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LARGE HIGH-EXCITATION PLANETARY NEBULAE

JAMES B. KALER
Astronomy Department, University of Illinois
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ABSTRACT

Absolute total and relative emission-line fluxes are given for: (1) the two planetary nebulae, Abell 30 and 78, that exhibit zones of nearly pure helium near their cores, and (2) a list of other large, high-excitation nebulae that are outwardly similar to A30 and A78, and which are prime candidates for further investigation. All the nebulae are optically thin in the hydrogen Lyman continuum and have luminous central stars. They are morphologically similar, most being spherical shells.

Subject heading: nebulae: planetary

I. INTRODUCTION

The enrichment of helium in planetary nebulae is a common occurrence. The degree of enrichment is ordinarily under 50%, and the phenomenon is apparently caused by dredge-up processes that take place in the star before ejection of the nebula (Kaler, Iben, and Becker 1978). But a recent remarkable discovery by Hazard *et al.* (1980), which shows knots of nearly pure helium near the nucleus of Abell 30, indicates a different physical process, one whose study should further illuminate evolutionary and mass loss processes in prewhite dwarf stars.

Abell 30 is not unique. Jacoby and Ford (1981, private communication) find that Abell 78 also shows a zone of intense helium concentration. We do not yet know how common this phenomenon is. The purpose of this *Letter* is to present a list of likely candidates that wide-aperture photometry shows to be outwardly similar to A30 and A78. Total absolute and relative fluxes are presented for the two prototypes and for the objects in the candidate list.

II. THE OBSERVATIONS

The data presented here are a selected part of a large survey of planetary nebulae made with the 1 m reflector at the University of Illinois's Prairie Observatory. The observations were made with interference filters and a single-channel photometer (see Kaler 1976, 1980). The data are presented in Table 1.

The absolute fluxes in columns (4) and (5) were calibrated on Barker's (1978) measurements. Errors were calculated from the photon-counting statistics. The effect of temperature shifts on the blue filters was taken into account, but their effect on the red filters (and that of unknown radial velocities) is uncertain. An additional $\pm 10\%$ error has been added quadratically to that computed for Hα and [N II], based upon calibration with unpublished Reticon data.

Table 1A presents new data on 13 nebulae, with the prototype objects as the first two entries. The 11 other nebulae in Table 1A are those in the Illinois survey that best match the characteristics of A30 and A78: large radius, > 0.2 pc, high excitation, $I(\lambda4686) > 0.75\,I(\mathrm{H}\beta)$, and weak or absent [O II] or [N II] lines. All the nebulae in Table 1A, except Abell 75 (see remark No. 8), were observed with either a 4′ or 40″ diameter aperture, whichever was large enough to encompass the whole object. In addition, five nebulae with diameters $> 40''$ were observed with the 40″ aperture centered in their brightest regions to increase signal to noise. These are indicated by the aperture position in column (3) and by the remarks, which describe the region observed. Surface brightnesses of zones defined by the restricted apertures are given in columns (4) and (5), which should not be confused with the total fluxes (marked "T" in col. [3]). In some cases only an Hα flux was observed with the large aperture. For these the standard Hβ fluxes, enclosed in parentheses, were computed from the theoretical Hα/Hβ intensity ratio (Brocklehurst 1971) and the interstellar extinction measured with the restricted aperture.

In some instances, the necessary data were taken from preliminary reductions of Intensified Reticon Scanner (IRS) observations made at Kitt Peak with a 20″ aperture. These are indicated by the remarks, column (10). Table 1B contains three previously studied nebulae that also meet the criteria above. The $\lambda4686$ intensities observed by others, and a reference code, are given in columns (11) and (12); references are at the end of the table. The agreement between the two sets of $\lambda4686$ intensities is quite good, especially considering the stratification effects that may be present.

