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OBSERVATIONS OF STARLIGHT-EXCITED LINES IN THE ORION NEBULA

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ABSTRACT

Image tube spectra have been obtained of the Orion Nebula for wavelengths between 5000 and 9000 Å. Permitted lines of N I and O I are identified and are explained by direct starlight excitation.

Subject headings: line formation — line identifications — Orion Nebula

I. INTRODUCTION

Seaton (1968) and Kaler (1972) have discussed direct starlight excitation of permitted lines in gaseous nebulae. Based on the unexpected strength of permitted O I lines in the Orion Nebula as observed by Morgan (1971) and others, Grandi (1975) invoked this mechanism to explain the excitation of the O I lines. In the same paper, Grandi predicted that permitted lines of N I should also be seen in the Orion Nebula. Accordingly, we have taken spectra of the Orion Nebula to search for these lines and to further observe the lines of O I.

II. OBSERVATIONS

Several spectra with exposure times of up to an hour were taken covering the wavelength range 6500–9100 Å at a dispersion of 94 Å mm^{-1} with an ITT image tube with a 40-mm S25 photocathode attached to the Cassegrain spectrograph of the Steward Observatory 90-inch (2.3 m) reflector. The slit was oriented east-west and was placed on the bright inner part of the nebula, about 15″ south of the Trapezium stars. Spectra of the same region were also taken with a dispersion of 48 Å mm^{-1} covering the wavelength range from 5000 to 6300 Å with an RCA C33063 image tube.

Table 1 lists the lines identified from the far red

TABLE 1

Line Identifications in the ITT Orion Nebula Spectrum

λ_{obs} (Å)	ID (Å)	Ion	Strength ($H\beta=1$)	Corrected Strength	λ_{obs}	ID (Å)	Ion	Strength ($H\beta=1$)
... .	6548.1	[N II]	*		8272.1.......	8271.9	P33	
... .	6562.8	Hα	*		8276.7.......	8276.3	P32	
... .	6583.4	[N II]	*		8281.4.......	8281.4	P31	
6677.8.........	6678.1	He I	*		8287.5.......	8286.4	P30	
6716.3.........	6716.4	[S II]	0.05	0.03	8292.5.......	8292.3	P29	
6730.4.........	6730.8	[S II]	0.09	0.06	8299.1.......	8298.8	P28	
7002.6.........	7002.2	O I	0.003	0.002	8306.6.......	8306.1	P27	
7065.1.........	7065.3	He I	*		8314.7.......	8314.3	P26	
7136.1.........	7135.8	[Ar III]	*		8323.8.......	8323.4	P25	
7155.1.........	7155.1	[Fe II]	0.009	0.005	8334.5.......	8334.8	P24	
7231.2.........	7231.3	C II	0.01	0.005	8345.8.......	8345.6	P23	
7236.9.........	7236.4	C II	0.01	0.005	8359.2⎫......	8359.0	P22	
7254.2.........	7254.4	O I	0.01	0.005	8361.2⎭......	8361.7	He I	
7281.6.........	7281.3	He I	0.03	0.02	8374.9.......	8374.5	P21	
7320.3.........	7319.9	[O II]	*		8393.0.......	8392.8	P20	
7330.2.........	7330.2	[O II]	*		8413.7.......	8413.3	P19	
7378.6.........	7377.9	[Ni II]	0.005	0.003	8348.3.......	8438.0	P18	
7412.1.........	7411.6	[Ni II]	0.002	0.001	8447.2.......	8446.4	O I	0.012
7469.0.........	7468.3	N I	0.005	0.002	8467.7.......	8467.3	P17	
7751.3.........	7751.0	[Ar III]	*		8502.9.......	8502.5	P16	
7816.3.........	7816.2	He I	0.004	0.002	8545.8.......	8545.4	P15	
8046.5.........	8046.1	[Cl II]	0.003	0.001	8579.5†......	8579.5	[Cl II]	0.001
8185.1.........	8184.8	N I	0.004	0.002	8598.8.......	8598.4	P14	
8188.7.........	8188.0	N I	0.005	0.002	8617.1.......	8617.0	[Fe II]	0.0007
8204.9.........			0.002	0.0009	8665.6.......	8665.0	P13	
8216.9.........	8216.3	N I	0.006	0.003	8751.0.......	8750.5	P12	
8223.7.........	8223.1	N I	0.008	0.003	8863.5.......	8862.8	P11	
8243.4.........	8242.3	N I	0.004	0.002	9015.7.......	9014.9	P10	
8268.0.........	8267.9	P34			9069.6.......	9069.0	[S III]	

