1980ApJ...239..592K

THE ASTROPHYSICAL JOURNAL, **239**:592–597, 1980 July 15

NEUTRAL OXYGEN AND NITROGEN LINES IN PLANETARY NEBULAE

JAMES B. KALER
Department of Astronomy, University of Illinois at Champaign-Urbana

Received 1979 November 26; accepted 1980 January 21

ABSTRACT

The strength of the λ6300 [O I] line in optically thin planetary nebulae is linearly dependent on that of λ3727 [O II] over a range of more than two orders of magnitude, and averages 6.7% of $I(\lambda3727)$. In optically thick planetaries with cool central stars (log $T_* < 4.65$), which contain significant neutral helium, the strengths of [O I] and [O II] are also correlated, but for these the strength of $I(\lambda6300)$ is suppressed and averages only 1.9% of $I(\lambda3727)$. The λ5199 [N I] and λ6584 [N II] lines show an analogous but not quite so linear behavior; $I(\lambda5199)$ averages 1.3% of $I(\lambda6584)$ for thin nebulae, and only 0.3% for above thick nebulae. Real differences from the averages are indicated for specific nebulae. The lower relative strengths of the neutral lines in optically thick nebulae with cooler central stars imply that these nebulae exhibit less clumping than do the optically thin planetaries.

Subject headings: nebulae: planetary

I. INTRODUCTION

The [O I] lines of planetary nebulae have historically presented a problem that now is considered largely solved. When compared with homogeneous photoionization models, the forbidden lines at λ6300 and λ6363 are far too strong (Campbell 1968; Flower 1969; Williams 1970). Williams (1973), however, showed that with the inclusion of condensations and charge exchange, theory can be made consistent with the observations.

The most extensive studies of [O I] to date are by Khromov (1965), who used line intensities measured in 30 objects by Vorontsov-Vel'yaminov *et al.* (1964), and by Campbell (1968), who determined the $I(\lambda6300)/I(\mathrm{H}\alpha)$ ratio in 16 nebulae. Both authors show that the strength of [O I] correlates with that of [N II], and Khromov suggests a correlation with λ5876 He I, implying that the abundances of low-ionization species are also correlated. Khromov also indicated a possible positive relation between the strength of [O I] and electron density.

There is now so much more data available, however, particularly from the investigations of Aller and Czyzak (1979), Barker (1978), Kondratyeva (1978), and Torres-Peimbert and Peimbert (1977), that it is possible to examine [O I] line-strength variations among nebulae in much greater detail. In addition, the work of Hawley and Miller (1977, 1978*a*) and Hawley allows point-to-point examination of [O I] in single nebulae.

The [N I] line at λ5199 is more difficult to study because it is weaker than [O I]. But extensive observations, principally by Aller and Czyzak (1979) and Aller and Walker (1970), now allow the detailed study of the behavior of this line, and its relation to that of the [O I] line strengths.

II. THE BEHAVIOR OF [O I] AND [N I]

The relation between [O I] and [N II] discovered by Khromov (1965) and Campbell (1968) suggests that [O I] and [N I] should be examined with respect to [O II] and [N II], respectively. The oxygen-line data are presented in Table 1. Column (1) gives the nebula's name, and columns (2) and (3) the logarithms of $I(\lambda6300)$ and $I(\lambda3727)$, respectively, on the scale $I(\mathrm{H}\beta) = 100$, corrected for interstellar extinction. In cases where λ6300 was blended with λ6312 [S III], $I(\lambda6300)$ was set equal to 3.14 $I(\lambda6363)$ (Garstang 1968). Column (4) gives $r(\mathrm{O}) = I(\lambda6300)/I(\lambda3727)$, and column (5) the reference to the λ6300 observation. Precedence was given to studies in which both λ3727 and λ6300 were observed. When λ3727 was not observed by the given reference, a mean $I(\lambda3727)$ was taken from Kaler (1976) plus the references of column (5). References to notes are shown in column (6). Averages of $r(\mathrm{O})$ for nebulae with multiple observations are also placed in parentheses in column (6). Points are considered "half-weight" if the [O I] and [O II] data were taken from different references, if there was serious disagreement between two observations, or if $I(\lambda6363)$ and $I(\lambda6300)$ were discrepant. If $I(\lambda6300)$ as computed from $I(\lambda6363)$ was significantly larger than the [O I] and [S III] blend, $I(\lambda6300)$ was set equal to the blend intensity, and given half-weight.