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TABLE 1

DATA FOR HIGH EXCITATION LARGE NEBULAE

			ergs cm^{-2} s^{-1}		$I(\mathrm{H}\beta) = 100$					OTHER	
NEBULA (1)	PEREK-KOHOUTEK 1967 (2)	APERTURE AND POSITION (3)	$-\log F(\mathrm{H}\beta)$ (4)	$-\log F(\mathrm{H}\alpha)$ (5)	λ4686 He II (6)	λ4959 [O II] (7)	λ6563[d] Hα (8)	λ6584 [N II] (9)	REMARKS (10)	λ4686 (11)	REF. (12)
A. New Data											
Abell 30	208+33°1	4′	12.19 ± 0.04	11.84 ± 0.09	152 ± 7	138 ± 27	230 ± 40	...	...	...	...
Abell 78	81−14°1	4′ T[a]	12.04 ± 0.04	...	187 ± 54	440 ± 150	...	...	...	158	KON
		40″ SW	13.00 ± 0.06[b]	12.53 ± 0.12[b]	135 ± 36	...	294 ± 100	...	1	...	...
NGC 1360	220 − 53°1	4′	10.2 ± 0.1	...	99 ± 2	244 ± 9	279	...	2	...	...
NGC 7094	66 − 28°1	4′	(11.77 ± 0.06)	11.25 ± 0.06	116	175	324	...	3	100	CLZ2
Abell 15	233 − 16°1	40″	12.47 ± 0.04	12.01 ± 0.05	128 ± 17	127 ± 29	294 ± 46	33 ± 18	...	...	...
Abell 20	214 + 7°1	4′ T	(12.04 ± 0.05)	11.59 ± 0.05	...	...	...	...	4	...	...
		40″ S	12.71 ± 0.02[b]	12.39 ± 0.06[b]	149 ± 13	150 ± 50	210 ± 31	72 ± 20	...	...	...
Abell 43	36 ± 17°1	4′ T	12.40 ± 0.07	11.82 ± 0.08	...	...	...	...	5	105	KON
		40″ C	12.94 ± 0.05[b]	12.36 ± 0.06[b]	94 ± 17	277 ± 56	382 ± 65	52 ± 16	...	...	...
Abell 51	17 − 10°1	4′ T	(11.80 ± 0.10)	11.35 ± 0.08	...	...	...	...	6	...	...
		40″ N	12.66 ± 0.06[b]	12.23 ± 0.08[b]	90 ± 23	200 ± 68	268 ± 64	...	...	...	...
Abell 72	59 − 18°1	4′ T	11.88 ± 0.07	11.56 ± 0.12	111 ± 18	183 ± 30	266 ± 33	...	...	150	KON
		40″ E	12.89 ± 0.02[b]	...	106 ± 11	...	...	...	7	...	...
Abell 75	101 + 8°1	40″	12.30 ± 0.07[c]	11.55 ± 0.04[c]	81 ± 12	473 ± 120	580 ± 120	...	8	...	...
K1-14	45 + 24°1	4′	(12.40 ± 0.10)	11.95 ± 0.10	160:	145:	260:	...	9	124	KON
K1-16	94 + 27°1	4′	12.00 ± 0.04	11.55 ± 0.14	126 ± 20	134 ± 60	250 ± 100	...	...	...	...
K3-27	61 + 8°1	40″	12.11 ± 0.03	11.69 ± 0.05	92 ± 10	198 ± 26	267 ± 35	...	...	100	KON
B. Published Data for Additional Nebulae											
NGC 246	118 − 74°1	...	10.53 ± 0.05	...	121 ± 14	285	...	...	10	150	HE
NGC 4361	294 + 43°1	...	10.56 ± 0.05	...	115 ± 5	...	...	...	11	118	TPP
Abell 36	47 + 42°1	...	10.86 ± 0.03	...	118 ± 10	100 ± 20	...	...	12	...	...

[a] T refers to total flux.

[b] Surface brightness for restricted aperture.

[c] Total flux.

[d] May be different from combination of columns (4) and (5) because of weighting effects.

REMARKS.—1. A78: Region SW, 20″S, 36″W of central star. 2. NGC 1360: Hβ flux from Kaler 1978; λ4686, λ4959 for central 4′; Hα from IRS. 3. NGC 7094: Hβ flux inferred from measured Hα flux; λ4686, λ4959, λ6563 from IRS, 34″N of central star. 4. A20: Hβ flux inferred from measured Hα flux; region S in ring, 20″S of central star. 5. A43: See Kaler and Hartkopf 1981; region C centered on object. 6. A51; Hβ flux inferred from measured Hα flux; region N in ring, 10″N of central star. 7. A72: Region E in east arc, 50″E of central star. 8. A75: Observed with 40″ aperture only, at center; $F(\mathrm{H}\beta)$ and $F(\mathrm{H}\alpha)$ are approximate total fluxes found by multiplying observed fluxes by 2.0 = nebular area/aperture area. 9. Kl-14: Hβ flux inferred from measured Hα flux; λ4686, λ4959, λ6563 from IRS, and are approximate because of spectral contamination from companion to central star (see text). 10. NGC 246: Kaler 1976, 1978; Hα, λ4959 from IRS, 1′N of central star. 11. NGC 4361: Kaler 1976. 12. A36: Kaler 1976.

