THE ASTROPHYSICAL JOURNAL, 203:636–646, 1976 February 1

A SPECTROGRAPHIC SURVEY OF 21 PLANETARY NEBULAE

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Received 1975 June 2

ABSTRACT

We present a blue spectral survey and coarse photographic photometry for 21 planetary nebulae, of which eight have not been heretofore observed with any detail. We have observed eight of the nebulae photoelectrically. Most of the planetaries studied are of intermediate excitation; five present no detectable He II lines, and two are of high excitation with powerful He II λ4686. The chief value of the photographic part of the study is to locate objects deserving of further study. We have, however, derived rough electron densities for the nebulae from either or both of the [O II] or [Ar IV] doublet ratios, and electron temperatures from the [O III] lines. Values are generally within the normal range except for Hb 12, for which N_e may be as high as 4×10^5.

Subject headings: nebulae: planetary — spectrophotometry

I. INTRODUCTION

The original purpose of this work was to examine the spectra of a number of planetary nebulae of intermediate excitation, and to make accurate measurements of the relative line intensities. To this end we took 55 spectrograms of 23 nebulae. We had hoped to observe each of these nebulae photoelectrically. The photoelectric observations would be used to calibrate the photographic. We were able to complete all the necessary observations for two nebulae (NGC 6445 [Aller *et al.* 1973], and NGC 6803 [Lee *et al.* 1974]). Because of limitations on telescope time and several runs of poor weather, completion of the entire program would have taken an inordinate amount of time. For the remaining 21 nebulae we have some photoelectric observations on only eight. Our photographic observations, while of low precision by themselves, are nevertheless valuable. They show what lines are present in each nebula; and the line intensities, though coarse, still provide valuable information, especially for lines which are close together in the spectrum. We present a spectral survey which indicates a number of nebulae which are interesting enough to pursue by more detailed examination.

II. THE OBSERVATIONS

We present a list of the photographic plates we used in Table 1. Column (1) gives the nebula's common name, column (2) the Perek-Kohoutek (1967) designation, and column (3) the plate number. We took those designated ES at the prime focus of the 120 inch (3 m) reflector at Lick Observatory, on IIa-O films with a dispersion of 120 Å mm^{-1}. Those plates designated CS were taken with the 36 inch (91 cm) Crossley on IIa-O plates at a dispersion of 430 Å mm^{-1} at Hγ. All plates were taken during the period 1966–1967. Column (4) gives the exposure time for each plate, and column (5) indicates the number of microphotometer runs of the spectrogram. Many of these nebulae are extended objects, and we were able to examine the spectrum at different positions. We combined and averaged all these observations except in the cases of NGC 2452 and NGC 6853 where stratification is obvious. The last column gives information on the scaling of the line intensities to the strong lines in the cases where Hβ was not observed photographically, and other remarks.

We calibrated the ES plates with the 120 inch coudé step slit device, and constructed characteristic curves about every 300 Å from λ3400 to λ4500. Longward of λ4500 we used the λ4500 curve, which probably results in a small, but unknown, systematic error. We calibrated the CS plates with a spot sensitometer at only one wavelength near the midpoint of the observed wavelength range. Except in the case of blends, we measured the areas under the lines, after correction through the characteristic curve.

Close blends were resolved by using the ratios of the line peaks. For the λ3967–λ3970 line pair the sum of the intensities is more accurate than the ratios.

In order to correct the intensities from the ES plates to outside the atmosphere we employed BD+28°4211 as a standard source for all observations except those of NGC 3132, for which we also used θ Crt. The fluxes

* 1972–1973 John Simon Guggenheim Memorial Foundation Fellow.

TABLE 1

THE OBSERVATIONS

Nebula (1)	Designation (2)	Plate (3)	Exposure (min) (4)	Runs (5)	Remarks (6)
NGC 2346*†	215+3°1	ES 1446	90		
NGC 2452†‡	243−1°1	1428	120	3	Mean correction, no standard star
NGC 3132	272+12°1	1436	60	3	
		1447	90	3	
NGC 6565†	3−4°5	1372a	40	}	Scaled to Hγ, assuming $c = 0.36$
		1372b	10		
NGC 6629	9−5°1	1365a	24		
		1365b	60		
NGC 6644†	8−7°2	1373a	52		
		1373b	17		
		ES 1373c	7		
NGC 6781	41−2°1	CS 5635	120		
NGC 6790‡	37−6°1	ES 1354a	30		Scaled to photoelectric
		1354b	11		
NGC 6833	82+11°1	1368b	40		
		1375a	16		
		1375b	5		
NGC 6853	60−3°1	1357	120	4	
		1358	31		
		1360	45	3	
		1361	120	3	
		1362a	20		
		1369	40		
NGC 6884‡	82+7°1	1363a	30		
		1363b	10		
		1370	11		
NGC 6891‡	54−12°1	1366a	5		
		1366b	15		
		ES 1366c	50		
NGC 6894	69−2°1	CS 5636a	70	2	
		CS 5636b	10	2	
		ES 1363c	50	2	
IC 289*†	138+2°1	1444	120	2	
IC 4776†	2−13°1	1371a	17	}	No Hβ, scaled so that H9–H13 agree with theoretical
		1371b	45		
		1371c	5		
IC 4846‡	27−9°1	1356a	10		
		1356b	30		
		1356c	16		
Hb-5 = CD−29°13998	359−0°1	ES 1351a	45		
		1351b	14		
		1351c	5		
Hb-12*‡	111−2°1	1370	22		
		1376	10		
M1–1	130−11°1	1443a	20		
		1443b	60		
M1–4†	147−2°1	1445a	22		
		1445b	60		
Me 1–1	52−2°2	1367b	19		No Hβ, scaled to intensities of Aller (1951)

* Observed photoelectrically at Prairie Observatory.
† Nebula not heretofore extensively observed.
‡ Observed photoelectrically at Mount Wilson.

for these stars were taken from the work of Stone (1974) and Hayes (1970) respectively. In order to correct the Crossley observations we observed NGC 7009, where we took the intensities from Aller and Kaler (1964) as standard, as well as BD+28°4211.

