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A PHOTOMETRIC SURVEY OF COMPACT AND SELECTED PLANETARY NEBULAE

JAMES B. KALER
Astronomy Department, University of Illinois
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ABSTRACT

Absolute and relative line fluxes are given for 31 planetaries, including several that have not been heretofore examined. Most are compact, and some have extraordinarily high reddening constants. Principal results include revision of some previously measured Hβ fluxes, the discovery of two very high excitation nebulae, examination of three very low excitation objects, and the discovery of at least one and possibly more nebulae with high N/O, including one (NGC 6537) that appears to be highly enriched in both nitrogen and helium.

Subject headings: nebulae: abundances — nebulae: planetary — spectrophotometry

I. THE OBSERVATIONS

This paper presents the results of a survey of compact nebulae that was conducted to improve the absolute data for several objects and to look for nebulae of unusual interest. Also included are photometric data for a few well-known planetaries that are part of a study of central star magnitudes, which will be reported on later.

All the observations were made with the Illinois 1 m telescope at Prairie Observatory, a single-channel photometer, and a set of interference filters. Observation and reduction procedures are discussed by Kaler (1976, 1980*a*, 1981). Absolute fluxes are tied to the new Hβ (plus He II Pi 8) flux determined for NGC 7027 by Shaw and Kaler (1982) of 7.60×10^{-11} ergs cm^{-2} s^{-1}. Temperature shifts and, where possible, radial velocity shifts were taken into account.

The data are presented in Table 1, where columns (1) and (2) give the nebula's common name and Perek-Kohoutek (1967) number, and column (3) gives the diameter of the photometer aperture used. The observed absolute Hβ and Hα fluxes are given in columns (4) and (5). In all but three cases (see footnote "a"), the nebulae were observed with apertures large enough to encompass the whole object. An estimate of the total log F(Hβ) for one of these (A77), based upon the nebular diameter, is given in footnote "b." Two nebulae, NGC 6537 and NGC 7008, were observed with both restricted and adequately large apertures.

Relative line fluxes, on the scale F(Hβ) = 100, are presented for λ3727 [O II], λ4471 He I, λ4686 He II, λ4959 [O III], λ6563 Hα, and λ6584 [N II] in columns (6) through (11). All absolute and relative data are given uncorrected for interstellar extinction. The relative Hα flux in column (10) will not always be consistent with that derived from columns (4) and (5) because of weighting effects between different night's observations. Column (12) gives the ratio of the λ6584 [N II] flux to that of Hα, called N/α. This ratio is the same as that found by dividing the values of column (11) by those in column (10), but the error is different, since the error in Hβ is removed. Column (13) gives the interstellar extinction constant, the logarithmic extinction at Hβ, c, derived from the Hα/Hβ flux ratio, Brocklehurst's (1971) theoretical value of 2.85, and the Whitford (1958) reddening function [f(Hα) = −0.335]. Note the number of heavily reddened nebulae, one with $c \approx 2.8$ (M1-78).

Notes to remarks and references at the end of the table are given in column (14). Seven nebulae previously observed with this system are presented with improved and/or more extensive data. The nebulae M4-18 was recently observed by Sabbadin (1980): the two sets of relative line fluxes are in good agreement. Na-1 and M1-11 were observed by Kondratyeva (1978, 1979): for the latter, the N/α ratios are in excellent agreement, but the present Hα/Hβ ratio is almost double that found earlier. For the three nebulae noted by "poor night," the errors on the absolute fluxes are probably higher than given; the relative fluxes should be reasonably reliable, however.

The fainter nebulae had to be observed by blind offset, usually from a nearby SAO star. As a consequence, new coordinates were measured for selected nebulae from the Palomar Sky Survey and are presented in Table 2. The positions are for the central star where it is seen, or for the optical center of the extended nebula. The errors assigned to two of the objects are derived from offsets from two SAO stars. The mean errors, as found from extensive unpublished measurements, are ±3″.