REFERENCES.—CLZ2: Chopinet and Lortet-Zuckerman 1976; HE: Heap 1975; KON: Kondratyeva 1979; TPP: Torres-Peimbert and Peimbert 1977.

III. DISCUSSION

a) *Basic Data, Extinctions, and Errors*

The 14 candidate nebulae given in Table 1 are outwardly similar to the two nebulae that contain high helium zones, and they should consequently be examined in detail. NGC 4361 has already been studied a number of times, and no such zones have been found (Heap, Aller, and Czyzak 1969; Torres-Peimbert and Peimbert 1977; Barker 1978). NGC 246 has also received some attention (Minkowski 1942; Heap 1975; Kaler 1976).

The data in Table 1 are used to calculate nebular distances, radii, and the Zanstra temperatures and luminosities of their central stars, all of which are given in Table 2. The necessary input parameters, the angular radius, ϕ, and the apparent B and V magnitudes of the central star, are given in columns (2), (3), and (4) (see col. [13] for references). The magnitude for K3-27 is derived from continuum photometry at Illinois (see Kaler 1976 for procedure). The central star of K1-14 is the fainter of a partially resolved binary (Fig. 1, Pl. L2), as confirmed by *IUE* photometry (Kaler and Feibelman, 1981 unpublished). The magnitude used here is derived

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TABLE 2

PARAMETERS FOR HIGH EXCITATION NEBULAE

Nebula (1)	ϕ'' (2)	B (3)	V (4)	c (Hβ) (5)	D (kpc) (6)	r (pc) (7)	10^3 T_z (H) (8)	10^3 T_z (He II) (9)	L_z (H) (10)	L_z (He II) (11)	Morph. (12)	Ref. (13)
Abell 30	64	14.23	14.30	0.0	1.7	0.53	25	73	29	470	1	A
Abell 78	54	13.04	13.25	0.04 ± 0.42	1.7	0.45	23	70	69	1240	2	A
NGC 246......	125	11.58	11.95	0.0	0.53	0.32	33	85	56	730	2	Ko, SL
NGC 1360	198	11.00	11.34	0.0	0.34	0.33	35	86	47	530	...	Ko, K
NGC 4361	58	12.74	13.04	0.04	0.85	0.24	42	97	97	1030	3	Ko, SL
NGC 7094	48	13.36	13.61	0.16	1.6	0.36	26	73	78	1140	2	Ko, SL
A15...........	17	15.41	15.72	0.04 ± 0.18	4.2	0.35	28	76	72	1090	1	A
A20...........	34	16.29	16.56	0.0	2.4	0.38	40	99	24	290	1	A
A36...........	196	11.18	11.51	0.0	0.47	0.45	27	74	35	540	2	A
A43...........	40	14.53	14.71	0.38 ± 0.22	2.1	0.41	24	68	73	1020	1	A
A51...........	34	15.30	15.42	0.00 ± 0.19	2.1	0.34	36	87	40	420	1	A
A72...........	64	15.79	16.12	0.00 ± 0.06	1.5	0.46	49	106	25	220	2	A
A75...........	29	17.20	17.20	0.92 ± 0.27	1.9	0.27	41	93	69	660	1	A
K1-14	24	15.7:	...	0.0	3.4	0.39	30	83	42	630	1	Ko, K
K1-16	58	14.74	15.09	0.00 ± 0.26	1.6	0.47	30	81	24	320	2	Ko, SL
K3-27	8	18.1:	...	0.00 ± 0.07	5.7	0.23	61	117	83	510	...	Ko, K

REFERENCES.—A: ϕ, B, V from Abell 1966. K: B and V for NGC 1360 from Kaler 1978; for K1-14 estimated from Palomar Sky Survey (see text); or K3-27 from Prairie photoelectric data. Ko: ϕ from Kohoutek, quoted in Perek and Kohoutek 1967. SL: B and V from Shao and Liller, private communication.

from the image diameter and King and Raff's (1977) calibration.