We encounter a problem with overlapping spectral orders in correcting the ES plates to outside the atmosphere. All of the ES series of observations were made in the second order; hence longward of λ4500 there is overlap with the third order ultraviolet. Nebular lines of differing orders are well separated and present no problem, but second and third order contributions from the continuous spectra of the standard stars do overlap. The stellar light intensity impinging upon the film will be the second order contribution (as attenuated by atmospheric extinction), plus the third order contribution (as attenuated by ultraviolet atmospheric extinction). If one ignores the third order, the derived response function will be falsified in such a way as to give systematically too low nebular line intensities for all emissions longward of λ4500. This problem was handled by observing stars of differing but supposedly known energy distribution, e.g., θ Crt and BD+28°4211 whose ultraviolet fluxes differ considerably. Since the energy distributions are available and the atmospheric extinctions may be determined from the work of Hayes (private communication) for any given zenith distance, it is possible to isolate the relative contributions of the second and third orders and obtain a proper instrumental sensitivity function.

In order to reduce our plates we first corrected our stellar observations for atmospheric extinction and derived the instrumental sensitivity function for $\lambda < 4500$ Å. The mean curve was then fitted to the above function in order to derive the proper curve for $\lambda > 4500$ Å. We then multiplied this function by the atmospheric extinction function derived for the mean air mass of the nebular observation, which allowed us to correct the line intensities to outside the atmosphere. No standard was observed with NGC 2452. These line intensities were corrected by a mean function.

The nebulae which we observed photoelectrically are denoted by footnotes in Table 1. The Mount Wilson observations were made with the Oke scanner at the 60 inch (1.5 m) telescope where we used Vega, α Leo, 58 Aql, and ξ^2 Cet as the standard stars and Hayes's (1970) fluxes. The Prairie Observatory observations employed the University of Illinois 40 inch (1 m) telescope and a set of interference filters (see Kaler 1974 for details). The Mount Wilson observations were made in 1964–1966 and the Prairie observations in 1972–1974.

The photoelectric line intensities, relative to $I(\mathrm{H}\beta) = 100$, are presented in Table 2 for the eight nebulae so observed. Absolute Hβ fluxes are presented for the three nebulae observed at Prairie Observatory. The observations of NGC 2346 are affected by stellar absorption lines within the filter passbands. We determined the degree of line blanketing by using a spectrogram of the central star taken with the 120 inch, properly convolved with the filter transmission functions.

We present the photographic line intensities in Tables 3*a* and 3*b*. The nebulae are presented in the order of Table 1, and are divided into the two tables only for the ease of use. Again, the intensities are scaled to $I(\mathrm{H}\beta) = 100$. Note that for high-excitation nebulae, Hβ contains He II Pickering 8. In these tables, as in Table 2, blends are denoted by trying the two components with a brace. For some nebulae, close lines could be separated, for others they could not. In almost all cases Hβ was observed photographically, and these intensities are presented independently of the photoelectric. The agreement between the photographic and photoelectric is generally satisfactory, and further scaling was considered unnecessary. Hβ was too strong to be measured on the plates of NGC 6790, IC 4776, and Me 1–1. NGC 6790 was scaled to the photoelectric intensities in Table 2, and Me 1–1 to the intensities given by Aller (1951). IC 4776 has not been observed before. We assumed that *c* (logarithmic interstellar extinction at Hβ) = 0, and we scaled the intensities such that the observed H9–H13 intensities agreed with the theoretical predictions of Brocklehurst (1971), so that the intensities in Table 3 are approximately on the scale $I(\mathrm{H}\beta) = 100$. After reduction it was apparent that either the lines of NGC 6565 were too bright as compared with Hβ, or that the latter was in error. We have scaled these intensities to Brocklehurst's (1971) Hγ intensity which had been decreased for an extinction of $c = 0.36$.

III. EVALUATION OF THE DATA

It is difficult to assess the precision of the photoelectric data, as there is little with which they can be compared. The Prairie Observatory data were derived from an ON–OFF technique which allows the mean errors to be computed; these are presented in Table 2. Our Hβ fluxes for IC 289 and Hb 12 agree well with those observed by O'Dell (1963). NGC 6884 was observed by Peimbert and Torres-Peimbert (1971); except for the [O III] lines our intensities (relative to Hβ) are on the average about 15 percent greater than theirs. For six nebulae we can compare our values of $I(\lambda4959)$ or $I(\lambda5007)$ with those of others (O'Dell 1962, 1963; Collins *et al.* 1961; Peimbert and Torres-Peimbert 1971) where in appropriate instances we made use of the theoretical $I(\lambda5007)/I(\lambda4959)$ ratio of 2.9 (Nussbaumer 1971). For four of the six we find reasonable (±15%) agreement. For the other two (NGC 6790 and Hb 12) our values are 50 percent higher than those of O'Dell (1962, 1963). However, the Mount Wilson and Prairie observations of $I(\lambda4959)$ for Hb 12 agree to better than ±1 percent, and we will adopt our observations as correct.

The photographic data are more easily discussed. At the outset we expect some systematic errors though of unknown sense. The Hβ line, and most of the stronger lines, are frequently on the shoulder of the characteristic curve, resulting in scaling errors, and errors in the ratios involving strong lines. Systematic errors will also result from the lack of characteristic curves for $\lambda < 3400$ Å and $\lambda > 4600$ Å, and from the fitting procedure we were required to adopt for $\lambda > 4500$ Å to correct the data to outside the atmosphere. Mostly, the intensities suffer from lack of sufficient observational data. For proper photographic emission-line photometry, one needs a sequence of plates with carefully graded exposure times, such that sufficient lines are observed in common on the straight part of the (density, log *I*)-curve. Because of the survey nature of the program and the expectation that the stronger lines would all be measured photoelectrically in a separate program, this condition was not fulfilled —especially for the stronger lines. Unfortunately, adverse weather conditions frustrated our photoelectric efforts in this direction. The photographic photometry is, in general, adequate to give only a semiquantitative survey of the line intensities.

