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SPECTROPHOTOMETRY OF THE COMPACT PLANETARY NEBULAE NGC 6879 AND NGC 6881*

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ABSTRACT

We have observed the spectra of the two compact planetary nebulae NGC 6879 and NGC 6881 between λ3727 and λ6731 with both the IRS and the IIDS at Kitt Peak and calculate extinction constants, electron densities and temperatures, and a wide variety of ionic abundances. Both nebulae have high densities. NGC 6881, the more highly excited of the two, is significantly enriched in nitrogen and possibly exhibits some elevation in helium.

Key words: planetary nebulae–abundances–nebular parameters

I. The Observations

In the course of a spectroscopic survey of large planetary nebulae begun with the No. 1 0.9-meter telescope and the Intensified Reticon Scanner (IRS) at Kitt Peak, the results of which will be published later, we observed two angularly small objects: NGC 6879 (57−8°1 in the Perek and Kohoutek 1967 catalog) and NGC 6881 (74+2°1). Both have angular diameters of about 5 arc seconds. Neither had been well observed, and we believed they would provide an interesting comparative study. The IRS observations, made on 1980 October 17 UT, cover the spectrum from [O II] λ3727 to [S II] λ6731. In order to check the data and to provide better analysis, we followed up with observations made on 1985 June 16 with the Kitt Peak 2.1-meter telescope and the Intensified Image Dissector Scanner (IIDS), which cover from He II λ4686 again to [S II] λ6731. We therefore have the ability not only to examine two apparently young high-density nebulae but also to compare the observational results acquired from two quite different systems.

Our observations were made with aperture sizes of 20 and 8 arc seconds for the IRS and IIDS, respectively, so that we include all of the nebular light. We calibrated the data with standard stars from the KPNO Standard Star Manual (BD +28°4211 and Feige 15 for the IRS and BD +25°3941 and Feige 92 for the IIDS: see Oke 1974 and Stone 1977), and reduced them with standard Kitt Peak software. The IIDS standards were reduced along with the nebulae and the results checked against the published flux distributions to ensure accuracy. Line fluxes were derived at Illinois with the sophisticated Gaussian fitting program SPEC, developed by Illinois graduate students, which allows for accurate deconvolution of blends. We can force blended lines such as Hγ and [O III] λ4363; [S II] λ6717, λ6731; and the [O I], [S III] pair to have equal widths. In the special case of the [N II]-Hα triple blend, we can in addition require that λ6548 be in the theoretical ratio to λ6584 in order to remove it from Hα, in which it may be lost. See Kaler (1985) for further details.

Finally, we converted all the line fluxes into relative observed intensities, $I_o(\lambda)$, on the scale $I(\mathrm{H}\beta) = 100$. For lines longward of λ4686 we may have two observations. Since the IIDS data were acquired at higher resolution and have superior signal-to-noise levels we give them double weight. We derived the [S II] line intensities by applying the weighted average ratio of these blended lines to the weighted average sum.

We present our results in Table I, where the first three columns, respectively, give the wavelengths and identifications of the observed emission lines and the values of the interstellar reddening function from Whitford (1958), cast into its standard nebular mode, in order to correct, or deredden, line fluxes that are given relative to Hβ. The two columns labeled I_o give the final observed relative line intensities on the scale $I(\mathrm{H}\beta) = 100$ for NGC 6879 and NGC 6881, respectively. In the columns labeled I_c we present the dereddened relative intensities, where $\log I_c = \log I_o + cf_\lambda$ and c, the adopted reddening constant (the logarithmic extinction at Hβ), is given in a footnote to Table I and is discussed in Section II. We derived these constants from the accurately determined Hα intensities,

*Work done at KPNO/NOAO, operated by AURA, Inc., under contract with the NSF.

