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SPECTROPHOTOMETRIC STUDIES OF GASEOUS NEBULAE. XIX. THE MODERATE-EXCITATION PLANETARY NGC 6826

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ABSTRACT

Photoelectric and photographic spectrophotometric observations of the relatively bright, moderate-excitation planetary NGC 6826 obtained at Lick, Mount Wilson, and Kitt Peak Observatories are combined to yield estimates of its density, temperature, and ionic concentrations. Data for ions of helium, carbon, nitrogen, oxygen, neon, sulfur, chlorine, and argon are presented. The nebula appears to be relatively homogeneous in the sense that dense low-excitation pockets with strong emissions of [N I], [N II], or [S II], prominent in many planetaries, play no important role here. In other words, the range of excitation seems to be relatively restricted. The surface brightness and spectroscopic data are consistent with a density of about 2300 electrons cm^{-3} and an electron temperature of 10000° K.

I. INTRODUCTION

Because of its convenient northern declination and relatively high surface brightness, NGC 6826 (83+12°1), excitation class 5 (Aller 1956), has been studied extensively; Perek and Kohoutek (1967) give detailed references. Since the pioneering spectrophotometry by Berman (1930), line-intensity measurements of the principal emissions have been carried out by Aller (1941), by O'Dell (1963), and by Liller and Aller (1963). Numerous faint lines have been observed in the region λ4600–λ5900 (Aller and Walker 1970).

The present series of observations embrace photoelectric spectrum measurements made with Oke's Cassegrain scanner at the 60-inch reflector, two plates secured at Kitt Peak National Observatory with the Cassegrain and coudé spectrographs, one plate obtained with a Newtonian spectrograph at the 60-inch reflector, and two spectrograms secured with the nebular spectrograph on the Lick 120-inch reflector. In addition, we secured three plates at the coudé focus of the Mount Wilson 100-inch, and one plate with the Lick 120-inch coudé.

We have used procedures described in previous papers of this series to reduce and combine the observations. In so far as possible, we have supplemented and calibrated the photographic data by photoelectric measurements. Lines of intensity 4 or stronger should have an error less than 15 percent. Intensities between 1 and 4 should be good to 25 percent, while lines of intensity less than 1 may be affected by errors of about 50 percent.

The spectrum of NGC 6826 shows lines of the following ions: H, He I, C II, [N I], [N, II], N III, O II, [O II], O III, [O III], [Ne III], Si IV, [S II], S III, [S III], [Cl III], [Ar III], and [Ar IV]. Identifications of C IV and [Fe III] are uncertain, but ionized helium is absent in the nebula, although present in the central star.

II. INTERSTELLAR EXTINCTION

Determinations of the interstellar-extinction parameter, $C = \log F(H\beta)/F_0(H\beta)$ (where $F_0(H\beta)$ is the observed flux in ergs cm^{-5} s^{-1} corrected to the top of the Earth's atmosphere), by O'Dell (1963) and Kaler (1970) yield 0.29 and 0.18, respectively. Since planetary nebulae are thermal sources, one may also derive the interstellar extinction by comparing $F_0(H\beta)$ with the radiofrequency flux. An assessment of the available data by L. A. Higgs (private communication) indicates a low (if not vanishingly small) value of C. Our data on the Balmer decrement (Table 1) suggest $C = 0$. Except where otherwise noted, we have taken $C = 0$.

III. DENSITY AND TEMPERATURE

The electron temperature obtained from the usual [O III] line ratio (on the assumption $C = 0$) is $T_\epsilon = 10300°$ K. Adopting $R'' = 13$, $\log F_0(H\beta) = -9.924$ (Liller and Aller 1954; Liller 1955; Capriotti and Daub 1960), and employing equations (4), (5), and (124) and Table 6 from Aller and Liller (1968), we find $N_\epsilon = 2310$ (for Minkowski's distance of 890 pc) or $N_\epsilon \simeq 1800$ (for Cahn and Kaler's 1971 distance of 1480 pc). From the 3729/3726 [O II] line-intensity ratio, 0.70, and Seaton and Osterbrock's formula (1957), we find $N_\epsilon = 2100$.

Employing tables of Krueger, Aller, and Czyzak (1970), we predict an intensity $I(4068)$ for [S II] 0.15, close to the observed value.

The [Ar IV] and [Cl III] lines are too weak to give reliable density estimates.

IV. THE HELIUM SPECTRUM

Since no doubly ionized helium ions are detected in NGC 6826, the abundance of this element will be derived from singly ionized atoms.