In order to test the general accuracy of the data we have made a number of comparisons. In Figure 1 we present a logarithmic plot of our photographic

TABLE 2

PHOTOELECTRIC LINE INTENSITIES

λ	ID	NGC 2346	NGC 2452	NGC 6790	NGC 6884	NGC 6891	IC 289	IC 4846	Hb12
5007	[O III]	...	1213	1532	...	...	...	1089	459
4959	[O III]	335 ± 15	410	462	465	293	150 ± 50	424	141 ± 2
4861	Hβ	100	100	100	100	100	100	100	100
4740	[Ar IV]	...	...	2.7	...	...	...	...	...
4686	He II	12 ± 3	...	3.5	...	...	94 ± 8	...	...
4471	He I	...	...	...	...	7.6	...	...	...
4363	[O III]	...	...	16.2 }					{ 18.9
4340	Hγ	...	...	45.8 }	45.8	46.0	...	...	{ 48.0
4101	Hδ	...	...	26.5	22.9	23.6	...	...	18.9
3970	[Ne III] }	...	...	28.2	...	20.0	...	...	31.1
3967	H7 }								
3889	H8, He I	...	...	7.7	15	13.8	...	...	7.1
3868	[Ne III]	74 ± 14	...	64.7	93	39.9	16 ± 7	...	42.1
3835	H9	...	...	...	...	6.3	...	...	...
3727	[O II]	311 ± 35	...	15.2	44	20.3	...	...	8.5
log $\mathscr{F}$(Hβ)		−11.33 ± 0.02	...	...	...	...	−11.67* ± 0.03	...	−11.06 ± 0.02

* Contains significant contribution from He II Pickering 8. True log $\mathscr{F}$(Hβ) = −11.69.

TABLE 3*a*

Photographic Line Intensities

λ	ID	NGC 2346	NGC2452* C	NGC2452* E	NGC 3132	NGC 6565	NGC 6629	NGC 6644	NGC 6781	NGC 6790	NGC 6833	NGC 6853† C	NGC 6853† M	NGC 6853† E
4959	[OIII]	326	356	356	257		222	459	300	b	299	317	354	325
4921	HeI							2.2		3.0	2.1			
4861	Hβ	100	100	100	100	(100:)	100	100	100	(100)	100	100	100	100
4740	[ArIV]		5.2	6.4	2:	1.3		4.0	3.9	3.3	1.0	4.7	2.7	
4726	[NeIV]							0.3						
4711+13	HeI } [ArIV]		7.0	8.3	5:			2.5	5.7	2.5	1.9	4.5	3.4	
4686	HeII	30	58	47	24‡	17		21	18	3.3		64	51	24§
4658	CIV							0.3						
4650	CIII,OII							0.9		0.9				
4640	NIII		3.7	4.2	2:			1.4		0.9	0.2			
4634	NIII		2.7	2.3				0.9		0.3				
4571	MgI					1.2		0.4						
4541	HeII		1.7	3.0	2:	1.0		1.1						
4471	HeI	5.2	2.4	4.5	5.8	5.1	5.4	6.7	3.9	5.5	6.1	5.6	4.4	8.4
4387	HeI						0.6	0.7		0.8	0.7			
4363	[OIII]	11	15	15	6.5	8.7	2.0	25		17	15	15	14	13
4340	Hγ	35.7	39.6	39.0	40	42	32.9	40.0		b	35.9	51	52	49
4267	CII						0.7:	0.6		0.5	0.3			
4200	HeII		3.0	2.1				0.5						
4143	HeI						0.5	0.5		0.2	0.4			
4121	HeI						0.2	0.3		0.3	0.4			
4101	Hδ	27.4	23.1	22.0	26	25	16.7	24.6	18	b	15.9	30	28	28
4097	NIII		1.8	1.8		1	0.2	0.6:		0.4				
4076	[SII]		2.1	2.5	4.5	3		0.8:		0.5	0.4	3	2	4
4068	[SII]		3.1	5.1	6.3	8.7		1.8		1.4	1.0	4	4	5
4026	HeI	2.9	2.4	2.5	4.8	3	2.6	2.8		1.9	1.9		3	2
4009	HeI									0.3	0.4			
3970	H7 }	53		16	18	17	8.9	14	} 29	8.2	7.5	} 58:	55:	62:
3967	[NeIII] }			28	30	38	6.4	31		17.9	13.8			
3889	H8, HeI	21.5	15.9	16.0	25	22	10.5	15	20	7.8	8.7	20	23	25
3868	[NeIII]	67	56	54	72	112	20.6	78	50	b	29:	130:	120:	160:
3835	H9	10.0	7.7	8.9	10	8	6.2	6.1	5	4.3	4.0	11	8	9
3819	HeI	3.0		2	3	1	1.1	1.3		1.0	1.0	2	3	
3797	H10	6.3	5.7	8.5	8	6.4	3.9	4.7		3.2	2.8	9	6	6
3771	H11	3.8	5.1	5.5	7	5.1	3.3	3.6		2.5	2.0	7	6	5
3759	OIII		4.9	4.7				1.9		0.5		4	2	
3754	OIII		1.8	2.0				0.4		0.2			2	
3750	H12		3.7	4.7	6	3.7	2.8	2.7		1.9	1.9	6	6	3
3734	H13	1.6	3.1	4.9	4	2.3	2.4	2.1		1.4		1.6	3	4
3729	[OII]	120:	34	44	100	190	10.3	10	} 147	2.2	1.6)	} 230	190	200:
3726	[OII]	105:	44	53	100	170	15.0	21		5.3	3.6)			180:
3722	H14 } [SIII]	0.8	4.7	6.0		4.5	1.7	2.1		1.6	1.6		5	
3712	H15	1.7	1.1	3.7		2.0	1.6	1.4		1.2	1.1			
3704	H16 } HeI	2.9	1.7	3.2		2.3	1.9	1.5		1.6	1.5			
3697	H17	1.0	0.8	3.2		1.3	1.1	0.9		1.1	0.9			
3691	H18	0.8		1.3		1	0.9	0.7		1.0	0.8			
3686	H19					1	0.8	0.6		0.8	0.6			
3682	H20						0.7			0.7	0.6			
3679	H21						0.6			0.6	0.6			
3676	H22						0.6			0.6	0.5			
3673	H23									0.6	0.3			
3671	H24									0.4	0.3			
3669	H25									0.5				
3634	HeI									0.3	0.3			
3614	HeI									0.2	0.4			
3587	HeI									0.2				
3444	OIII		20	28		6.6		6.0		0.8				
3428	OIII		3	3				0.7						
3425	[NeV]		40	37				2.5						
3345	[NeV]		20	9										
3340	OIII		7:	14				1.8						
3312	OIII		10:	14:										
3203	HeII		31	22										
3133	OIII		44	77										