* Line is overexposed. † Line appears to be a blend.

spectra. Column (1) contains the measured wavelength, column (2) contains the wavelength of the identified line, column (3) lists the ion producing the line, and column (4) contains a crude estimate of the strength (on the one-hour exposure) for some of the lines (on a scale such that Hβ = 1). For wavelengths below 8250 Å, the strengths were obtained by calibrating the observed relative intensities (derived from a density tracing of a calibrated stepwedge) by a 1-hour exposure of the white dwarf EG54 which has been measured in absolute energy units by Oke (1974). These strengths were normalized to Hβ via the line strength of the [S II] doublet at λ6716/6730 as given by Aller and Liller (1959). The line strengths were then fully corrected for the smoothed reddening of the Trapezium as listed in Mathis (1957) and discussed in Johnson (1968). Column (5) of Table 1 contains the line strengths corrected for reddening. For lines longward of 8250 Å, the strengths were compared with those of the neighboring Paschen lines which were in turn related to the strength of Hβ through the theoretical hydrogen recombination line strengths for $T_e = 10^4$ K and $N_e = 10^4$ calculated by Brocklehurst (1971). Reddening corrections are, of course, unnecessary for these values.

Table 2 lists the lines identified on the RCA spectra. While the wavelength calibration of the ITT plate came from an He-Ar comparison source, the easily identified strong nebular lines were used to calibrate the RCA plate. The strength estimates contained in column (4) of Table 2 were obtained by normalizing the observed intensities of the stronger lines to the values listed in Aller and Walker (1970). These strengths were corrected for reddening as described above and the corrected values are listed in column (5).

The line identifications in both Tables 1 and 2 came from Johnson (1968), Morgan (1971), Aller and Walker (1970), and Danziger and Aaronson (1974). OH airglow lines identified by Chamberlain (1961) were excluded from consideration, as were unidentified lines which were also present on the spectrum of EG54.

Lines of [Ni II] are here detected in the Orion Nebula for the first time. The two strongest members of the a^2D (the ground term)–a^2F multiplet at λ7377.9 and λ7411.6 (Garstang 1968; Thackeray 1953) are present. Although Ni II has an ionization potential of only 18.2 eV and is therefore unlikely to be the dominant ionization stage of Ni, Fe II has an even smaller ionization potential (16.2 eV) and many lines of [Fe II] have been identified in the spectra of the Orion Nebula (Wyse 1942). The two strongest members of the N II $3p\ ^3P$–$3d\ ^3D^o$ multiplet at 5941.7 and 5931.8 Å are also identified for the first time in the Orion Nebula.

Permitted lines of N I are also seen for the first time. The five strongest members of the multiplet $3s\ ^4P$–$3p\ ^4P^o$ at 8184–8242 Å and the strongest member of the multiplet $3s\ ^4P$–$3p\ ^4S^o$ at 7468 Å are all identified. The excitation mechanism for these lines will be discussed in the next section.

Several permitted lines of O I are identified in our spectra, and they will also be discussed in the next section. There is a possibility of a very weak line at 7772.9 Å that might be O I λ7773.4 (the quintet counterpart of λ8446) which was identified by Morgan (1971), but this is highly uncertain.