TABLE I

Line Strengths for NGC 6879 and NGC 6881

λ	I D	f_λ	NGC 6879 I_o	NGC 6879 I_c*	NGC 6881 I_o	NGC 6881 I_c*
3727	[O II]	.30	≤11:	≤17:	32	131
3868	[Ne III]	.26	57	82	46	156
3889	H8+He I	.25	17	24	10	32
3967+70	[Ne III]+H7	.235	27	37	...	...
4068+76	[S II]	.205	6:	8:	...	...
4101	Hδ	.195	23	30	22*	55†
4340	Hγ	.135	43	52	33*	62†
4363	[O III]	.13	10	12	19	35
4471	He I	.105	7	8	...	...
4640+47	N III+C III	.06	3:	3:	...	...
4658	C IV	.05	..	..	7	9
4686	He II	.045	1.2	1.3	32±1	40
4711+13	[Ar IV]+He I	.04	2.8	3.0	4.6	5.6
4724	[Ne IV]	.04	..	..	1.0:	1.2
4740	[Ar IV]	.04	2.1	2.2	1.2±0.3	1.4
4861	Hβ	.00	100	100	100	100
4921	He I	-.01	1.4	1.4	...	...
4959	[O III]	-.02	387±4	376	675±19	614
5007	[O III]	-.035	1243±4	1184	2283±37	1937
5200	[N I]	-.075	..	..	1.8	1.3
5411	He II	-.12	..	..	6.3±0.8	3.6
5517	[Cl III]	-.14	0.5:	0.4:	1.1	0.6
5537	[Cl III]	-.145	..	..	1.4	0.7
5577	[O I]	-.16	..	..	1.8	0.8
5754	[N II]	-.19	..	..	15±1.5	6.1
5801	C IV	-.20	..	..	0.7:	0.3
5876	He I	-.215	19.1±1	14.2	35±3	12.7
6300	[O I]	-.29	1.5	1.0	49±5	12.5
6312	[S III]	-.29	1.7	1.1	15.2±1.4	3.9
6363	[O I]	-.30	..	..	17.6±1.7	4.3
6435	[Ar V]	-.31	..	..	4.1	1.0
6548	[N II]	-.33	..	..	274	58
6563	Hα	-.332	450±1	285	1357±3	285
6584	[N II]	-.335	257±0.6	16.2	965±43	200
6678	He I	-.35	5.1	3.1	12.7±1.1	2.5
6717	[S II]	-.35	0.5:	0.3:	21.5±3.6	4.2
6731	[S II]	-.355	2.1:	1.3	42.6±4	8.0

*c = 0.60 and 2.04 for NGC 6879 and NGC 6881, respectively.

†Low signal-to-noise level is apparently responsible for large errors, 30% at the Hγ line strength and 100% at the Hδ strength. These errors should be applied to the three lines shortward of Hδ. The ratio of I(λ4363)/I(Hγ) should be much better determined, which results in I_c(λ4363) = 26, I_o(λ4363) = 14. The corrected value is used in the calculation of electron temperature.

where we assume the true dereddened value to be 285 (Brocklehurst 1971).

Errors are quoted in Table I for I_o for lines that we observed with both systems. These are simply the differences between the weighted means and the IIDS intensities and are meant to indicate the spread between the two sets of results. The agreement is excellent for the strong lines but not so good for the weaker ones observed in the spectrum of NGC 6881. For this object the IRS intensities are significantly higher, by about 30% for He I λ5876 and [O I] λ6300, and nearly a factor of two bigger for the weak (and marginal) [Ar V] λ6435. Part of the problem might be due to some weather problems experienced during the IRS run, and some may be caused by incomplete sky cancellation with the IRS as a result of a weak but visually observed auroral display. Nevertheless, the averaging produces line intensities that provide satisfactory results. The weaker lines observed longward of λ4686, those without errors, were all observed with the IIDS. We have no means of determining the likely errors except to say that the weakest are just above the noise background and are probably subject to a 50% or greater error.

Shortward of λ4686 we have only one data set available so that errors again are not available. However, we can make some judgments on the basis of the corrected intensities of the Hγ and Hδ lines, which from Brocklehurst (1971) should be 46.9 and 26.0, respectively (we use Hα exclusively in the calculation of reddening because of its demonstrable accuracy: see the next section). The results for NGC 6879 are reasonably satisfactory, with Hγ and Hδ too high, but only by about 10%. The problem of violet systematic error is considerably worse for NGC 6881, which is more heavily reddened and exhibits a poorer signal-to-noise figure. Here, the error is 30% at Hγ and 100% for the weaker Hδ line, which provides reliability estimates for other lines in this wavelength region of similar strength. It is probably proper to decrease the λ4363 [O III] strength by 30% (i.e., we apply the λ4363-Hγ ratio to the theoretical intensity). The λ3727 line might be affected by between 30% and 100% depending upon whether the error is related to intensity or wavelength. We will discuss this matter further in the analysis below.