* NGC 2452, C=center, E=edge
† NGC 6853, C=center, M=60" from center, E=150" from center
‡ I(λ4686) falls to < 5 at edge
§ I(λ4686) falls to 12, 170" from center
Note: "b" indicates line is overexposed. ( ) around Hβ intensity indicates Hβ was overexposed, but intensities still scaled to I(Hβ) = 100.

TABLE 3b

Photographic Line Intensities

λ	ID	NGC 6884	NGC 6891	NGC 6894	IC 289	IC 4776	IC 4846	Hb5	Hb12	M1-1	M1-4	Me1-1
5007	[OIII]			875								
4959	[OIII]	543	314	271	111		280	715	178	168	357	
4921	HeI		3.0			1.2	1.9		2.5			
4881	[FeIII]					0.4						
4861	Hβ	100	100	100	100	(100:)	100	100	100	100	100	(100)
4740	[ArIV]	6.3	0.6		10	0.5	1.6	22		7.0		4.0
4726	[NeIV]				7:			5.3		2		
4711+13	HeI [ArIV]	4.8	2.0		11	0.7	2.0	9.3	1.1	9.7		4.2
4686	HeII	18.7		15	83		0.6	58		88	8.7	2.8
4658	CIV					6.7	0.2			1.3		
4650	CIII,OII	0.8	0.4			0.3	0.3					
4640	NIII	3.3	1.3			0.2		6.9				
4634	NIII	1.6	0.4									
4624	[ArV]									0.9:		
4591	OII		0.5									
4571	MgI					0.2						
4541	HeII	0.9						2.5		4.8		
4510	NIII		0.4:									
4471	HeI	5.2	6.7			4.6	5.7	3.3	6.9	1.6	3.2	6.3
4387	HeI		1.0			0.6	1.1		0.8	1.1		0.6
4363	[OIII]	11.9	5.7		7.8	5.7	7.7	18.5	22	12.2	8.2	9.3
4340	Hγ	42.4	41.5	32	32.6	b	46.0	27.3	31	45.6	32.2	36:
4267	CII	0.8	1.0						0.4			0.5
4227	[FeV]	0.3				0.2						
4200	HeII	0.4								3.0		
4143	HeI	0.4	0.6			0.4	0.5		0.4			
4121	HeI	0.3	0.8			0.3	0.5					
4101	Hδ	21.4	25.3	18	20.1	17.3	24.2	10.6	19.6	26.2	17.4	
4097	NIII	1.9	0.8			0.2						
4076	[SII]	0.6	0.4			1.0	0.6	0.5	0.5			3.0
4068	[SII]	1.4	0.8			0.3	1.4	2.9	1.4	2.8		8.8
4026	HeI	2.5	4.1			0.2	2.2		3.1	2.4		
4009	HeI	0.3	0.3				0.2		0.1			
3970	H7	15.9	16.7	34 } (3970+3967)	11.6	14	16	15.9 } (3970+3967)	16.5	29.6 } (3970+3967)	11.6	12
3967	[NeIII]	35.6	17.8		7.1	18	19.7		19.3		21.4	27
3964	HeI		2.1									
3922	CII,HeII		0.5:							1.3		
3889	H8,HeI	14.6	20.3	20	8.3	13	16	10.2	12.1	16.6	12.6	13
3868	[NeIII]	93	41	59	20	b	65	47	31	33	41	b
3858	HeII									1		
3835	H9	7.0	9.7		6.4	6.9	7.5	3.3	7.7	9.3	3.9	5.6
3819	HeI	1.2	2.4			1.5	1.2		1.6	1.1		1
3814	HeII									1.4		
3797	H10	4.9	6.9			5.3	4.5	2.9	5.9	8.6	3.3	2.8
3771	H11	3.5	5.0			4.3	3.7		4.9	5.2	4.3	3.0
3759	OIII	2.5								3.1		0.5
3754	OIII	0.9								1.1		0.5
3750	H12	3.0	5.3			3.5	2.8		4.3	3.5	1.5	2.0
3740	HeII									0.9:		
3736	OIV									0.8:		
3734	H13	2.1	4.5			2.4	1.7	16 } (3734+3729+3726)	3.4	2.8	0.7	1.8
3729	[OII]	6.9	8.0	93		11.5	7.9		1.5	9.7	1.5	11
3726	[OII]	15.4	12.8	93		22	18		4.5	14.3	4.8	22
3722	H14 [SIII]	1.9	3.8			3.5	2.5		6.5	3.1		2.8
3712	H15	1.7	3.4			2.0	1.7		2.4			0.8
3704	H16 HeI	1.8	3.9			2.1	1.9		2.2	1.7		1.3
3697	H17	1.2	2.6			1.5	1.4		1.9	1.3		0.8
3691	H18	1.1	1.8			1.3	1.1		1.5	1.4		0.8
3686	H19	1.0	1.4			1.2	1.1		1.2	1.5		0.5
3682	H20	0.8	1.3			1.1	0.9		1.0	1.0		
3679	H21	0.75	1.0			1.0	0.8		1.0	0.7		
3676	H22	0.6	1.0			1.0	0.7		0.9			
3673	H23	0.7	0.9			0.7			0.8			
3671	H24	0.6	0.7			0.7			0.6			
3669	H25		0.9						0.7			
3634	HeI	0.5	0.9			0.6	0.4		0.8			
3614	HeI	0.4	0.4			0.3	0.4					
3444	OIII	11.1								7.5		
3428	OIII	2.5										
3425	[NeV]				54					145:		
3362	[NaIV]									1.6		
3345	[NeV]				21					76		
3340	OIII	5.6								3.6		
3312	OIII	4.2								2.7		
3299	OIII	1.6								2.2		
3242	[NaIV]									4.1		
3203	HeII	6.3			14					51		
3187	HeI	2.7	0.8			1.6	3.0			4.3		
3133	OIII	37										