The nebulae of Table 1 are divided into three groups, depending upon the excitation of the nebular spectrum and the central star temperature (T_*), which indicates whether a nebula can be called optically thick or thin in the Lyman continuum. The nebulae in Table 1*a* all have more than a trace of He II λ4686, and from Hummer and Seaton (1964) are likely to be optically thin. Those in Table 1*c* all have log $T_* < 4.65$. These nebulae contain neutral helium (Kaler 1978), and must

TABLE 1

[O I] AND [O II] LINE DATA

Nebula (1)	log $I(6300)$ (2)	log $I(3727)$ (3)	$r(O)$ (4)	Ref. (5)	Notes (6)
a) $I(\lambda 4686) \gtrsim 5\% \ I(H\beta)$ (thin)					
NGC 650	+1.60	2.90	0.050	A	
NGC 2346	+1.19	2.56	0.043	A	
NGC 2371	+0.62	1.57	0.113	T	
NGC 2392	+0.35	1.99	0.025	A, Z	
NGC 2438	+1.25	2.46	0.061	T	
NGC 2440	+1.46	2.28	0.151	T	
NGC 2452	+0.77	1.90	0.081	A	
NGC 3132a	+1.18	2.51	0.046	T	
NGC 3132b	+1.47	2.58	0.078		
NGC 3132c	+1.32	2.65	0.047		(0.057)
NGC 3132d	+1.65	2.96	0.049		
NGC 3132e	+1.77	2.95	0.067		
NGC 3242	+0.00	1.16	0.069	C, BR	½
NGC 3587	+1.06	2.54	0.033	BR	½
NGC 3918	+0.59	1.79	0.063	T	D
NGC 6644	+0.96	1.76	0.156	BA	d
NGC 6720-1	+0.36	1.90	0.029	H1	
NGC 6720-2	+0.63	2.24	0.024		
NGC 6720-3	+0.85	2.22	0.043		
NGC 6720-4	+1.41	2.83	0.038		(0.042)
NGC 6720-5	+2.09	3.25	0.069		
NGC 6720-6	+1.99	3.30	0.049		
NGC 6741	+0.30	2.09	0.016	C	½
NGC 6778	+0.70	1.78	0.083	A	
NGC 6790	+0.52	1.36	0.145	A	D
NGC 6818	+0.27	1.72	0.036	A	
NGC 6853-2	+1.10	2.54	0.036	H2	
NGC 6853-5	+1.89	3.22	0.047		(0.047)
NGC 6853-6	+1.96	3.21	0.057		
NGC 6884	+0.03	1.59	0.028	A	d
NGC 6886	+1.00	2.20	0.063	A	d
NGC 6905	+0.20	1.28	0.083	A	½
NGC 7009	−0.32	1.24	0.026	CA, P	
NGC 7009A[a]	+1.41	2.11	0.20	CA	½
NGC 7026	+0.63	1.74	0.078	A	d
NGC 7027	+1.15	1.52	0.425	KA, O, P	D
NGC 7293-A1	+1.60	2.37	0.171	H	
NGC 7293-A2	+1.43	2.42	0.102		
NGC 7293-A3	+1.45	2.48	0.092		
NGC 7293-A4	+1.68	2.66	0.106		(0.117)
NGC 7293-B1	+1.69	2.71	0.097		
NGC 7293-B2	+1.70	2.68	0.103		
NGC 7293-B3	+1.80	2.65	0.142		
NGC 7293-B4	+1.83	2.74	0.123		
NGC 7662	−0.24	1.14	0.041	C	½
IC 351	−0.14	1.04	0.066	BA	
IC 1747	+0.28	1.62	0.046	A	
IC 2003	+0.54	1.70	0.069	A	
IC 2165	+0.37	1.68	0.046	A, T	
IC 4406	+1.50	2.65	0.072	T	
IC 5117	+0.70	1.46	0.174	A	D
IC 5217	+0.28	1.41	0.073	A	d
BB 1	+0.02	0.86	0.144	H3	
Ha 4-1	+0.86	2.27	0.039	T1, H3	
Hu 1-1	+1.45	2.61	0.070	A, BA, K	
Hu 1-2	+0.80	1.76	0.125	A	d
J900	+0.55	1.84	0.051	A	
M1-1	−0.02	1.20	0.070	A, BA	½
M1-17	+1.34	1.58	0.57	K	D
M1-33	+1.01	1.78	0.17	K	D
Vy 1-2	+0.51	1.60	0.081	BA	½, d
b) log $T_* \geq 4.65$, $I(4686) \lesssim 5\% \ I(H\beta)$					
NGC 5315	+0.76	1.66	0.127	T	D
NGC 6210	+0.35	1.63	0.054	BA	
NGC 6543	+0.11	1.49	0.035	A, BC, C	d
NGC 6567	+0.35	1.36	0.100	BA	
NGC 6572	+0.79	1.67	0.131	P	d
NGC 6751	+0.54	2.55	0.0098	A	d
NGC 6826	−0.85	1.41	0.0054	BR	½
NGC 6833	+0.17	1.20	0.093	BA	d
NGC 6891	−0.07	1.37	0.037	C	½
IC 2501	+0.65	1.81	0.070	T	D
IC 4846	+0.51	1.52	0.094	A, BA	D
J320	−0.10	1.29	0.041	BA	
M1-9	+0.49	1.54	0.089	K	D
M1-74	+0.55	1.53	0.105	A, BA	D
M2-50	+0.76	1.31	0.279	BA	D, ½
Me 2-2	+0.29	1.48	0.065	BA	d
Sn 1	+0.69	1.28	0.253	BA	½
c) log $T_* < 4.65$ (thick)					
NGC 40	+0.47	2.65	0.0066	A	
IC 418	+0.36	2.23	0.013	A, O, T	D
IC 2149	−0.09	1.93	0.0096	BA	
IC 4593	+0.23	1.80	0.025	BA, C	
BD +30	+0.41	1.99	0.026	O, P	d
Cn 3-1	+0.25	2.28	0.0097	A, BA	
Hb −12	−0.86	1.17	0.0095	A	½
He2-131	+0.31	1.88	0.027	T	D
He2-138	+0.05	1.56	0.031	T	
Hu 2-1	+0.18	1.95	0.018	A, BA	d
M1-5	+0.47	2.06	0.026	BA	d
M1-14	+0.55	2.27	0.019	T	
M1-65	+0.11	1.90	0.016	K1	D
M2-9	+1.08	2.33	0.056	BA	D, ½