II. Analysis

These two nebulae have recently been observed by Aller and Keyes (1987, hereafter AK). The agreement is good and rather illuminating. Our Hα observations for NGC 6879 agree with theirs to 3%; we are 10% high for NGC 6881, but our IIDS and IRS data agree beautifully with one another in spite of very different degrees of blending with the strong [N II] lines. A very noticeable trend is that our higher excitation lines (He II, [Ne IV], [Ar IV], [Ar V]) have lower intensities than theirs, and our lower excitation lines (He I, [O I], [S II]) are brighter. The difference is rather obviously due to ionic stratification. They state that their aperture settings were the same as used by Aller and Czyzak (1979), which would be 2 × 2 arc seconds. Presumably, AK sampled the central regions of these 5-arc-second diameter nebulae, which would emphasize the higher excitation regions closer to the nuclei. Our data, on the other hand, are global in character, i.e., they are appropriate to the entire objects and will include the effects of lower excitation regions. Our new data agree reasonably well with the global filter measurements made by Kaler (1983). The largest discrepancy is that the He II λ4686 line of NGC 6879 is considerably weaker than reported earlier.

It is also interesting to compare the various measurements made of extinction. From the Hα to Hβ ratio, we find 0.60 and 2.04, respectively, for NGC 6879 and NGC 6881 as compared to Kaler's (1983) values of 0.42 and 1.77, and AK's determinations of 0.61 and 2.0. Clearly, the higher values seem correct and may indicate some systematic trend in the Hα filter data (which are derived by means of a difficult deconvolution of Hα and λ6584 filter observations). More interesting is a comparison with the extinctions derived from the Hβ and radio fluxes. For NGC 6879 we use Milne and Aller's (1982) 14.7 GHz flux of 0.042 ± 0.05 and adopt $\log F(\mathrm{H}\beta) = -11.59 \pm 0.02$ from Kaler (1983) and Collins, Daub, and O'Dell (1961); for NGC 6881 we find an effective 5 GHz flux of 0.162 ± 0.015 Jy from the multifrequency measurements by Higgs (1971) and use Kaler's (1983) $\log F(\mathrm{H}\beta) = -12.26 \pm 0.03$. From these values, the formula used by Cahn and Kaler (1971), and the helium abundances and [O III] electron temperatures in Table II below, we calculate radio/Hβ extinctions of 0.77 ± 0.05 and 1.89 ± 0.06 for NGC 6879 and NGC 6881, respectively. We commonly find that c(radio/Hβ) is higher than c(Hα/Hβ): see Gutiérrez-Moreno, Moreno, and Cortés (1985) and Kaler and Lutz (1985). That is the case for NGC 6879, but not for NGC 6881, although we can get near equality by considering the errors.

Next, we consider the analysis of the spectra for the derivation of nebular parameters and ionic compositions. All analysis is made with the Illinois abundance program ABUNDR, described by Kaler (1985). The results are presented in Table II. First, let us examine NGC 6879. For this object we have a well-determined intensity for [O III] λ4363 so that an accurate [O III] electron temperature can be assessed. However, we lack an observation of the weak [N II] λ5754 auroral line and consequently cannot calculate a temperature appropriate to low-excitation ions. We do not wish to adopt any intensities from AK because stratification makes our data mutually incompatible and, besides, an independent analysis is more meaningful. We can make an estimate, however, from the temperature study by Kaler (1986), from which we find that for the measured He II λ4686 line strength T_e [N II]/T_e [O III] = 1.07, with a reasonable range in the ratio of from 0.95 to 1.25.

In order to calculate T_e [O III], as well as the various ionic abundances, we need a good assessment of electron density, which is not readily available. The [S II] doublet line strengths are very uncertain and yield only a high, but indeterminable, density. The [Ar IV] lines are not strong enough, nor is the density high enough, for them to be useful. Consequently, we have to make use of assumptions and estimates. A very high density, say 10^5 cm^{-3}, which is still below that implied by our poor [S II] data, yields an $\mathrm{N}^+/\mathrm{O}^+$ ratio (which we equate with N/O, as usual) that is well below solar. It is perhaps not unreasonable to assume simply that N/O *is* solar, especially in view of the normal-to-low He/H ratio (see below). We therefore calculate the density needed to drive N/O to 0.12 (Ross and Aller 1976) for a given ratio of T_e [O III]/T_e [N II] and a self-consistent calculated value of T_e [O III], which is only minimally dependent upon N_e. We find that N_e (adopted) is $6 \pm 2 \times 10^4\ \mathrm{cm}^{-3}$, where the error reflects the allowed range in T_e [N II]/T_e [O III]; the error in T_e [O III] (see Table II) reflects the small systematic error at Hγ and that in N_e, and the error in T_e [N II] the range in the