Note: "b" indicates line is overexposed. () around Hβ intensity indicates Hβ was overexposed, but intensities still scaled to I(Hβ) = 100.

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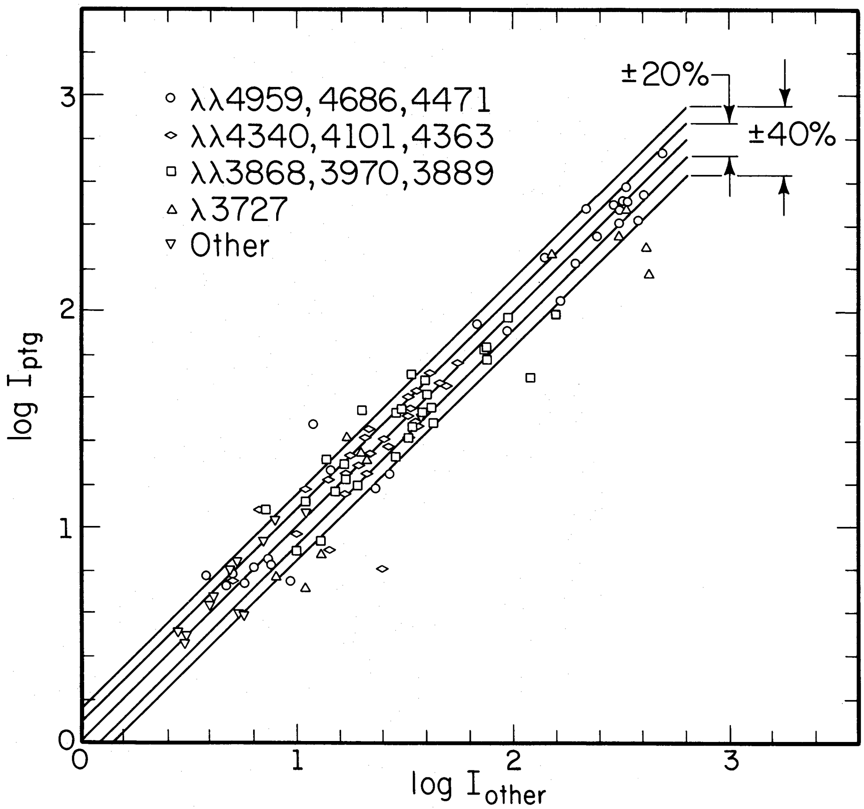

FIG. 1.—Plot of the log of our photographic intensities (I_{ptg}) against the log of other published values plus our photoelectric (I_{other}). Lines are drawn to indicate errors of ±20% and ±40%.

intensities against other observations. For the comparison we use our own photoelectric data, and those data of Aller and Faulkner (1964), O'Dell (1962, 1963), Aller (1951), Minkowski (1942), Chopinet (1963), Collins *et al.* (1961), and Razmadze (1961). Different lines are indicated by different symbols. This comparison is useful for lines with $I \geqslant 5$. Below this limit there are virtually no comparison data available. We exclude H9, H10, etc., because of clear systematic effects. Little overall systematic trend is present; the points cluster rather well around the 1:1 line. The only really obvious systematic effect is that for some nebulae we tend to measure $I(\lambda3727)$ too low. This effect may not be systematic error, but may be due to stratification effects. The λ4686 Å line of He II is probably affected by stratification as well. Error lines for ±20 percent and ±40 percent are also drawn onto Figure 1. A count of the points shows that half of them are within ±20 percent of the 1:1 line. The mean error assigned to any given point would then be about ±30 percent. If we assume that I_{other} shares the errors equally with I_{ptg}, the true mean error for our photographic data for the stronger lines is then ±20 percent. At worst, it is probably between ±25 percent and ±30 percent.

In Table 4 we compare our data with the theoretical predictions of H and He II line intensities by Brocklehurst (1971). We give the nebula name in the first column, and the value of the interstellar extinction constant, c, in the second. Where possible, c is adopted independently of the present data, generally from radio/Hβ flux ratios which we take from a compilation by Cahn (1976). The next four columns give the ratio $[I(\text{H}n)/I(\text{H}\beta)]_c/[I(\text{H}n)/I(\text{H}\beta)]_t$, where the subscripts c and t denote intensities corrected for extinction, and theoretical intensities, respectively. We choose Hγ, Hδ, H9, and H13 for comparison. The last row of Table 4 gives the average error of the observations. The mean spread in the errors is indicated by a ±. Our Hγ observations appear to be reasonably accurate, and there is a tendency to measure Hδ about 10 percent too bright; this figure is within our expected error. The higher hydrogen lines appear subject to a clear systematic error in that we measure them on the average to be about 50 percent too bright. The lines H9 ... are often well exposed, and the error may be a development effect, as the dispersion we used is low and these lines are crowded together. We have analyzed our He II Pickering observations the same way. In columns (7) and (8) we present $[I(\text{Pi } n)/I(\lambda4686)]_c/[I(\text{Pi } n)/I(\lambda4686)]_t$ for $n = 9$ and 11, respectively. These lines are overestimated by factors of the order of 2. The He I lines are also generally overestimated. If we assume that He/H = 0.1, then $I(\lambda4471)$, $I(\lambda4026)$, and $I(\lambda3819)$ are on the average too large by factors of 1.5, 1.9, and 1.6, respectively. The cause of these errors may be a combination of low-signal-to-noise, placement of the continuum, and scale factor errors.