[a] NGC 7009A, east ansa.

NOTES.—½ = half weight; D = log $N_e > 4$; d = $3.8 < \log N_e < 4$.

REFERENCES.—A: Aller and Czyzak 1979; BA: Barker 1978; BC: Boeshaar, Czyzak and Aller 1975; BR: Boeshaar 1974; C: Campbell 1968; CA: Czyzak and Aller 1979; H: Hawley 1978; H1: Hawley and Miller 1977; H2: Hawley and Miller 1978*a*; H3: Hawley and Miller 1978*b*; K: Kondratyeva 1978; K1: Kondratyeva 1979; KA: Kaler *et al.* 1976; O: O'Dell 1963; P: Peimbert and Torres-Peimbert 1971; T: Torres-Peimbert and Peimbert 1977; T1: Torres-Peimbert and Peimbert 1979; Z: Zipoy 1976.

TABLE 2

[N I] AND [N II] LINE DATA

Nebula (1)	log $I(5199)$ (2)	log $I(6584)$ (3)	10^2 r(N) (4)	Ref. (5)	Nebula (1)	log $I(5199)$ (2)	log $I(6584)$ (3)	10^2 r(N) (4)	Ref. (5)
a) $I(4686) \gtrsim 5\%\ I(\mathrm{H}\beta)$ (thin)									
NGC 650	+1.1	2.88	1.66	A	NGC 6818	−0.19	1.40	2.57	A
NGC 2371	−0.16	1.98	0.72	A	NGC 6884	−0.60	1.33	1.17	A
NGC 2392	−0.22	1.93	0.71	T	NGC 6886	+0.06	2.24	0.66	A
NGC 2440	+1.11	3.07	1.10	AW	NGC 7009	−0.44	1.10	0.36	CA, P
NGC 2452	+0.19	2.19	1.00	A	NGC 7009A[a]	+0.56	2.56	1.00	CA
NGC 3242	−0.55	0.49	9.1	T	NGC 7026	−0.04	2.09	0.74	A
NGC 3587	+0.08	2.10	0.96	BR	NGC 7027	−0.18	1.96	0.74	KA, P
NGC 3918	−0.26	1.83	0.81	T	NGC 7293S[b]	+1.43	2.94	3.18	W
NGC 5882	−0.64	1.14	1.66	T	NGC 7293C	+1.06	2.11	8.91	W
NGC 6302	+1.10	2.70	2.51	AW	NGC 7662	−0.97	0.71	2.09	A
NGC 6309	−0.08	2.15	0.59	AW	IC 351	−0.85	0.29	7.24	A
NGC 6720-1	−0.23	1.70	1.17	H	IC 2003	+0.09	1.49	3.98	A
NGC 6720-2	+0.20	2.02	1.51		IC 2165	−0.83	1.30	0.74	A
NGC 6720-3	+0.07	2.35	0.53		IC 5117	−0.53	1.58	0.78	A
NGC 6720-4	+0.75	2.71	1.10		IC 5217	−0.90	1.39	0.51	A
NGC 6720-5	+1.49	2.97	3.31		Ha 4-1	−0.01	1.99	1.0	T1
NGC 6720-6	+1.29	3.04	1.78		Hu 1-1	+0.37	2.35	1.05	A
NGC 6741	+0.32	2.31	1.02	AW	Hu 1-2	+0.16	2.27	0.78	A
NGC 6778	+0.38	2.53	0.71	A	J900	−0.55	1.55	0.79	A
NGC 6790	−0.38	1.16	2.88	A					
b) $\log T_* \geq 4.65$, $I(4686) \lesssim 5\%\ I(\mathrm{H}\beta)$									
NGC 5315	−0.09	2.30	0.41	T	NGC 6826	−1.40	1.00	0.40	AW
NGC 6543	−0.67	1.21	1.32	A	NGC 6891	−0.72	1.02	1.83	AW
NGC 6572	−0.16	1.74	1.26	A, P	IC 4997	−0.72	1.29	0.98	AW
c) $\log T_* < 4.65$ (thick)									
NGC 40	−0.08	2.42	0.31	A	Cn 3-1	−0.65	2.29	0.12	A
IC 418	−0.53	2.21	0.18	A, T	Hb 12	−0.55	1.96	0.31	A
IC 2149	−0.36	1.62	1.05	T	Hu 2-1	−1.77	1.68	0.04	A
BD +30	−0.18	2.46	0.23	P					

[a] NGC 7009A, east ansa.

[b] NGC 7293S, southwest part of ring; NGC 7293C, central region.