TABLE II

Parameters and Compositions

	NGC 6879	NGC 6881
T_e [O III]	10800 ± 500	12900 ± 1500 K
T_e [N II]	11600 ± 1300*	12500 ± 1300 K
N_e [Cl III]	...	5.0×10^3 cm^{-3}
N_e [S II]	...	9.5×10^3 cm^{-3}
N_e (adopt)	$6±2 \times 10^4$ cm^{-3}*	...
He^+/H^+	0.091 ± 0.007	0.082 ± 0.013
He^{2+}/H^+	0.001	0.035 ± .001
N°/H^+	...	1.42×10^{-6}
N^+/H^+	3.8×10^{-6}	2.44×10^{-5}
O°/H^+	1.4×10^{-6}	1.2×10^{-5}
O^+/H^+	3.1×10^{-5}	4.9×10^{-5}
O^{2+}/H^+	3.7×10^{-4}	3.5×10^{-4}
Ne^{2+}/H^+	6.2×10^{-5}	6.5×10^{-5}
Ne^{3+}/H^+	...	7.9×10^{-5}
S^+/H^+	3.0×10^{-7}	4.7×10^{-7}
S^{2+}/H^+	1.8×10^{-6}	3.5×10^{-6}
Cl^{2+}/H^+	1.9×10^{-7}	4.8×10^{-8}
Ar^{3+}/H^+	6.3×10^{-7}	2.9×10^{-7}
He/H	0.092 ± 0.007	0.117 ± 0.013
O/H	$4.1 \pm 0.6 \times 10^{-4}$	$5.8 \pm 1.5 \times 10^{-4}$
N/O	0.12†	$0.50^{+0.27}_{-0.3}$

*T_e[N II], N_e, and limits estimated from T_e[O III], I(He II λ4686), and the assumption that N/O is solar; see the text.

†Assumed to be solar.

temperature ratio and the error in T_e [O III]. Interestingly, this density is just that listed by AK (although their [S II] ratio yields $N_e = 6 \times 10^3$ cm^{-3}, which would drive our N/O upward to around 0.40, still not all that high). If we adopt Withbroe's (1976) higher solar value of N/O = 0.16, then N_e drops to $4 \pm 2 \times 10^4$, and T_e [O III] and T_e [N II] rise to 11,100 K and 11,900 K, respectively.

The calculations of the parameters for NGC 6881 are much more straightforward since we have measurements of both the [O III] and [N II] auroral lines, a fairly good determination of the [S II] ratio, and even the [Cl III] λ5517, λ5537 ratio. [Ar IV] again gives a nonsensical result, partly because of unresolved blends, and is ignored. The densities from the two good line ratios yield reasonably consistent results. The difference might reflect a density gradient but more likely is the result of errors in the line intensities. This time we do not agree with AK who list a much higher density in their Table 1, although now our [S II] densities agree better than before.

For our calculations of the [O III] and [N II] temperatures we use the [Cl III] and [S II] densities, respectively. We also scale the λ4363 [O III] intensity downward according to the systematic error for Hγ as discussed above (and in a footnote to Table I), which yields I(λ4363) = 14. The error given for T_e [O III] reflects the size of the systematic error at Hγ (i.e., T_e [O III] is 1500 K higher if the intensity in Table I is used), and the error stated for T_e [N II] reflects both the errors in Table I and the uncertainty in the density (i.e., T_e [N II] was also calculated for the [Cl III] density and the result included in the error).

The ionic abundances are calculated with these parameters and are listed in the central portion of Table II. As usual, calculations for low ionization species (O°, O^+, N°, N^+, S^+) use T_e [N II]; all others use T_e [O III]. The

He^+/H^+ ratios are the means of those derived from He I λ5876 and λ6678, where the error reflects the difference of either from the mean. The λ5876 intensity is corrected for self-absorption effects according to the rule developed by Kaler (1978*b*). For NGC 6879 the two measurements of I(λ5876) are in excellent agreement; in addition, that line and λ6678 yield quite similar values, so that we can have considerable confidence in the final result. The λ4471 line, derived from IRS measurements alone, gives an anomalously high value for this nebula and is rejected out of hand. For NGC 6881 we use the λ3727 intensity given in Table I with no correction.

Total abundances are possible only for helium, oxygen, and nitrogen, which we give in the lower part of Table II. The He/H ratios are simply the sums of He^+/H^+ and He^{2+}/H^+; the excitations are too high for neutral helium to be a problem (Kaler 1978*b*). NGC 6881 seems to have the higher abundance of helium, and might even be somewhat enriched, but given the errors, the difference is marginal at best. The values (and their difference) agree with those found in AK.