TABLE 2

LINE IDENTIFICATIONS IN THE RCA ORION NEBULA SPECTRUM

λ_{obs} (Å)	ID (Å)	Ion	Strength (Hβ=1)	Corrected Strength
4959.1.....	4958.9	[O III]	*	...
... .	5006.8	[O III]	*	...
... .	5015.7	He I	*	...
5047.1.....	5047.7	He I	0.002	0.002
5056.2.....	5056.1	Si II	0.002	0.002
5158.5.....	5158.3	[Fe VII]	0.002	0.002
5191.6.....	5191.4	[Ar III]	0.002	0.002
5198.6.....	5198.7	[N I]	0.006	0.006
5270.5.....	5270.3	[Fe III]	0.006	0.006
5513.4.....	5513.7	O I	0.001	0.0009
5517.5.....	5517.7	[Cl III]	0.007	0.006
5537.7.....	5537.6	[Cl III]	0.01	0.009
5554.6.....	5554.9	O I	0.001	0.0009
5576.9.....	5577.4	[O I]	0.005	0.004
5679.7.....	5679.6	N II	0.002	0.002
5754.7.....	5754.6	[N II]	0.02	0.02
5875.7.....	5875.6	He I	*	...
5931.4.....	5931.8	N II	0.0005	0.0004
5941.1.....	5941.7	N II	0.0008	0.0006
5958.0.....	{5957.6 {5958.5	Si II} O I }	0.003	0.002
5978.9.....	5979.0	Si II	0.003	0.002
6046.4.....	6046.4	O I	0.003	0.002
6087.3.....	...	...	0.002	0.002
6300.6.....	6300.3	[O I]	0.008	0.006
6312.4.....	6312.4	[S III]	0.009	0.007

* Line is overexposed.

III. STARLIGHT EXCITATION OF PERMITTED LINES

Grandi (1975) considered direct starlight excitation as well as Lyman line fluorescence and recombination as excitation sources for λ8446 and the other O I permitted lines seen in the spectrum of the Orion Nebula. That paper concluded that fluorescence and recombination were unable to account for the observations and that direct starlight excitation could explain both the strength and the presence of the various O I lines. Münch and Taylor (1974) conclude otherwise—that inside dense condensations straddling the transition region of the nebula, Lβ photons and O I ions will coexist enough to generate the observed 8446 Å flux. The same argument put forward in Grandi (1975) applies, however: Lyman line fluorescence cannot account for the other permitted O I lines besides λ8446 seen in the Orion Nebula. If starlight excitation is invoked to explain these other lines, the strength of λ8446 from this mechanism is quite sufficient to account for the observations.

Table 3 lists the observed and predicted line strengths of the permitted O I lines. All but the first two observed strengths come from the present work, while all the predicted strengths come from the model of Grandi (1975) (these predicted strengths are normalized such that the observed and predicted [O I] λ6300 line ratios are forced to agree, in order to correct roughly for the inaccuracies of the model). The line at 5958.5 Å appears

TABLE 3

OBSERVED AND PREDICTED STRENGTHS OF O I LINES

Line (Å)	Observed Strength	Predicted Strength	Transition
4368.3....	0.001*	0.006	$3s\ ^3S^o$–$4p\ ^3P$
5299.0....	0.0006†	0.0004	$3p\ ^3P$–$8s\ ^3S^o$
5513.7....	0.0009	0.0001	$3p\ ^3P$–$6d\ ^3D^o$
5554.9....	0.0009	0.0008	$3p\ ^3P$–$7s\ ^3S^o$
5958.5....	0.002	0.002	$3p\ ^3P$–$5d\ ^3D^o$
6046.4....	0.002	0.002	$3p\ ^3P$–$6s\ ^3S^o$
7002.2....	0.002	0.02	$3p\ ^3P$–$4d\ ^3D^o$
7254.4....	0.005	0.005	$3p\ ^3P$–$5s\ ^3S^o$
8446.4....	0.012	0.032	$3s\ ^3S^o$–$3p\ ^3P$

* From Kaler and Aller 1965. † From Aller and Walker 1970.

as a blend with Si II λ5957.6, but a strength may be determined for this line by utilizing the theoretical *LS*-coupling multiplet ratio in the Si II $4p\ ^2P^o$–$5s\ ^2S$ multiplet and the observed strength of Si II λ5979.0 to subtract the λ5957.6 contribution from the blend.

Morgan (1971) identified the same O I lines that we report from our own spectra, and her line strengths agree reasonably well with those reported here, except for λ5513.7. Morgan lists this line as 4 times stronger than our strength estimate; and on the basis of her value, Grandi (1975) argued that the line was a misidentification. The present line strength reduces the discrepancy between the observed and predicted line strength to a factor of 9, however, and makes it more likely that the line at 5513.4 Å is in fact the O I λ5513.7 line and that the difference between observation and theory is principally due to uncertainties in the theoretically determined Einstein *A*-values.