Several hypotheses of helium recombination mechanisms have been proposed (cf. Seaton 1960; Robbins 1968). In model I, total collisional redistribution is postulated for all levels with $n > 12$; in model II, purely radiative processes are postulated (Pengelly 1963 has carried out the appropriate nonhydrogenic calculations). In model III, due to Robbins (1968), account has been taken of collisional effects involving triplet levels in helium. If t is defined as the rms fluctuation in the electron temperature, then, following Peimbert and Costero (1969), we may write

$$\frac{N(He^+)}{N(H^+)} = C_j(\lambda 5876)(1 - a_j t^2)\frac{I(\lambda 5876)}{I(H\beta)} = C_j(\lambda 4471)(1 - c_j t^2)\frac{I(\lambda 4471)}{I(H\beta)}, \quad (1)$$

where $a_j = 0.38$, 0.35, 0.43 and $c_j = 0.24$, 0.18, and 0.25 for models I, II, and III, respectively, and the C_j's are given by Table 2. We may also employ $I(\lambda 4026)$, noting that the theoretical ratio of $I(\lambda 4026)$ to $I(\lambda 4471)$ is 0.468 at $T_\epsilon = 10000°$ K and 0.481 at 20000° K.

Table 3 gives the adopted intensities for the lines λλ4026, 4471, and 5871, the C_j coefficients, and the derived helium/hydrogen ratios. The collisional-redistribution hypothesis (I) gives a mean value of 0.136 ± 0.006, while the more detailed theory by Robbins gives 0.125 ± 0.005. We adopt $N(He)/N(H) = 0.13$. The results are not much changed if one adopts a space-absorption correction, $C = 0.18$.

Further, we may compare the observed intensities of some of the helium lines shortward of λ3850 with the predictions of Robbins's theory (see Table 4). We use $I(\lambda 4471)$ to normalize the theoretical to the observed intensity systems. The agreement is generally satisfactory, except that weaker lines often tend to be measured stronger than predicted by theory.

Helium lines are well represented in the spectrum of NGC 6826; an accurate theory of their intensities could provide a useful check on measured line strengths in this and other objects.

TABLE 1

LINES MEASURED IN NGC 6826

λ	Identification	I
3132.8	O III	1.0
3187.6	He I	5.0
3354.7	Ne II?	0.6
3447.9	He I	0.8
3530.6	He I	0.2
3554.4	He I	0.4
3587.1	He I	0.6
3613.8	He I	0.8
3634.2	He I	0.8
3661.3	H31	p
3662.3	H30	0.2
3663.4	H29	0.2
3664.7	H28	0.3
3666.2	H27	0.4
3667.7	H26	0.5
3669.4	H25	0.6
3671.4	H24	0.6
3673.7	H23	0.7
3676.4	H22	0.7
3679.4	H21	0.8
3682.8	H20	0.9
3686.8	H19	1.0
3691.5	H18	1.2
3697.7	H17	1.3
3703.8	H16	1.6
3705.0	He I	1.1
3712	H15	2.0
3722	H14+[S III]	3.0
3726.0 }*	[O II]	12.0
3728.8 }	[O II]	8.4
3734.8	H13	2.5
3750.1*	H12*	3.3
3770.6	H11	4.0
3776.9	Ne II	p
3778	S III	0.2
3791.3	O III	0.1
3797.8*	H10*	5.2
3805.1	He I	p
3819.6	He I	1.6
3835.1*	H9*	7.9
3868.7*	[Ne III]	43.1
3888.9*	H, He I	18.0
3919	C II	p
3920.7	C II	0.2
3926.6	He I	0.3
3961.2	O III, S III	p
3964.8	He I	1.7
3967.5 }*	[Ne III]	15.1
3970.0 }	Hε	15.3
4009.2	He I	0.3
4026.2*	He I	2.9
4068.6	[S II]	0.2
4069.9	O II	0.1
4072.1	O II	p
4076.4	[S II]	p
4089.2	Si IV	0.1
4097.4	N III	0.9
4101.7*	Hδ	26.0
4103	O II, N III	0.2
4110.7	O II	p
4116	Si IV	0.2
4120.7	He I	0.6
4132.2	O II	0.2
4143.8	He I	0.6
4153.0	O II	0.3
4168.9	O II	p
4267.1	C II	0.9
4317.2	O II	0.2
4340.4*	Hγ	45.8
4349.5	O II	0.3
4363.2*	[O III]	5.9
4366	O II	p
4387.8	He I	1.0
4471.4*	He I	6.4
4634.1	N III	0.5
4640.6	N III	1.2
4641.9	N III	0.4
4649.1	O II	0.5
4651.0	O III	0.2
4658.4	C IV?	0.3
4661.6	O II	0.2
4711.3	[Ar IV]	0.7
4713.1	He I	1.0
4740.2	[Ar IV]	0.5
4861.3*	Hβ	100.
4922.0	He I	1.7
4959.0*	[O III]	253.
5006.9*	[O III]	770.
5015.6	He I	2.0
5875.6*	He I	13.9
6562.9*	Hα	287.
6678.2*	He I	4.66
6716. }* 6730. }	[S II]	1.69
7135.8*	[Ar III]	5.73

* Denotes lines whose intensities have been measured photoelectrically (p denotes that line is present but too weak to measure; probably *I* is about 0.1).

