even though lines of these predicted strengths should have been observed by Morgan (1971), the uncertainties involved in our calculations make this lack of detection not surprising.

Offhand, it may seem likely that if starlight excitation is dominant in exciting the permitted lines of O I, the same mechanism should be just as dominant in exciting the H I lines since the ionization potential and nebular ionization structures for these two ions are so similar. However, for the most part, the stellar radiation that excites the O I line is not subject to absorption lines in the stellar spectrum or opacity in the nebula. The Lyman line radiation required to excite the neutral hydrogen lines, on the other hand, is reduced by both the presence of Lyman absorption lines in the stellar spectrum and a great deal of opacity due to neutral hydrogen in the nebula. In essence, for the same reasons as discussed in § VI for Lβ fluorescence, the starlight Lyman line photons are largely confined to the inner parts of the nebula, while the neutral hydrogen is present in quantity only in the transition region. Therefore, recombination easily dominates over direct starlight excitation in the production of the Balmer lines.

We have calculated with our idealized Orion Nebula model the ratio of the Hβ flux produced by direct starlight excitation by Lγ to that produced by recombination. Assuming that the stellar Lγ line is depressed from the surrounding continuum by a factor of 10, we arrive at a ratio of 5×10^{-4}. As we showed in § II, the corresponding ratio for O I λ8446 is over 100.

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Note added in proof.—A recent far-red spectrum of the bright inner region of the Orion Nebula shows the strongest member of the N I multiplet near 7468 Å and the five strongest members of the N I multiplet near 8216 Å. The observed line strengths are in fair agreement with the predictions of § VII.

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