REFERENCES.—A: Aller and Czyzak 1979; AW: Aller and Walker 1970; BR: Boeshaar 1974; CA: Czyzak and Aller 1979; H: Hawley and Miller 1977; KA: Kaler *et al.* 1976; P: Peimbert and Torres-Peimbert 1971; T: Torres-Peimbert and Peimbert 1977; T1: Torres-Peimbert and Peimbert 1979; W: Warner and Rubin 1975.

all be optically thick. The objects in Table 1*b* are intermediate between the above two groups; they are usually considered as thick since there is little or no He II in their spectra, but they have $\log T_* > 4.65$.

Table 2 is entirely analogous to Table 1. Columns (2), (3), and (4) give $\log I(\lambda 5199)$ [N I], $\log I(\lambda 6584)$ [N II], and $r(\mathrm{N}) = I(\lambda 5199)/I(\lambda 6584)$, respectively. Since the data on the [N I] lines are intrinsically poorer than those on [O I], "half-weight" nebulae are not singled out.

The ratios r(O) and r(N) will show some dependence on electron density. From the target areas of Saraph and Seaton (1974), Pradhan (1976) and Henry and Williams (1968), and the transition probabilities of Garstang (1968) and Nussbaumer (1971), the critical densities at which radiative de-excitation of the nebular lines equals collisional de-excitation (for $T_e = 10^4$) for [O I], [N I], [O II], and [N II] is 10^6, 2×10^3, 8×10^3, and 7×10^4 cm^{-3}. Electron densities were calculated from [O II], [Cl III] or [S II] data provided by the references in Table 1, and Saraph and Seaton (1970), and nebulae with $\log N_e \geq 4.0$ or with $3.8 \leq \log N_e < 4.0$ are indicated as such in column (6) of Table 1. Collisional de-excitation is not significant for [O I], but it is important in suppressing λ3727 of [O II] for higher densities. Consistent with this expectation, Table 1 shows that the nebulae with the highest density have the highest values of r(O). A plot of r(O) against N_e shows that r(O) tends to be larger for densities above about 6×10^3.

The effect of density on r(N) should be the opposite of that for r(O); [N I] will show a larger relative collisional de-excitation rate than will [N II]. The observed effect is not so obvious as it is for oxygen. The suppression of [N I] can be seen in that for optically thin nebulae with $\log N_e \leq 3.8$, 39% of the nebulae have $r(\mathrm{N}) > 0.015$, whereas for $\log N_e > 3.8$, the figure is only 10%. Yet a large number of low-density nebulae also have low $r(\mathrm{N})$. In general, the density effects cannot be considered quantitatively for either [O I] or [N I] since the densities in the regions where the neutral lines are formed may be different from those which produced the ionized lines.