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TABLE 1

Observed Line Fluxes and Extinctions for Compact and Selected Planetary Nebulae

Nebula (1)	PK (2)	Ap (3)	Observed −log F(Hβ) (4)	Observed −log F(Hα) (5)	F(Hβ) = 100: 3727 [OII] (6)	4471 HeI (7)	4686 HeII (8)	4959 [OIII] (9)	6563 Hα (10)	6584 [NII] (11)	N/α (12)	c (13)	Rmks (14)
NGC 2392	197+17°1	40"	10.57±0.01[a]	10.07±0.04			44±3		314±32	90±10	0.29±0.03	0.12±0.13	1
NGC 6445	8+ 3°1	40"		11.69±0.06[a]			34±7	647±100					2,3
NGC 6537	10+ 0°1	40"	11.71±0.03[a]	10.52±0.04[a]	29±7	4.9±2.8	65±5	413±22	1360±150	1600±175	1.18 ±0.12	2.02±0.14	
		4'	11.40±0.03										
NGC 6543	96+29°1	40"	9.59±0.03	9.11±0.05					307±31	44±5	0.14 ±0.02	0.10±0.12	
NGC 6572	34+11°1	26"	9.83±0.01					406±8					
NGC 6778	34− 6°1	40"	11.18±0.04	10.49±0.09					537±114	331±62	0.62 ±0.16	0.82±0.28	3
NGC 6790	37− 6°1	26"	10.86±0.01	10.13±0.04	11±1	5.3±0.4		548±5	540±55	24±4	0.045±0.007	0.82±0.13	
NGC 6804	45− 4°1	40"	11.51±0.02[a]			<3.8	88±4						4,5
NGC 6807	42− 6°1	26"	11.46±0.02	10.86±0.04				478±34	369±43	10±5	0.028±0.003	0.33±0.15	5
NGC 6879	57− 8°1	26"	11.57±0.01	10.97±0.04			13±4	425±17	395±42	7±4	0.018±0.010	0.42±0.14	
NGC 6881	74+ 2°1	26"	12.26±0.03	11.21±0.05	33±10		25±5	578±45	1120±150	780±96	0.70 ±0.09	1.77±0.18	
NGC 7008	93+ 5°2	40"	11.50±0.01[a]	10.80±0.05[a]		1.3±0.8	106±2	118±40	570±166			0.84±0.14	5,6
		4'	10.84±0.03	10.17±0.05	4±2		113±8	353±23	516±142	23±13	0.044±0.023		
IC 2149	166+10°1	40"	10.55±0.01	10.01±0.04					352±35	52±5	0.148±0.015	0.27±0.13	
A 77	97+ 3°1	40"	12.44±0.06[b]	11.15±0.04[a]	51±21		<2	176±86	1740±180	140±20	0.08 ±0.01	2.34±0.13	
Ha3 29	174−14°1	40"	12.49±0.03	11.64±0.04	0.0:		112±11	242±25	707±89	10±12		1.17±0.16	
J 900	194+ 2°1	26"	11.34±0.02	10.71±0.04	43±3		39±2		465±47	84±11	0.18 ±0.03	0.63±0.13	5,7
K3 60	98+ 4°1	40"	13.17±0.18	12.04±0.05			0:	490±260	1335±715	252±135	0.19 ±0.03	2.00±0.77	
K3 63	98+ 2°1	40"	12.97±0.06	12.16±0.05	<70		79±18	336±70	637±131	77±48	0.12 ±0.07	1.04±0.27	
M1 2	133− 8°1	40"	11.88±0.06	11.09±0.04			<24	182±52	610±114	25±14	0.04 ±0.02	0.98±0.25	8
M1 4	147− 2°1	40"	12.14±0.05	11.23±0.05			16±10	417±82	816±137	<58	<0.07	1.36±0.22	9
M1 7	189+ 7°1	40"	12.05±0.03	11.33±0.04	132±14		15±7	429±43	523±62	611±71	1.17 ±0.12	0.78±0.15	
M1 11	232− 4°1	40"	11.85±0.01	10.87±0.06	41±13		<2	23±13	960±98	620±63	0.65 ±0.07	1.57±0.13	10
M1 13	232− 1°1	40"	11.85±0.06	10.95±0.04	360±60		<60	470±89	800±140	241±50	0.30 ±0.05	1.34±0.23	
M1 78	93+ 1°1	40"	12.88±0.24	11.50±0.09					2440±1300	860±690	0.34 ±0.04	2.78±0.77	3
M1 79	93− 2°1	40"	11.73±0.01	11.00±0.06	151±9	7.2±1.7	11±5	261±9	539±88	577±75	1.07 ±0.19	0.82±0.21	7
M2 2	147+ 4°1	40"	12.22±0.02	11.32±0.07	0.0		36±5	417±18	747±140	130±100	0.17 ±0.13	1.25±0.15	
M2 54	104− 6°1	26"	12.01±0.07	11.26±0.06	38±20		0:	59±40	553±123	156±50	0.28 ±0.08	0.85±0.29	11
M4 18	146+ 7°1	40"	11.88±0.04	11.19±0.04	55±12		0:	8±7	488±67	303±40	0.62 ±0.07	0.69±0.18	12
Me2 1	342+27°1	26"	11.31±0.01	10.81±0.05			84±6		310±43	0.0[c]	0.0[c]	0.11±0.17	7,13
Na 1	18+20°1	40"	11.98±0.03		<2			370±40					14
Vy2 3	107−13°1	26"	11.96±0.01		31±5		10±3	337±21					5

[a] Nebula larger than aperture; value given is the surface flux through the aperture in col. (3).