The logarithmic interstellar extinction constants, c, are given in column (5). These are derived from the Hα/Hβ ratios of Table 1, the theoretical ratio of 2.86 (Brocklehurst 1971), and Whitford's (1958) reddening function. Except for A30 (see Greenstein 1981) and possibly A51 and A72, the values (with errors) are consistent with stellar $B - V$. Occasional low Hα/Hβ ratios demonstrate the presence of some systematic error, which can be caused by the inclusion of field stars in the 4′ aperture and by unknown radial velocities which can affect the simultaneous solution of the [N II] and Hα intensities. To allow for these systematic effects, an additional error in log F(Hα) for the 4′ aperture might typically be ± 0.03, and perhaps ± 0.02 for log F(Hβ), to be added quadratically to the errors in Table 1.

b) Distances, Radii, and Zanstra Temperatures and Luminosities

Columns (6) and (7) give the distances and radii of the nebulae calculated on the system used by Cahn and Kaler (1971), with the data given in Tables 1 and 2. These depend on the assumption that all the nebulae have the same ionized mass, namely that implied by Seaton's (1968) scale. The uniformity of the nebulae, indicated by the common selection criteria and by the analysis below, suggests that at least the relative distances and radii are correct.

Blackbody Zanstra temperatures (in units of 10^3 K) are given in columns (8) and (9), and the companion luminosities (in $L/L_\odot$) are shown in columns (10) and (11). They are calculated both from Hβ [T_z(H), L_z(H)] and λ4686 He II [T_z(He II), L_z(He II)], using the procedure of Harman and Seaton (1966) and the distances in column (6). In all cases but one, the nebulae seem to be simple shells (see below), and the fractional solid angle subtended by the nebula at the star, ξ, is set to unity. For A72 (see below and Fig. 1), $\xi = 0.4$ is adopted.

In order that the Zanstra temperature be a realistic evaluation and that T_z(H) = T_z(He II), three conditions must be met: the star must indeed be a blackbody, the nebula must be optically thick to ionizing radiation, and there must be no significant internal dust. We see from Table 2 that in all cases, T_z(H) $\ll$ T_z(He II). The work of Pottasch *et al.* (1978) suggests that the blackbody assumption for this class of stars is fairly safe. Both internal dust (Helfer *et al.* 1981) and low optical depth will cause T_z(H) to be underestimated in the direction seen. Dust is certainly present in A30 (Greenstein 1981), but most of the other stars do not show a similar anomalous color excess (see § III*a*). The high λ4686 strength shows that helium is largely doubly ionized. If we assume the canonical value of He/H = 0.10, and T_e = 16,000 K (a reasonable value for these high-excitation objects), then helium is fully doubly ionized for any nebula with I(λ4686) > 115 (see Brocklehurst 1971), which is the case for over half the objects in the list. There would thus appear to be little, if any, He^+ shell, and consequently there should be no neutral hydrogen shell. The nebulae are thus mass-bounded and optically thin, consistent with the low T_z(H), and many are almost certainly optically thin in the He^+ Lyman continuum as well. T_z(He II) should probably be

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considered a lower limit for all the stars considered. Whatever the true physical situation, it is clear that the stars and nebulae all show a strong similarity to one another. The luminosities show the same apparent optical depth effects as do the temperatures. They are generally high: the L_z(He II) range from 220 to 1240 $L_\odot$, and again these may well be underestimates.

c) *Morphology*

Figure 1 (Plate L2) shows photographs of the 14 nebulae with visible structure on the Palomar Sky Survey. At the low resolution of the Sky Survey, we see that the nebulae of Figure 1 are characterized by simplicity of form. With some exceptions, they are relatively smooth circular rings or, put another way, limb brightened disks. NGC 1360 is not limb brightened and seems to be a filled ellipsoid similar to K1-16. A72 seems to be different, exhibiting two separate arcs. Other than that possibility, there are no complex or obviously bilobed structures typified by Greig's (1971) class *B* or Khromov and Kohoutek's (1968) class 3. Only NGC 4361, not shown, is called class 3 by these latter authors (Table 2, col. [12]).

The majority of the nebulae are simple rings. There seems to be little doubt that there is a strong relation here between nebular morphology and nebular excitation, or between morphology and the nature of the central star.

d) *Summary*

The nebulae presented in the tables exhibit strong similarities to one another and to the prototypical objects A30 and A78, which contain zones of intense helium concentration. They are characterized by: (1) high excitation, strong λ4686, (2) weak or absent [N II] and [O II], (3) large radius, > 0.2 pc, (4) low Lyman optical depth, (5) luminous central stars, and (6) similar ringlike morphology. The first three points are selection criteria, but the last three are the results of the analysis.