V. IONIC CONCENTRATIONS IN NGC 6826

We now use the data in Table 1 together with material published by O'Dell (1963), and by Aller and Walker (1970), to estimate ionic concentrations in NGC 6826. Intensities measured with the electronic camera may be reduced to our system by multiplying them by 1.3.

TABLE 2

COEFFICIENTS FOR CALCULATING THE ABUNDANCE OF HELIUM

	$C(\lambda 5876)$			$C(\lambda 4471)$		
T(°K)	Model I	Model II	Model III	Model I	Model II	Model III
8000......	0.875	0.662	0.705	2.28	2.02	2.03
10000......	0.921	0.714	0.745	2.34	2.10	2.09
15000......	1.01	0.797	0.815	2.47	2.26	2.20
20000......	1.08	0.866	0.860	2.56	2.37	2.29

TABLE 3

ABUNDANCE OF HELIUM IN NGC 6826

	ADOPTED	COEFFICIENT C_j		N(He)/N(H$^+$)	
	I	I	III	I	III
4026.....	2.9	4.2	4.46	0.122	0.130
4471.....	6.4	2.35	2.10	0.150	0.134
5876.....	14.9	0.926	0.750	0.138	0.112
Mean..	...	...	...	0.136	0.125

TABLE 4

COMPARISON OF PREDICTED AND OBSERVED INTENSITIES FOR HELIUM LINES IN NGC 6826

λ	3188	3530	3554	3587	3634	3704	3819
Observed I.....	5.0	0.2	0.4	0.6	0.8	1.1	1.5
Predicted I.....	5.9	0.22	0.3	0.5	0.64	1.0	1.5

Table 5 gives the calculated ionic concentrations. The first four columns are self-explanatory. The fifth column gives log $h(N_\epsilon, T_\epsilon)$, where

$$N(\text{ion})/N(\text{H}^+) = h(N_\epsilon, T_\epsilon)I_\lambda/I(\text{H}\beta) = 0.01h(N_\epsilon, T_\epsilon)I_\lambda\,, \qquad (2)$$

and the last column gives log N(ion)/N(H$^+$). We now consider data for the various ions in turn.

a) Carbon

The only usable transition is the permitted line λ4267, which we shall tentatively interpret as a recombination line. Using the $b(n, l)$ values of Bednarek and Clarke (1971), we may write (Aller 1971)

$$\frac{N(\text{C}^{++})}{N(\text{H}^+)} = 0.0058T^{0.256}\frac{I(4267)}{I(\text{H}\beta)}\,, \quad 6300° < T < 20000° \text{ K}\,. \qquad (3)$$

Substituting numerical values, we derive an abundance for the C^{++} ions which exceeds that for the O^{++} ions. Probably the $4f$ level is excited by direct resonance-line excitation

TABLE 5

IONIC CONCENTRATION IN NGC 6826

Ion	Line (Å)	Adopted Intensity	Ref.	log $h(N_\epsilon, T_\epsilon)$	log N(ion)/N(H^+)
C II......	4267	0.9	1	−1.20	−3.24
[N I]......	5200	0.05	2	−4.05	−7.34
[N II].....	5755	0.15	2	−2.99	−5.79
[O II].....	3727	20.4	1	−4.38	−5.07
[O III]....	{5007, 4959}	2023.	1	−4.65	−3.64
[Ne III]...	{3969, 3868}	58.2	1	−4.14	−4.38
[S II].....	6716, 6730	1.69	1	−5.27	−7.04
	4068	0.2:	3	−4.28	−6.98
[S III]....	9069	8.7	4	−4.72	−5.78
	3722	0.8:	3	−3.42	−5.52
[Cl III]....	5537	0.72	2	−4.87	−7.02
[Ar III]....	5192	0.11	2	−2.98	−5.94
	7136	14.8	4	−5.09	−5.92
[Ar IV]....	4740	0.52	1	−4.36	−6.64

REFERENCES.—(1) Table 1; (2) Aller and Walker (1970); (3) see text; (4) O'Dell (1963).

of the upper level (Seaton 1968; Kaler 1971). The high carbon abundance is spurious, as Peimbert and Costero (1969) suggested for the Orion Nebula.

b) *Nitrogen*

The weakness of the nitrogen lines in this nebula suggests that most of the ions are concentrated as N III. Assuming that the ^2D levels in the $2p^3$ ground configuration of neutral nitrogen are populated in accordance with Seaton's (1958) data, we have, near 10000° K, $b(^4S)/b(^2D) = 1 + 2900/N_\epsilon$. Then, utilizing equation (133) from Aller and Liller (1968), we find $N(O^{++})/N(N^0) \simeq 4800$. Similarly, the ratio $N(N^+)/N(O^{++})$ can be found provided we know N_ϵ and T_ϵ in the emitting regions. The permitted lines of N III are almost certainly excited by mechanisms other than recombination.