[b] Surface flux; total log $F(H\beta)$ estimated to be -12.40 ± 0.10.

[c] No detection.

Remarks.—(1) Misses some of outer shell. (2) Central core. (3) Poor night. (4) Inner ring only. (5) Kaler 1980*a*. (6) Bright blob. (7) Kaler 1978*b*. (8) VV8, extinction doubtful. (9) Aller, Kaler, and Czyzak 1976. (10) Kondratyeva 1979. (11) Kohoutek 1972 suggests emission-line star. (12) Sabbadin 1980. (13) Kaler 1976. (14) Kondratyeva 1978.

TABLE 2

Coordinates for Selected Nebulae

Nebula	(1950) α	δ
A 77	$21^h30^m36^s.2 \pm 0.3^s$	$+55°39'27'' \pm 1''$
Ha3-29	04 34 21.5	+24 56 50
K3-60......	21 25 58.1±0.1	+57 26 05±4
K3-63......	21 37 34.5	+55 32 27
M1-2	01 55 32.5	+52 39 10
M1-4	03 37 59.0	+52 07 26
M1-7	06 34 17.8	+24 03 07
M1-11	07 09 05.9	−19 46 01
M1-13	07 19 02.6	−18 02 50
M1-78	21 19 05.7	+51 40 38
M1-79	21 35 11.7	+48 42 41
M2-2	04 09 10.2	+56 49 16
M2-54	22 49 30.9	+51 34 46
M4-18	04 21 30.8	+60 00 18
Me2-1	15 19 23.5	−23 26 52
Vy2-3......	23 20 36.0	+46 37 29

II. DISCUSSION

a) *Absolute Fluxes*

The new total Hβ fluxes are compared with previous measurements in Table 3. Where necessary, the older data are corrected to the Oke and Schild (1970) standard, as described by Shaw and Kaler (1982). The AD and BAR data were unchanged, the PTP value was reduced by 0.04 in the log, CD by 0.01, and the others by 0.02. Except for three nebulae, the agreement is generally satisfactory. The largest discrepancy is for NGC 6537, which is here measured to be 0.40 in the log brighter than previously believed. CDO measured only the inner core of the object, whereas the 4′ aperture used here encloses the entire outer diameter of this extended object. NGC 6778 was observed on a relatively poor night, and the CDO value is almost certainly the better of the two. NGC 6790, however, was observed on an excellent night, together with other nebulae that confirm the validity of the flux measurement, and the new value is probably preferable.

M1-2 (VV8), a well-known peculiar high density nebula, was observed in order to test for variability. Within the errors, there is no difference between the present flux and that measured by Barker (1978), but the object should be examined periodically. For future reference, the observation was made 1981 January 23 UT.

b) *High and Low Excitation Nebulae*

Several of the nebulae in Table 1 are of particular interest because they are at the extremes of the range of observed ionization. Ha 3-29 and K3-63 both exhibit strong He II λ4686. Helium appears to be fully doubly ionized in the former, and it is in that sense comparable to the high excitation nebulae studied by Kaler (1981). If we adopt Shao and Liller's (1973) central star magnitudes of $B = 18.8$, $V = 18.6$, the He II Zanstra temperature (Harman and Seaton 1966) is 113,000 K. This value is probably a lower limit to the true effective temperature because the nebula is likely to be optically thin in the He$^+$ Lyman continuum.

Three nebulae exhibit very weak [O III] lines: M4-18 (Sabbadin 1980), M1-11 (Kondratyeva 1978), and M2-54 (Kohoutek 1972). The present data confirm the [O III] intensities found earlier for M4-18 and M1-11. Kohoutek (1972) suggested that M2-54 might be an emission line star, based on the strength of the continuum, and a lack of blue emission lines. The strength of [N II], however, indicates a low excitation planetary. From Kaler (1978*a*), the central star temperatures of the three objects are all in the neighborhood of 30,000 K. All are very small and unresolved, consistent with their being young planetaries.