TABLE 4

ANALYSIS OF H AND He II LINES AND PROPERTIES OF THE NEBULAE

(1) Nebula	(2) c	(3) Hγ c/t	(4) Hδ c/t	(5) H9 c/t	(6) H13 c/t	(7) HeII Pi9 c/t	(8) HeII Pi11 c/t	(9) Excit class	(10) [OII] x	(11) [ArIV] x	(12) t
NGC 2346	0.87	1.00	1.56	2.3	1.2	-	-	6	0.04	-	1.32‖
2452 C }	.77	1.07	1.26	1.7	2.2	.9	3.6	7	0.10	< 1	1.35‖
2452 E }		1.06	1.20	2.0	3.2	2.0	3.1		0.10		
3132	.25	1.00	0.92	1.1	1.6	2.5	-	5	0.06	< 1	1.00‖
6565	.36	-	1.13	1.4	1.2	1.8	-	6	0.045	-	1.01‖
6629	.89	0.93	0.96	1.46	1.8	-	-	4	0.2	-	0.85
6644	.32*	0.94	1.09	1.0	1.1	1.6	1.5	7	0.6	8	1.49
6781	.54†	-	1.13	-	-	-	-	6	-	< 1	-
6790	.56	1.16‡	1.31‡	0.8	0.9	-	-	5	1.1	5	1.24‖
6833	.78	1.09	0.97	0.9	0.9	-	-	5	0.9	< 1	1.53
6853 C }						-	-	7§	-	2	
6853 M }	.02	1.08	1.11	1.3	1.2	-	-		-	~ 1	1.30
6853 E }						-	-		0.05	-	
6884	.38*	1.02	0.98	1.2	1.1	1.5	1.3	6	0.9	4	1.11‖
6891	.22	0.97	1.08	1.5	2.1	-	-	5	0.25	< 1	1.02‖
6894	.70	0.85	0.95	-	-	-	-	5	0.06	-	-
IC 289	.87	0.92	1.14	-	-	-	-	10	-	⩽ 1	1.59‖
4776	.04	-	-	-	-	-	-	5	0.45	~ 7:	-
4846	.00	0.98	0.93	1.0	0.7	-	-	5	⩾ 1	1.5	0.97‖
Hb 5	1.7	1.00	0.89	1.3	-	1.5	-	7	-	10	1.30‖
Hb 12	.98*	0.89	1.18	1.9	2.7	-	-	4	⩾ 1	-	**
M1 1	.53	1.15	1.27	1.8	1.4	1.7	2.2	10	0.2	< 1	1.80
M1 4	1.04*	0.95	1.07	1.0	0.6:	-	-	6	⩾ 1	-	1.16‖
Me1 1	.46	0.88:		1.0	1.0	-	-	5	0.5:	~ 2	1.12‖
Mean Error		1.0 ± .1	1.12 ± .15	1.4 ± .4	1.5 ± .6	1.7	2.3				

* c determined from Hβ, γ, δ intensities from this paper
† c determined from Hβ, γ, δ of Minkowski (1942)
‡ Photoelectric intensities
§ λ3727 abnormally strong
‖ Photoelectric values used for I(λ4959) and/or I(λ5007)
NGC 3132: Webster (1969), Aller and Faulkner (1964); NGC 6629: O'Dell (1963); NGC 6565, Hb 5, Mel-1: O'Dell (1963); otherwise, Table 2
**If t = 1.4, x = 45 (see text)

In summary, the photoelectrically observed line intensities appear to be accurate, but the photographic intensities should generally be viewed as a survey. The stronger lines ($I \geqslant 10$) are dominated by random errors of the order of ± 20–30 percent. The weaker lines can be overestimated by factors of up to 2. Possibly, we could derive empirical corrections for the weaker lines from a comparison of the observed Balmer and Pickering decrements with theory. Judicious use of the data can still tell us a great deal about the nebulae observed.

IV. PROPERTIES OF THE NEBULAE

We present the general properties of the nebulae we have studied in columns (9)–(12) of Table 4. In column (9) we give the excitation classes of the nebulae (Aller 1956). Most of the nebulae are of intermediate excitation, but two (IC 289 and M1–1) show a very high level.

We have derived values of $x = 10^{-4} N_e/\sqrt{t}$, where $t = 10^{-4} T_e$(K), from the ratio of $I(\lambda3729)/I(\lambda3726)$ of [O II] and the $I(\lambda4740)/I(\lambda4711)$ ratio of [Ar IV]. We use the theoretical calculations by Saraph and Seaton (1970) and Krueger *et al.* (1970), respectively. We present the results in columns (10) and (11) of Table 4. The [O II] ratio has been measured previously in only three of the nebulae discussed here, and the agreement is good, which lends credence to our values of x (see Table 5). The ratio approaches an asymptotic limit for $x \geqslant 1$, and is not useful above this value.