Note that A30 and A78 are frequently extreme objects: they have the strongest λ4686 intensity and are among the nebulae with the largest diameters. Their central stars have generally the lowest Zanstra temperatures, and A78 has the highest calculated luminosity. Perhaps these extremities are connected with the high helium zones. Nevertheless, the other objects on the list should be examined in detail.

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

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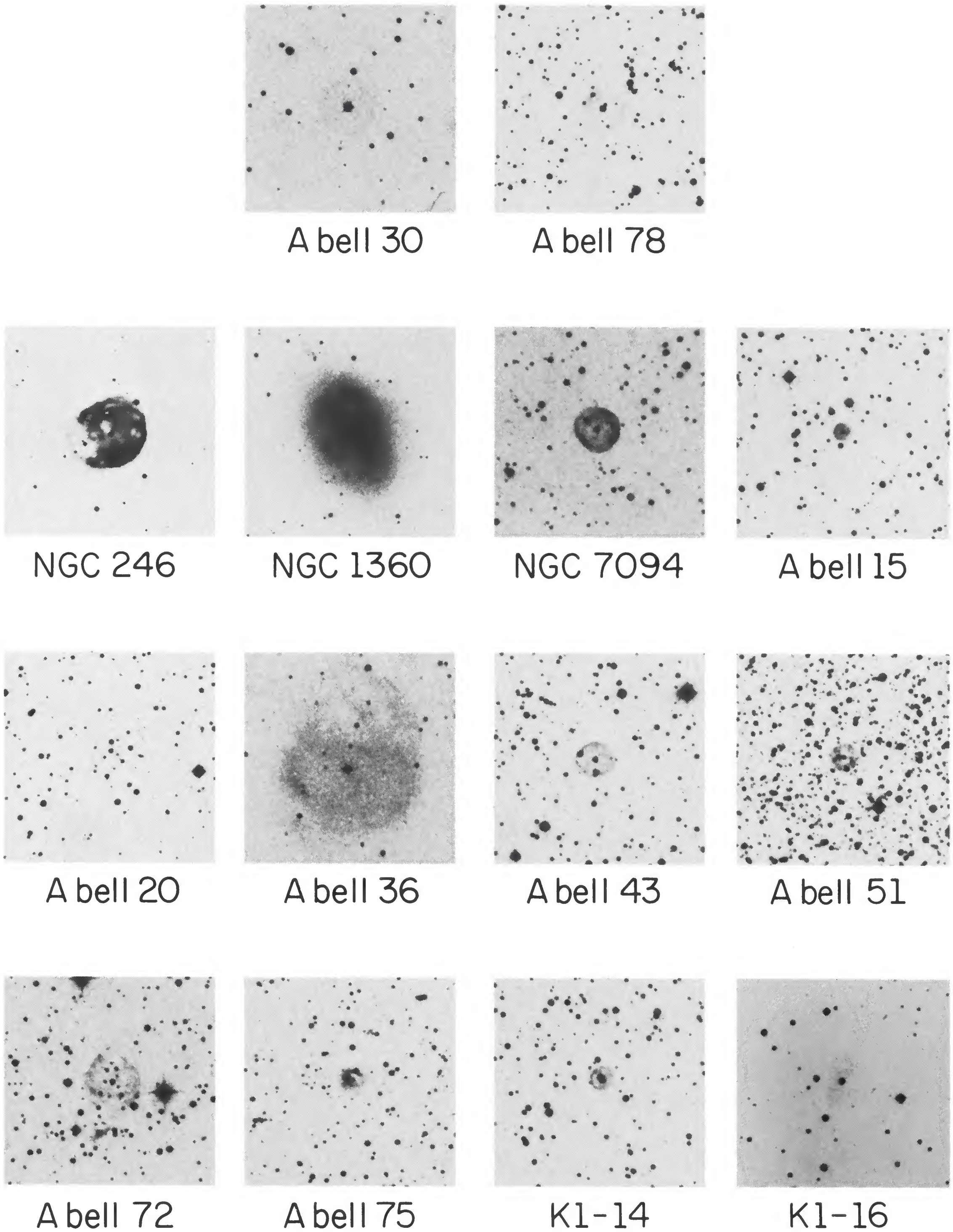

FIG. 1.—Palomar Sky Survey prints of large, high-excitation planetary nebulae. All are from the red prints, except Abell 30, 72, and K1-16, which are better seen on the blue prints. All are enlarged by 6, except NGC 246 and NGC 1360, which are enlarged by 4. North is to the top, east to the left. Copyright by the National Geographic Society, Palomar Observatory Sky Survey. Reproduced by permission.

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