c) *Oxygen*

We have observed no lines of [O I]. We computed $N(O^+)/N(H^+)$ from $I(\lambda 3727)$ with precise b-factors for the $^2D_{3/2}$ and $^2D_{5/2}$ levels. For $T_\epsilon = 10300°$, $N_\epsilon = 2300$, $h = 4.16 \times 10^{-5}$. The Faulkner and Aller (1965) or Peimbert and Costero (1969) formulae give higher values, differing only by 8 and 4 percent, respectively. The $N(O^{++})/N(H^+)$ ratio is found from the green nebular lines (Aller and Liller 1968, eq. [139], Table 11). The permitted O II lines are probably excited by resonance-excitation effects rather than by recombination.

d) *Neon*

This ion is represented by the [Ne III] λλ3969, 3868 lines; the Ne^{++} concentration is calculated from Aller and Czyzak (1970).

e) *Sulfur*

If the [S II] auroral lines λλ6716, 6730 are produced in the same volume as Hβ, then

$$\frac{N(S^+)}{N(H^+)} = 0.184 \times 10^{-10} \frac{N_\epsilon E^0{}_{4,2}(T_\epsilon)^{1.840}}{(b_2 + 0.381 b_3)} \frac{I(6716) + I(6730)}{I(H\beta)}, \quad (4)$$

where $b_2 = b(^2D_{3/2})$ and $b_3 = b(^2D_{5/2})$ have been tabulated by Czyzak, Krueger, and Aller (1970) and $E^0{}_{4,2}$, due to Clarke (1965), is tabulated by Aller and Liller (1968). The [S II] λ4068 line intensity is too poorly determined to yield other than a rough estimate of $N(S^+)/N(H^+)$.

For S^{++}, we use O'Dell's (1963) measurement of $I(9069)$ and the formula

$$\frac{N(S^{++})}{N(O^{++})} \cong 3.1 \exp\left(-\frac{13400}{T_\epsilon}\right)\frac{I(9069)}{I_0}\,, \tag{5}$$

where I_0 refers to the sum of the intensities of the green nebular lines. The intensity of the [S III] λ3722 transauroral line is too unreliable to give a valid abundance determination.

We conclude that sulfur is mostly in the form of S^{++} and is probably about two orders of magnitude less abundant than oxygen.

f) Chlorine

Our estimates are based on λλ5537, 5517 [Cl III] which are rather weak; see Table 22 of Aller and Walker (1970).

g) Argon

The Ar^{++} concentration can be estimated from the rather weak auroral λ5191 line or the nebular λ7136 line:

$$\frac{N(Ar^{++})}{N(O^{++})} = 0.90 \exp\left(-\frac{9300}{T}\right)\frac{I(7136)}{I_0} = 7.9 \exp\left(\frac{18.100}{T}\right)\frac{I(5192)}{I_0}\,, \tag{6}$$

Probably most of the argon exists as Ar^{++}. The rather weak $I = 0.52$, λ4740 [Ar IV] line yields $N(Ar^{++})/N(O^{++}) \sim 0.001$.

VI. CONCLUSIONS

Our spectral-line data give an internally consistent picture for NGC 6826 as a relatively homogeneous nebula with a density about 2000 electrons cm^{-3} and $T_\epsilon = 10000°$ K. The emissions of [N I], [N II], and [S II], often enhanced in cooler, denser condensations in many planetaries, are relatively weak in NGC 6826.

Pending construction of a detailed model, only a few general remarks can be made about the chemical composition of NGC 6826:

1. The He^+/H^+ ratio is probably nearly the same as the He/H ratio because doubly ionized helium is negligible and helium is probably ionized throughout all the volume occupied by hydrogen. The carbon abundance probably cannot be obtained from the permitted λ4267 line.

2. Nitrogen must certainly exist mostly as N III, and no reliable abundance estimate can be made from its observed lines. The oxygen and neon abundances probably do not differ greatly from the concentrations of Ne^{++} and O^{++}. Sulfur and chlorine abundances may exceed the concentrations of the observed ions by much larger factors, while argon must exist mostly as Ar^{++} and Ar^{+3}.

We summarize the above remarks in Table 6. Compare Aller and Czyzak (1968).

TABLE 6

IONIC ABUNDANCES

Ion	log N	Ion	log N	Ion	log N
H......	12.00	N......	≫6.2	S.......	>6.3
He.....	11.12	O......	>8.4	Cl......	>5.0
C......	<8.8	Ne.....	>7.7	Ar......	>6.2

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