The nebulae for which radial velocities are available (see Perek and Kohoutek 1967) are consistent with Kaler's (1980*b*) contention that high excitation nebulae are confined to the disk. The LSR radial velocity of Ha 3-29 is low, at -36 km s^{-1}. M1-11, with a high velocity of $+92$ km s^{-1}, is one of the very low excitation objects discussed above, and M1-13, 116 km s^{-1}, also appears to be of low excitation, although the λ4686 strength is not well defined.

TABLE 3

Comparison of Hβ Fluxes

Nebula	$-\log F$(Hβ) New	Other	Reference
NGC 6537 ...	11.40±0.03	11.80[a]	CDO
NGC 6543 ...	9.59±0.03	9.63	CD
NGC 6572 ...	9.83±0.01	9.78	CD
		9.80	PTP
		9.87	P71
NGC 6778 ...	11.18±0.04	11.28	CDO
NGC 6790 ...	10.86±0.01	10.77	OD 62
NGC 6879 ...	11.57±0.01	11.62	CDO
NGC 7008 ...	10.84±0.03	10.88	CDO
IC 2149.......	10.55±0.01	10.51	Li11
		10.55	CD
J 900	11.34±0.02	11.30	CD
M1-2	11.88±0.06	11.92	BAR
		11.99	AD
Me2-1	11.31±0.01	11.32	P71
		11.37	OD 63

[a] Excludes outer part of outer shell.

References.—AD: Adams 1975. BAR: Barker 1978. CD: Capriotti and Daub 1960. CDO: Collins, Daub, and O'Dell 1961. Li11: Liller 1955. OD 62: O'Dell 1962. OD 63: O'Dell 1963. P 71: Perek 1971.

TABLE 4

SURVEY OF NEBULAR PROPERTIES

				Adopted						
Nebula (1)	ϕ'' (2)	D (pc) (3)	R (pc) (4)	10^{-3} $\langle N_e \rangle$ (5)	10^{-4} T_e (6)	10^{-3} N_e (7)	He/H (8)	10^{-4} O/H (9)	N/O (10)	Notes (11)
NGC 6537	...	...	...	...	1.6	4[a]	0.24±0.10	1.6	1.8	1
	...	...	...	...	1.0	4	...	6.2	1.0	
NGC 6790	3.9	1300[b]	0.02	11	1.2	20[a]	0.13±0.01	3.2	0.16	
NGC 6879	...	...	...	...	1.0	...	...	...	...	
NGC 6881	1.6	2100[b]	0.02	20	1.5[a]	...	...	2.9	0.56	2
NGC 7008	4.4	780	0.17	0.4	1.1	20[a]	0.13±0.02	...	1.4±1.0	3
A 77............	21	1300	0.13	0.9	1.0	1.0	...	2.6	0.04	4
Ha3 29	7:	4300	≤0.15	0.6	1.5	1.0	≥0.10	...	...	5
K3 63	3.6	8500	0.15	0.6	1.0	1.0	...	...	>0.11	
M1 4...........	2.0	3000[b]	0.03	8.6	1.0	10[a]	...	7.7	...	
M1 7...........	4.5	5500	0.12	1.0	1.0	1.0	...	5.7	0.68	6
M1 11	<5	1700[b]	...	>60	1.0	60	...	4.3	...	
M1 13	5.0	2200[b]	0.05	3.5	1.0	4.0	...		0.08	
M1 79	16.5	2100	0.17	0.4	1.0	1.0	0.18±0.04	4.2	0.45	
M2 54	<5	4600[b]	...	>13	1.0	10	...	1.2	...	
M4 18	<5	4800[b]	...	>12	1.0	10	...	0.9	...	

NOTES.—(1) T_e from observations of central core; mean value for 40″ aperture probably between the two values adopted. (2) If $T_e = 10{,}000$ K, N/O drops to 0.31. (3) High value adopted for N_e is for high excitation blob, appropriate to 40″ data. (4) Low N/O may reflect underestimate of T_e. (5) ϕ estimated from Palomar Sky Survey. (6) High N/O may reflect underestimate of N_e.

[a] T_e and/or N_e adopted from measurements from one or more of the following sources: Aller and Czyzak private communication, Aller and Epps 1975, Aller, Kaler, and Czyzak 1976, Minkowski 1942, and for NGC 6881 unpublished Kitt Peak IRS data.

[b] Distance based on assumption of constant luminosity and Cudworth's 1974 absolute nebular magnitude, scaled to Cahn and Kaler 1971. Others based on usual constant mass assumption.

c) *Abundances*

An accurate abundance analysis is not possible from these data because the nebular conditions are not well known. In particular, the ionic abundances are quite sensitive to the frequently unknown but high densities. Nevertheless, we can use the data to survey the nebulae to look for objects of interest that can then be studied in greater detail. This survey is presented in Table 4.