The values of $\log I(\lambda 6300)$ in Table 1 are plotted against those of $\log I(\lambda 3727)$ in Figure 1. The nebulae of Tables 1*a*, 1*b*, and 1*c* are plotted with different symbols, as shown in the caption. The objects in Tables 1*a* and 1*b* with $\log N_e > 3.8$ are not plotted; those with $\log N_e > 3.8$ from Table 1*c* are indicated by a horizontal bar. The "half-weight" points are denoted by smaller symbols.

This figure displays a number of interesting features. First is the extreme linearity of curve defined by the optically thin nebulae. A quadratic least-squares fit is almost exactly a straight line, with a slope of 1. For these nebulae, $I(\lambda 6300)$ is directly proportional to $I(\lambda 3727)$. If we consider the optically thin points of Figure 1, excluding those of half-weight and first averaging the nebulae with multiple observations, $I(\lambda 6300)/I(3727)$ averages 0.067. The standard deviation is large, here ± 0.035. Much of this scatter is due to observational error, but some is clearly intrinsic. Note, for example, that all the individual points of NGC 7293 (see the legend to Fig. 1) are above the mean line, and that all but one of the points for NGC 6720 are below it.

Second, the nebulae of Table 1*c*, those thick objects with the coolest central stars, and which contain neutral helium, are clearly below the line indicated by the thin nebulae. Note that for this set, $r(\mathrm{O})$ is *not* significantly higher for the dense nebulae:

$$\langle r(\mathrm{O})\rangle(\log N_e \geq 3.8)/\langle r(\mathrm{O})\rangle(\log N_e < 3.8) = 1.26 \pm 0.33 .$$

For these thick nebulae, $I(\lambda 6300)$ averages only 1.9% of $I(\lambda 3727)$, where the dense nebulae are included. The difference between the thin nebulae of Table 1*a* and the thick objects of Table 1*c* is highly significant:

$$\langle r(\mathrm{O})\rangle(1a)/\langle r(\mathrm{O})\rangle(1c) = 3.5 \pm 0.6 .$$

For these thick nebulae, $I(\lambda 6300)$ is suppressed relative to $I(\lambda 3727)$ by over a factor of 3.

Third, note that λ6300 bears about the same relation to λ3727 within a given nebula as it does from one nebula to another. For example, the curve defined by NGC 6720 is similar to that defined by the general run of thin objects.

Finally, the thick nebulae with hotter central stars, those of Table 1*b*, fit well with the thin nebulae of Table 1*a*, and not with the thick objects of 1*c*. The strength of λ6300 is suppressed only when a nebula is very thick, as defined by the facts that the central star temperature is low and that helium is neutral in the outer zone.

The relation between [O I] and electron density found by Khromov (1965) is not confirmed. In fact, the effect is just the opposite; the highest [O I] strengths are found in the large, low-density nebulae such as NGC 7293.

The [N I] and [N II] data are similarly plotted in Figure 2. However since the effects of density on $r(\mathrm{N})$

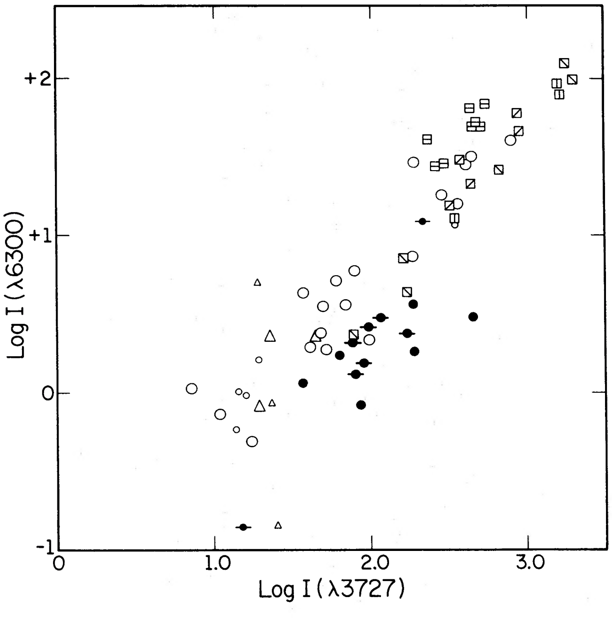

FIG. 1.—Log $I(\lambda 6300)$ [O I] plotted against log $I(\lambda 3727)$ [O II]. ○: optically thin; □: optically thin nebulae for which point-to-point observations are available; ⧄: NGC 3132; ⧅: NGC 6720; ◫: NGC 6853; ⊟: NGC 7293; △ : optically thick nebulae with $\log T_* \geq 4.65$ (weak or absent He II); ●: optically thick nebulae with $\log T_* < 4.65$; -●-: same as above but with $\log N_e > 3.8$; half-weight points are denoted by small symbols.