The λ4711 [Ar IV] line is blended with λ4713 of He I. We assume that $I(\lambda4713)/I(\lambda4471)$ is 0.1 (Brocklehurst 1972), and thereby find the true value of $I(\lambda4711)$. The [Ar IV] line ratio is sensitive to density only for $x \geqslant 1$, so that it can be used to indicate those nebulae which have high densities. For the compact nebulae we might expect x([Ar IV]) > x([O II]) because of density gradients, as has been found for NGC 6803 (Lee *et al.* 1974) and NGC 7027 (Saraph and Seaton 1970; Kaler *et al.* 1976). The λ4740 and λ4711 + 13 lines are relatively weak, and may be overestimated as is λ4471. Since all these lines are similar in wavelength and their intensities are comparable, we expect their ratios to be reasonably accurate, however. The correction required for He I λ4713 will produce an additional error, but for the higher excitation nebulae at least the

TABLE 5

VALUES OF $I(\lambda3729)/I(\lambda3726)$ OF [O II] AS MEASURED HERE, AND BY OTHER AUTHORS

Nebula	Present Value	Other Value
NGC 6853......	1.11	1.16 (Osterbrock 1960)
NGC 6884......	0.45	0.47 (Lutz 1974)
NGC 6891......	0.63	0.64 (Lutz 1974)

corrections and resulting errors are small. As a consequence of these problems, the [Ar IV] densities should be viewed only as fairly rough indicators. The values of x from the two ions are generally compatible with one another, however.

In all but three nebulae we observe λ4363 of [O III], and use the ratio $I(\lambda4959)/I(\lambda4363)$ to derive electron temperatures. We use the new collision cross sections and the formula given by Seaton (1975), and present the resulting values of $t = 10^{-4} T_e$ in column (12) of Table 4. When available, we generally use photoelectrically observed intensities of λ4959 and for λ5007; these nebulae are so designated in Table 4. Otherwise, we use the photographic intensities from Table 3. The λ4363 line is usually partially blended with the night-sky λ4358 Hg line, which we feel we have adequately removed. If the error in $I(\lambda4363)$ is as much as 30 percent, the resulting error in T_e is only about 1200 K, so that the results presented in Table 4 are still qualitatively useful. For several objects they are the only values available.

Hb 12 represents a special case. $I(\lambda4363)$ is very strong with respect to λ4959, indicating a high electron density. For this object we reverse the procedure, and find that for $t \approx 1.4$, x must be substantially greater than 10. Our new value of $I(\lambda4363)$ confirms that found earlier by Aller (1951).

V. COMMENTS ON INDIVIDUAL NEBULAE

NGC 2346 is of particular interest because its apparent central star is of spectral class A0 (Kohoutek and Senkbeil 1973). The nebular spectrum appears quite typical, with very strong [O II] λ3727. The [O II] data are approximate since the lines are high on the shoulder of the characteristic curve; λ3729 is clearly stronger than λ3726, however, indicating a low density. A comparison of the photoelectric and photographic data shows marked stratification. The photographic data show λ4686 relatively stronger and λ3727 relatively weaker. With the photoelectric technique we observe the entire nebula including the low-excitation outer regions, whereas the slit spectrogram is of the higher-excitation inner region. Our Hβ flux is almost an order of magnitude greater than that derived from a photographic estimate by Kohoutek (see Cahn and Kaler 1971).

NGC 2452 exhibits effects of stratification, especially for the ultraviolet [Ne V] and O III lines, with the higher ionization level being closer to the center of the nebula as expected. To our precision there is no significant variation in T_e or N_e. The data presented here are only approximate over a large wavelength baseline, as no standard star was observed, and we adopted a mean correction to outside the atmosphere.

NGC 3132 is difficult to observe because of its low declination ($\delta = -40°$). Consequently the spectra are of low quality and the line intensities are quite approximate. Stratification is evident as λ4686 becomes unmeasurable near the edge of the nebula. Note the strength of [O II] λ3727.

NGC 6565: The scaling to $I(\mathrm{H}\beta) = 100$ is approximate. The data were scaled to $I(\mathrm{H}\gamma) = 42$ which is the expected intensity for $I(\mathrm{H}\beta) = 100$ and $c = 0.36$. The λ4363 line is also fairly weak, and t is more uncertain than for most. $I(\lambda3727)$ is very strong.

NGC 6629: Note the very low electron temperature. The weakness of λ4363 will make the error in t rather high. Possibly T_e is even lower than 8500 K, because of the tendency to overestimate the weakest lines. He II λ4686 is present only in emission from the central star.

NGC 6644: There is disagreement between the values of x derived from [O II] and [Ar IV]. The lines are all well exposed. Of the two exposures with measurable [Ar IV] lines, the lower value of x is 6.5. The λ4740 line clearly appears stronger than λ4711. The [O II] lines are observed on all three plates; on one the ratio is at the limit, implying $x > 1$. These results should be viewed with caution, but the difference may be real, suggesting a density gradient.

NGC 6781 is a large nebula of low surface brightness, and one of the two objects observed with the Crossley reflector. We measure [Ne III] λ3868 and [O II] λ3727 to be weaker than Minkowski's (1942) measurements, probably a stratification effect. The weakest lines are very approximate. Hγ is so badly blended with Hg I λ4358 that measurement is impossible.

NGC 6790 is another small, high-density nebula somewhat similar to NGC 6644, though of lower excitation. The strong lines are overexposed, and the photographic intensities were calibrated with the photoelectric. The [Ar IV] ratios from the two plates are within 10 percent of one another. The value of x from [O II] is indeterminate.

NGC 6833 is a "stellar" nebula, for which x appears to be about 1. We use our photographic intensity of $I(\lambda4959)$ to derive the relatively high electron temperature. If we use O'Dell's (1963) value, it is even higher. He II is apparently absent.

NGC 6853 (the "Dumbbell," M27) is of interest primarily because of the strong stratification effects which it exhibits. He II λ4686 drops by a factor of 5 from center to extreme edge, while λ4471 increases. At the same time there is no evidence for a significant change in T_e for the points we observe. We again use our photographic intensities for $I(\lambda4959)$, which are in good agreement with those of Minkowski (1942) and Chopinet (1963), to derive T_e. Our value is at the upper end of the range found by Bohuski *et al.* (1974). [O II] λ3727 is poorly resolved, but λ3729 is definitely stronger than λ3726 indicating low density. The [Ar IV] lines indicate a higher density, but the precision is low as the lines are quite weak. Possibly the density is higher toward the center, and the [Ar IV] lines may arise in dense filaments, which is consistent with the photographs published by Capriotti *et al.* (1971).