Münch and Taylor (1974) present two very interesting image tube plates of the Orion Nebula, one taken in the light of [O I] λ6300 and the other in the light of O I λ8446. The λ8446 image appears as a collection of filaments superimposed on a diffuse background. The λ6300 image shows no such filaments. We believe that these λ8446 filaments can be easily understood in terms of direct starlight excitation of this line. Consider a condensation immersed in the lower-density nebular gas. As we go from the outside of this condensation toward the center, the ionization will drop until all the Lyman continuum radiation has been absorbed and all the hydrogen and oxygen atoms are neutral. However, this inner part of the condensation will still receive radiation longer than the Lyman limit that will excite λ8446. On the other hand, [O I] λ6300 requires not only the presence of O I but also the presence of electrons to collisionally excite the forbidden line. Therefore, the radiation of λ8446 will peak in the center of a condensation while the λ6300 radiation will be confined to the edge of such a condensation and will be weaker because there is less O I in the transition region of the condensation than in the center. Consequently, the λ8446 image should show clearly the high-density centers of the condensations while the λ6300 image should not.

It is interesting to note that a plate taken in [O I] λ6300 of the planetary nebula NGC 6853 (Capriotti, Cromwell, and Williams 1971) shows a quite filamentary structure. On the basis of the present discussion, we would predict that even more filaments would be seen in a plate taken in O I λ8446.

Grandi (1975) also considered the application of direct starlight excitation to ions other than O I and concluded that permitted lines of N I should also be significantly excited by this mechanism. That paper considered starlight excitation of the $3d\ ^4P$ and $4s\ ^4P$ terms of N I and calculated the line strengths for three multiplets, two of which were identified in our spectra (the third multiplet, near 8700 Å, occurs at a wavelength where the system has a much reduced sensitivity). Table 4 lists the predicted line strengths from Grandi (1975) (normalized such that the strength of $H\beta = 1$) and the observed strengths. As noted in Grandi (1975), the model used to predict these line strengths overestimates the strength of [N I] λ5199 by a factor of 3, which would imply that these predicted line strengths should be decreased by the same factor. But even so, the agreement between the observed and predicted strengths is adequate considering the uncertainties in the transition probabilities and the approximations involved in the calculations.

There is no apparent fluorescence mechanism which could excite these N I lines, so the competing process to starlight excitation would be recombination. However, by a calculation from an Orion Nebula model as described in equations (1)–(3) of Grandi (1975) where it was assumed that each recombination from N II to N I that does not go directly to the ground state leads to the production of a N I atom in the $3p\ ^4P^o$ state, the λ8218/Hβ line ratio has an upper limit of 4×10^{-5}, two orders of magnitude less than the observed value of 4×10^{-3}.

We conclude that direct starlight excitation clearly dominates over recombination and can adequately account for the observed N I permitted lines seen in the Orion Nebula, and this same mechanism can satisfactorily account for the O I lines as well.

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TABLE 4

OBSERVED AND PREDICTED STRENGTHS OF N I LINES

Line (Å)	Observed Strength	Predicted Strength	Transition
7423.6....	...	0.001	$3s\ ^4P_{1/2}$–$3p\ ^4S^o{}_{3/2}$
7442.3....	...	0.002	$3s\ ^4P_{3/2}$–$3p\ ^4S^o{}_{3/2}$
7468.3....	0.002	0.004	$3s\ ^4P_{5/2}$–$3p\ ^4S^o{}_{3/2}$
8184.8....	0.002	0.001	$3s\ ^4P_{3/2}$–$3p\ ^4P^o{}_{5/2}$
8188.0....	0.001	0.001	$3s\ ^4P_{1/2}$–$3p\ ^4P^o{}_{3/2}$
8200.3....	...	0.0002	$3s\ ^4P_{1/2}$–$3p\ ^4P^o{}_{1/2}$
8210.6....	...	0.0004	$3s\ ^4P_{3/2}$–$3p\ ^4P^o{}_{3/2}$
8216.3....	0.003	0.003	$3s\ ^4P_{5/2}$–$3p\ ^4P^o{}_{5/2}$
8223.1....	0.003	0.001	$3s\ ^4P_{3/2}$–$3p\ ^4P^o{}_{1/2}$
8242.3....	0.002	0.001	$3s\ ^4P_{5/2}$–$3p\ ^4P^o{}_{3/2}$

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