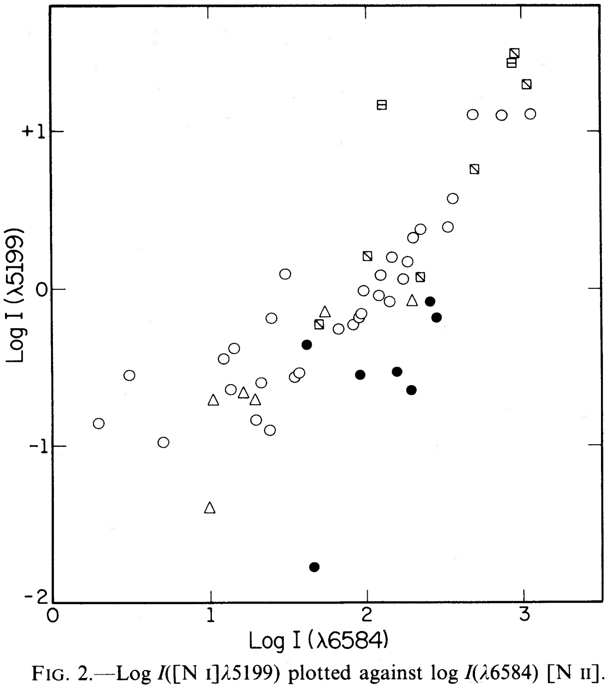

FIG. 2.—Log I([N I]λ5199) plotted against log $I(\lambda 6584)$ [N II]. See the caption to Fig. 1 for an explanation of the symbols.

are not very clear, all the nebulae are considered, regardless of N_e. The conclusions for nitrogen are very similar to those for oxygen. The curve for nitrogen is not quite linear; $\langle r(\mathrm{N}) \rangle$ for $I(\lambda 6584) > 2.4$, $1.8 < I(\lambda 6584) < 2.4$, and $1.0 < I(\lambda 6584) < 1.8$ is 0.016, 0.008, and 0.016, respectively. However, the effects of observational selection, especially at the faint end, cannot be evaluated. A least-squares linear fit to all the points for $\log I(\lambda 6584) > 1$ (where NGC 6720 is averaged) gives an overall slope of 1.03. The average value of $r(\mathrm{N})$ for these thin nebulae is 0.013. The λ5199 [N I] line is suppressed by a factor of 4.1 ± 1.8 for the optically thick nebulae of Table 2*c*, which agrees within the errors with the suppression factor for λ6300 [O I]. If we exclude the nebulae of Tables 1*c* and 2*c*, the values of $r(\mathrm{O})$ and $r(\mathrm{N})$ do not correlate.

The empirical results for $r(\mathrm{O})$ and $r(\mathrm{N})$ are summarized in Table 3. The half-weight points are not used for oxygen, the data for the four objects with multiple point-to-point observations are averaged and treated as a single data point, and the three nebulae with the weakest [N II] are not included in $r(\mathrm{N})$. High-density nebulae are excluded for oxygen from the set of thin nebulae and the thick nebulae with hotter central stars, but not from the thick nebulae with cool central stars, and not from the nitrogen data. Column (2) gives the mean r for both $I(\lambda 6300)/I(\lambda 3727)$ and $I(\lambda 5199)/I(\lambda 6584)$. Columns (3) and (4) give the standard deviations and the mean errors of the means, respectively, and columns (5) and (6) show the slopes and correlation coefficients for linear least-squares fits to Figures 1 and 2, under the assumption that all the error is in the y-axis.

III. DISCUSSION

The linear relationship between [O I] and [O II] and between [N I] and [N II] are simple to understand, since O^0 and N^0 must come from O^+ and N^+, whether by recombination or charge exchange. The surprise in this study is that [O I] and [N I] are suppressed, for a given $I(\lambda 3727)$ or $I(\lambda 6584)$, for the thick nebulae which have central stars cool enough such that a significant amount of helium is neutral.