NGC 6884 is again similar to NGC 6644 above. The [Ar IV] line ratio is rather well determined from two plates, and indicates a high density. Aller and Walker's (1970) [Cl III] data indicate $x \approx 0.9$, in agreement with the [O II] value. A density gradient probably exists. Note the strength of the ultraviolet O III lines. We adopt in Table 4 an extinction constant of 0.38 derived from our data, which is lower than that derived from Peimbert and Torres-Peimbert's observations (0.81). Their extinction is in better agreement with the ratio/Hβ extinction of 0.94. This difference reflects the fact that with respect to Hβ our intensities are systematically higher than theirs by 15–20 percent. If we reduce $I(\lambda 4363)$ accordingly, and use their value of c, the resulting temperature is not affected very much. We find then that $t = 1.13$, nearly the same as in Table 4.

NGC 6891 is another low-excitation object with no He II lines. [O III] λ4363 is comparable in intensity to λ4471, which may well be overestimated. Consequently, T_e may be less than 10^4 K. Aller and Walker's (1970) [Cl III] line ratio is at the low-density limit and indicates $x < 1$ in agreement with the other values presented here. The He I 2 ^{3}P continuum is seen on the tracings at λ3422, but is too weak to be accurately measurable.

NGC 6894 (the Annular Nebula in Cygnus) is an object of low surface brightness with strong [O II] lines. Our intensities are similar to those measured by Minkowski (1942).

IC 289 is a very high-excitation nebula with a powerful He II λ4686 line. He I λ4471 and [O II] λ3727 are not detected. Apparently nearly all the helium is doubly ionized. The [Ar IV] lines are weak and are of comparable intensity, so that x appears to be about 1. Given the expected errors, x could clearly be less than 1, however.

IC 4776. The strong lines are overexposed on all plates, and the scaling to Hβ is approximate. Cahn (1975) suggests $c = 0.04$, so for simplicity we adopt $c = 0$ and fit the line intensities to the theoretical predictions for H9–H13. In view of previous overestimates of these lines (see cols. [5] and [6] of Table 4), the intensities of the stronger lines may be too low. On the other hand, if c is significantly greater than zero, the intensities will all be overestimated by a constant factor. The object shows no He II lines, but the [Ar IV] lines are weakly present. The [Ar IV] density is very approximate because of the large correction required for He I, λ4713 but it appears to be above the lower sensitivity limit of the ratio. [O II] is observed on two plates, and the values of x so derived agree well. Possibly IC 4776 exhibits a density gradient.

IC 4846, like NGC 6833, is a stellar appearing object. The value of x derived from [O II] is near the upper sensitivity limit; that from [Ar IV] is near the lower; x is ~ 1. The He II λ4686 line is weak but definitely present; it seems too narrow to be of stellar origin. Hβ is nearly overexposed, and scaling may be a problem. Hγ and Hδ agree reasonably well with Aller's (1951) results, however.

Hb-5 is a high-density object with a rather strong He II λ4686 line. The [Ar IV] lines are very strong and well exposed, and the value of x derived from them should be reliable. The [O II] lines are unresolved.

Hb-12 is an unusual nebula reminiscent of IC 4997 (see Aller and Liller 1966), in that it has a very strong [O III] λ4363 line. For this discussion we use an average of the photographic and photoelectric data, and c derived from Hβ, γ, and δ. If collisional de-excitation is ignored, the [O III] lines yield $T_e \approx 30{,}000$ K. The density must be very high. If we assume that $T_e \approx 14{,}000$ K, we must adopt $x \approx 40$ to fit the observed $I(\lambda 4363)/I(\lambda 4959)$ ratio. Even if T_e is as high as 20,000 K, $x \approx 13$. If we adopt a lower c from Hδ/Hβ alone (0.67), x is still ~ 10 at 20,000 K.

The intensity of the λ4363 line in IC 4997 has decreased sharply over the past half-century. Such does not appear to be the case for Hb-12. Our measurements agree with the one obtained by Aller (1951) from plates taken in 1945. However the accuracy of the observations is such that variation cannot be ruled out, and the nebula should be monitored over the next few decades. Unfortunately, the [Ar IV] lines, if they exist at all, are below our level of detection.

M1–1, like IC 289, is of very high excitation. Note the strength of λ4686 He II and the extraordinary strength of the ultraviolet [Ne V] lines.

M1–4: The value of x from [O II] is at the indeterminacy limit; the density is certainly high, not surprising as the nebula appears quite small.

Me 1–1: The strong lines are overexposed, and the line intensities were normalized to the intensities of Aller (1951). The [O II] lines are on the shoulder of the characteristic curve, and the x derived has low precision. Apparently x is of the order of 1.

VI. SUMMARY

We have photoelectrically measured line intensities for eight planetary nebulae, and the results appear to be generally accurate. The photographic work for all 21 planetaries represents a spectral survey. Insofar as the photographically measured lines are concerned, the stronger lines are relatively free of systematic error, but contain random errors of the order of ± 20–30 percent. The weakest lines can be overestimated by up to a factor of 2. However, judicious use of the data still tells us a great deal about the nebulae concerned, and indicates which nebulae should be observed further.

We are indebted to Director Babcock and the staff of the Hale Observatories for the opportunity to secure photoelectric scanner measurements at Mount Wilson. We thank Mr. Victor Broquard for invaluable aid in the reduction of the data, Mr. Drake Deming for aid in securing some of the Prairie observations, and Dr. J. H. Cahn for providing results in advance of publication. One of us (J. B. K.) wishes to thank the John Simon Guggenheim Memorial Foundation for support while this work was in progress. We also thank the National Science Foundation for support through grants GP-22957 and MPS 73-05270 to the University of Illinois and MPS 71-03362 A03 to the University of California, Los Angeles.

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