The O/H ratios are the sums of O^+/H^+ and O^{2+}/H^+ (neutral oxygen is ignored as some of it is likely to exist in neutral hydrogen regions), with small corrections for O^{3+} according to the standard rule given by Seaton (1968):

$$O/H = [(O^+ + O^{2+})/H^+]\,[1 + He^{2+}/He^+] \ . \quad (1)$$

The errors reflect errors in T_e and N_e, and in the case of NGC 6881, the magnitude of an assumed 30% error in I(λ3727) based on that determined for Hγ. The results fall within the range given for the galactic disk by Kaler (1980). Given the errors, the difference between the two objects is not significant but again the results (and the direction of the difference) agree with AK. If the density of NGC 6879 is as low as 6×10^3, as suggested by AK's [S II] measurements, then O/H drops to 2.8×10^{-4}, which given its Milky Way position renders it anomalously oxygen deficient.

NGC 6879 has most of its oxygen in O^{2+}, and NGC 6881 has well over half in that ion. At an excitation level where oxygen is dominantly doubly ionized, so is neon (Kaler 1978*a*), so that Ne^{2+}/O^{2+} gives an indication of Ne/O. The ratios are 0.17 and 0.19, respectively, consistent with the standard value of 0.225 found in that paper.

As discussed above, N/O for NGC 6879 is indeterminate because of our lack of knowledge of density. It is likely solar, or close to it, and almost certainly less than 0.4. Interestingly, our adopted value is very close to that listed by AK. There is good evidence, however, that N/O (set, as before, equal to N^+/O^+) for NGC 6881 is enriched by roughly a factor of four above solar. The errors reflect those in N_e (i.e., the range between N_e [Cl III] and N_e [S II]) and T_e [N II], as well as the possibility that [O II] λ3727 is 30% weaker than given in Table I (consistent with the error in Hγ), and encompass AK's value. The ratio could be even higher (the order of unity) if we adopt a larger error for λ3727, that associated with Hδ. The He/H and N/O ratios for NGC 6881, if taken at face value and applied to the third dredge-up calculations by Becker and Iben (1980) for the case of C → N conversion in the stellar envelope at one-half the full rate (see their Fig. 9), suggest a progenitor mass of about 3 $\mathfrak{M}_\odot$.

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REFERENCES

Aller, L. H., and Czyzak, S. J. 1979, *Ap. Space Sci.*, **62**, 397.
Aller, L. H., and Keyes, C. D. 1987, preprint (AK).
Becker, S. A., and Iben, I., Jr. 1980, *Ap. J.*, **237**, 111.
Brocklehurst, M. 1971, *M.N.R. A. S.*, **153**, 471.
Cahn, J. H., and Kaler, J. B. 1971, *Ap. J. Suppl.*, **22**, 319.
Collins, G. W. II, Daub, C. T., and O'Dell, C. R. 1961, *Ap. J.*, **133**, 471.
Gutiérrez-Moreno, A., Moreno, H., and Cortés, G. 1985, *Pub. A.S.P.*, **97**, 397.
Higgs, L. A. 1971, *M.N.R.A.S.*, **153**, 315.
Kaler, J. B. 1978*a*, *Ap. J.*, **225**, 527.
———. 1978*b*, *Ap. J.*, **226**, 947.
———. 1980, *Ap. J.*, **239**, 78.
———. 1983, *Ap. J.*, **264**, 594.
———. 1985, *Ap. J.*, **290**, 531.
———. 1986, *Ap. J.*, **308**, 322.
Kaler, J. B., and Lutz, J. H. 1985, *Pub. A.S.P.*, **97**, 700.
Milne, D. K., and Aller, L. H. 1982, *Astr. Ap. Suppl.*, **50**, 209.
Oke, J. B. 1974, *Ap. J. Suppl.*, **27**, 21.
Perek, L., and Kohoutek, L. 1967, *Catalogue of Galactic Planetary Nebulae* (Prague: Czechoslovakia Academy of Science).
Ross, J. E., and Aller, L. H. 1976, *Science*, **191**, 1223.
Seaton, M. J. 1968, *M.N.R.A.S.*, **139**, 129.
Stone, R. P. S. 1977, *Ap. J.*, **218**, 767.
Whitford, A. E. 1958, *A.J.*, **63**, 201.
Withbroe, G. 1976, Special Session on Heavy Particles from the Sun, Ann. Mtg. Am. Geophys. Union.

Note added in proof. L. H. Aller informs us of a typographical error in the density column heading in the AK preprint. Their value of N_e for NGC 6879 should be 6×10^3 cm^{-3}, notably below ours, and for NGC 6881 it should be 10^4 cm^{-3}, which places it in reasonable agreement with that of Table II.