The neutral oxygen and nitrogen lines must be produced in transition zones between ionized and neutral matter. As pointed out by Williams (1970, 1973) condensations are necessary in order to produce the large transition zone area necessary for the production of the high observed line strengths. The data imply that the set of nebulae with the coolest central stars ($\log T_* < 4.65$) are more homogeneous than are the nebulae with higher temperature stars. The objects with low T_* are small and presumably relatively young. Possibly widespread filamentation has not yet had time to develop. The dependence of line strength on filamentary structure is supported by the data on NGC 7293, which exhibits some of the highest values of $r(\mathrm{O})$ and $r(\mathrm{N})$, and which exhibits some of the most extreme filamentary structure known (see the widely reproduced photograph taken by Baade in, e.g., Perek and Kohoutek 1967). The fact that $I(\lambda 6300)/I(\lambda 3727)$ is not increased for the dense, thick nebulae of Table 1*c* implies that for these objects the increased density correlates with a further decrease in the existence of filamentary structure.

IV. SUMMARY

The results presented here confirm the relation found by Khromov (1965) and Campbell (1968) between neutral and singly ionized species. The detailed analysis of the [O I] and [N I] lines in the spectra of planetary nebulae reveals the following:

1. The strength of λ6300 [O I] in optically thin planetaries is directly proportional to that of λ3727 [O II] over a range of more than two orders of magnitude.
2. $I(\lambda 6300)$ averages 6.7% of $I(3727)$ for optically thin, lower density planetaries.
3. High density ($\log N_e > 3.8$) increases the value of $r(\mathrm{O}) = I(\lambda 6300)/I(\lambda 3727)$ in optically thin nebulae because of collisional de-excitation of O^+ (^{2}D).

TABLE 3

LINE STRENGTH RATIOS, $r(\mathrm{O})$ AND $r(\mathrm{N})$

Type (1)	$\bar{r}(\mathrm{O}) = \langle I(6300)/I(3727) \rangle$ (2)	Standard Deviation (3)	m. e. of Mean (4)	Slope (5)	Correlation Coefficient (6)
Thin	0.067	0.035	0.007	0.97	0.95
Thick, $\log T_* \geq 4.65$	0.065	0.017	0.010	...	...
Thick, $\log T_* < 4.65$	0.019	0.008	0.002	0.43 0.93[a]	0.63 0.80[a]

Type	$\bar{r}(\mathrm{N}) = \langle I(5199)/I(6584) \rangle$	Standard Deviation	m. e. of Mean	Slope	Correlation Coefficient
Thin	0.0126	0.0089	0.0016	1.03	0.90
Thick, $\log T_* \geq 4.65$	0.0103	0.0056	0.0023	...	...
Thick, $\log T_* < 4.65$	0.0032	0.0034	0.0013	0.97	0.59

NOTE.—$\bar{r}(\mathrm{O})(\text{thin})/\bar{r}(\mathrm{O})(\text{thick}, \log T_* < 4.65) = 3.5 \pm 0.6$; $\bar{r}(\mathrm{N})(\text{thin})/\bar{r}(\mathrm{N})(\text{thick}, \log T_* < 4.65) = 4.1 \pm 1.8$.

[a] With two half-weight points.

4. Planetaries with central stars which have temperatures less than 44,000 K (log $T_* < 4.65$), which are optically thick and contain neutral helium, have relatively lower λ6300 strengths; $I(\lambda6300)$ averages only 1.9% of $I(\lambda3727)$. The [O I] and [O II] line strengths are again proportional, but the increase of r(O) for high-density nebulae is not seen.

5. The thick planetaries with higher central star temperatures show [O I] line strengths in agreement with those of the thin nebulae.

6. The [N I] and [N II] lines bear the same relations to one another as do the [O I] and [O II] lines, except that the curve defined by $I(\lambda5199)$ versus $I(\lambda6584)$ may not be quite linear, and density effects [here the reduction of $r(\mathrm{N}) = I(\lambda5199)/I(\lambda6584)$ for high density] are not clearly seen.

7. $I(\lambda5199)$ averages 1.35% of $I(\lambda6584)$ for thin nebulae and 0.32% for thick nebulae with cool central stars.

8. Real differences in [O I]/[O II] (and probably [N I]/[N II]) are seen among nebulae; for example, NGC 7293 and NGC 6720 show [O I] strengths consistently larger and smaller than the average, respectively.

9. The relation between [O I] and [O II], and between [N I] and [N II], is about the same within a particular nebula as it is from one nebula to another.

Since condensations are needed in order to produce the high neutral line strengths found in planetaries, the above results indicate that optically thin nebulae have a greater degree of filamentation than do the thick nebulae with cool central stars, in which the neutral lines are suppressed. There is also some evidence that high density in the thick, low T_* objects further suppresses the incidence of condensations and filamentary structure.