The first step is to make the best possible estimates of electron densities from the physical radii of the nebulae. Column (2) of Table 4 gives the angular radii (ϕ) of the nebulae in seconds of arc from Perek and Kohoutek (1967). When a nebula exhibits two shells, the inner one is used. The letter "s" means that the nebula appears stellar and that ϕ has not been measured. Columns (3) and (4) then present the distances (D) and the radii (R) in pc. These are given under the assumptions of either constant mass or constant luminosity, whichever yields the lesser distance, in accord with Minkowski's (1964) suggestion. The constant-mass approach is appropriate to the optically thin nebulae, the other to the optically thick. The "optically thin" distances are from the system used by Cahn and Kaler (1971), and the "thick" distances employ the mean absolute magnitude of the nebulae determined by Cudworth (1974). The latter distances are scaled to the former and are indicated by footnote "a." The rms electron densities in column (5) are then calculated from the adopted mass of 0.18 $M_\odot$ and a filling factor of 0.65. This procedure will overestimate the rms densities of thick nebulae. Columns (6) and (7) then list the adopted T_e and N_e, either from measurements by others (see the references in Table 4), or from column (5). The T_e are usually set equal to 10,000 K, except for Ha 3-29, for which 15,000 K was adopted because of the high excitation.

Columns (8), (9), and (10) present He/H, O/H, and N/O derived from the observations and the procedures (and atomic constants) given by Kaler (1978*b*, 1979, 1980*a*). The N/O are not presented for the very low excitation nebulae, for which the ratio is particularly unreliable (see Kaler 1979). The most interesting object is NGC 6537, which appears to be very highly enriched in helium and nitrogen. He/H appears to be at least 0.14, and N/O of order unity and the nebula clearly qualifies as another example of Peimbert's (1978) type I. The object fits well at the end of the correlation between N/O and He/H defined by Kaler (1979). It is difficult to drive the N/O ratio down by very much. Under what are probably the least favorable circumstances ($T_e = 9700$ K, $N_e = 10^4$ cm^{-3}), N/O still equals 0.53.

NGC 6790, NGC 7008, and particularly M1-79 appear to show elevated He/H ratios. For NGC 6790, Aller and Czyzak (1979) measure a more reliable value of 0.10 from three He I lines, implying that the He^+/H^+ ratios for the other nebulae might be reduced accordingly. If so, He/H for NGC 7008 and M1-79 is within the error of 0.10, but that for NGC 6537 is still high, > 0.12.

The N/O ratio for NGC 7008 is nominally high, but so too is the error, because of the barely detected λ3727 [O II] line. It may be a rewarding object for further study. Some of the other nebulae show elevated N/O, and still some other objects appear to have quite low values. The variation may reflect uncertainties in the conditions and possible systematic errors in λ3727 [O II]. The O/H ratios fall within the normal range. M4-18 is oxygen deficient, confirming Sabbadin's (1980) earlier result.

In summary, this survey uncovers a number of interesting objects. Particular nebulae that should be examined in more detail are the very high excitation Ha 3-29 and K3-63, the very low excitation nebulae M1-11 and M2-54, the new Peimbert type I nebula NGC 6537, and probably NGC 7008.

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Note added in proof.—Observations of BV-1 = PK 119+0°1 were inadvertently omitted from Table 1. The data are $\log F(H\beta) = -12.70 \pm 0.03$; $\log F(H\alpha) = -11.76 \pm 0.08$; $I(\lambda 3727) = 68 \pm 15$; $I(\lambda 4686) = 65 \pm 26$; $I(\lambda 4959) = 433 \pm 37$; $I(\lambda 6563) = 835 \pm 182$; $I(\lambda 6584) = 995 \pm 126$ [where $I(\lambda) = 100 F(\lambda)/F(H\beta)$]; $N/\alpha = 1.19 \pm 0.27$; $c = 1.40 \pm 0.25$. The excitation is high for its high radial velocity of -94 km s^{-1}, which yields $v_{LSR} = -89$ km s^{-1}, which is marginally counter to the results of Kaler (1980*b*): see § II*b*. However, the error on $I(\lambda 4686)$ is high, and the error on v_r is unknown. For $T_e = 10{,}000$ K and low density, $N/O \approx 1$, which suggests that BV-1 may be another Peimbert type I nebula. The object merits examination in greater detail.

JAMES B. KALER: Astronomy Department, University of Illinois, 341 Astronomy Building, 1011 W. Springfield, Urbana, IL 61801