This work was supported by NSF grant AST 78-23647 to the University of Illinois. I would like to thank Dr. J. S. Gallagher for helpful discussion.

REFERENCES

Aller, L. H., and Czyzak, S. J. 1979, *Ap. Space Sci.*, **63**, 397.
Aller, L. H., and Walker, M. F. 1970, *Ap. J.*, **161**, 917.
Barker, T. 1978, *Ap. J.*, **219**, 914.
Boeshaar, G. O. 1974, *Ap. J.*, **187**, 283.
Boeshaar, G. O., Czyzak, S. J., and Aller, L. H. 1975, *Ap. J. Suppl.*, **28**, 335.
Campbell, W. A. 1968, *Pub. A.S.P.*, **80**, 869.
Czyzak, S. J., and Aller, L. H. 1979, *M.N.R.A.S.*, **188**, 229.
Flower, D. R. 1969, *M.N.R.A.S.*, **146**, 243.
Garstang, R. H. 1968, in *IAU Symposium No. 34, Planetary Nebulae*, ed. D. E. Osterbrock and C. R. O'Dell (Dordrecht: Reidel), p. 143.
Hawley, S. A. 1978, *Pub. A.S.P.*, **90**, 370.
Hawley, S. A., and Miller, J. S. 1977, *Ap. J.*, **212**, 94.
———. 1978*a*, *Pub. A.S.P.*, **90**, 39.
———. 1978*b*, *Ap. J.*, **220**, 609.
Henry, R. J. W., and Williams, R. E. 1968, *Pub. A.S.P.*, **80**, 669.
Hummer, D. G., and Seaton, M. J. 1964, *M.N.R.A.S.*, **127**, 217.
Kaler, J. B. 1976, *Ap. J. Suppl.*, **31**, 517.
———. 1978, *Ap. J.*, **226**, 947.
Kaler, J. B., Aller, S. J., Czyzak, S. J., Epps, H. W. 1976, *Ap. J. Suppl.*, **31**, 163.
Khromov, G. S. 1965, *Astr. Zh.*, **42**, 543.
Kondratyeva, L. N. 1978, *Astr. Zh.*, **55**, 334.
———. 1979, *Astr. Zh.*, **56**, 345.
Nussbaumer, H. 1971, *Ap. J.*, **166**, 411.
O'Dell, C. R. 1963, *Ap. J.*, **138**, 1018.
Peimbert, M., and Torres-Peimbert, S. 1971, *Bol. Obs. Tonantzintla y Tacubaya*, **6**, 21.
Perek, L., and Kohoutek, L. 1967, *Catalog of Galactic Planetary Nebulae* (Prague: Czechoslovakian Academy of Sciences).
Pradhan, A. K. 1976, *M.N.R.A.S.*, **177**, 31.
Saraph, H. E., and Seaton, M. J. 1970, *M.N.R.A.S.*, **148**, 367.
———. 1974, *J. Phys. B*, **7**, L36.
Torres-Peimbert, S., and Peimbert, M. 1977, *Rev. Mexicana Astr. Ap.*, **2**, 181.
———. 1979, *Rev. Mexicana Astr. Ap.*, in press.
Vorontsov-Vel'yaminov, B. A., Kostyakova, O. D., Dokuchaeva, O. D., and Arkhipova, V. P. 1964, *Astr. Zh.*, **41**, 255.
Warner, J. W., and Rubin, V. C. 1975, *Ap. J.*, **198**, 593.
Williams, R. E. 1970, *Ap. J.*, **159**, 829.
———. 1973, *M.N.R.A.S.*, **164**, 111.
Zipoy, D. M. 1976, *Ap. J.*, **209**, 108.

Note added in proof.—L. H. Aller informs me that log $I(5199)$ [N I] for Hu 2–1 in Aller and Czyzak (1979) should read −0.77, not −1.77, which raises the low point in Figure 2 into good accord with the other optically thick points. With this change, columns (2)–(6) in the last row of Table 3 should read 0.0037, 0.0031, 0.0012, 0.39, and 0.53, respectively, and $\bar{r}(N)(\mathrm{thin})/\bar{r}(N)(\mathrm{thick}, \log T_* < 4.65) = 3.5 \pm 1.2$, the same suppression factor as for oxygen.

JAMES B. KALER: Department of Astronomy, 341 Astronomy Building, University of Illinois, Urbana, IL 61801