O VI AND He II EMISSION LINES IN THE SPECTRA OF QUASARS

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(Received 3 June, 1976)

Abstract. The plasma-laser star model for quasars, which is based on the hypotheses that there is no red shift in the spectra of quasars and that the strength of the emission lines is due to laser action, is further developed. Continuity is shown to exist between the spectra of O VI sequence planetary nuclei, Sanduleak stars, and 10 quasars. The O VI $\lambda\lambda3811$, 3834 and He II $\lambda4686$ emission lines in the spectra of these 10 quasars are identified. Candidate identifications for other quasar lines are also suggested. Making use of the similarity between the spectra of O VI sequence planetary nuclei and those of the 10 quasars, absolute magnitudes, temperatures, and masses of these quasars are estimated. The distribution of quasars in galactic coordinates is also discussed. Three predictions are made.

1. Introduction

The conventional interpretation of the spectral lines observed in quasars is based on the red-shift hypothesis. We have proposed an alternative explanation (Varshni, 1973, 1974a, b, 1975a) which is based on sound physical principles and is free of any basic difficulty. The essential ingredients of the new explanation are: (1) There is no red shift, and (2) The strength of the emission lines is due to laser action (more specifically, due to amplified spontaneous emission). The term 'no red shift' here, of course, refers to the large red shifts claimed to occur in the spectra of quasars. Very small red shifts, $z < 10^{-3}$, the type encountered in galactic stars, could certainly be present in the spectra of quasars. Further, it is assumed that the chemical composition of the emission region of quasars is approximately the same as that of normal stellar atmospheres. This assumption is merely a first approximation and a convenient starting point. As our knowledge of quasars improves, this assumption can be suitably modified. The situation is somewhat similar to that of the Wolf–Rayet stars, for which our knowledge of their chemical composition has been improving with years but is still far from a satisfactory state. These hypotheses lead to the following picture of a quasar: it is a star in which the surface plasma is undergoing rapid radial expansion giving rise to population inversion and laser action in some of the atomic species. We call this model the plasma-laser star (PLS) model.

The proposed model resolves many of the enigmas commonly associated with quasars, and is consistent with various pieces of evidence (Varshni, 1974b, c, 1975a, b, 1976a, b). Varshni and Lam (1976) have presented model calculations for laser action in He II $\lambda4686$ within the framework of the PLS model.

In the present paper we further develop the thesis that the quasars are stars. We

Astrophysics and Space Science **46** (1977) 443–464. *All Rights Reserved*

demonstrate the continuity of the spectra of ten quasars with those of O VI sequence planetary nuclei and stars. Although the present paper deals with this particular spectral class of quasars, certain general problems concerning the spectral classification of quasars are also discussed. We identify O VI λλ3811, 3834 and He II λ4686 emission lines in the spectra of these ten quasars. Candidate identifications for other quasar lines are also suggested. Making use of the similarity between the spectra of O VI sequence planetary nuclei and those of the ten quasars, we estimate the absolute magnitudes, temperatures and masses of these quasars. The distribution of quasars in galactic coordinates is also discussed. Three predictions are made.

2. O VI Sequence Planetary Nuclei and Stars

A line at about 3815 Å in Wolf–Rayet (W–R) spectra has been known since the work of Wright (1918). Beals (1930) observed two lines, λ3815 with intensity 3, and λ3835 with intensity 2. These two lines were identified by Edlén (1932, 1933) and Payne (1933) as being due to O VI, which has a doublet λλ3811.35, 3834.24 arising from the transition $3^2S-3^2P^\circ$. The theoretically expected ratio of the intensities of the two lines is 2:1. In Table I we summarize the wavelengths, intensities and proposed identifications for two lines near λλ3811, 3834 as given by a number of workers. In the spectra of classical W–R stars, the O VI lines usually occur in the WC class and

TABLE I

O VI emission lines in Wolf–Rayet spectra

Author(s)	Star	Wave-length (Å)	Intensity (arbitrary units)	Proposed identification
Wright (1918)		3815		
Plaskett (1924)	HD 192103	3813.5	3	
Beals (1930)		3815	3	
		3835	2	
Aller (1943)	HD 192103	3815	3.0	He I λλ3819.6, 3819.7, O VI
		3835	2.9	O VI, He II λ3833.8
	HD 193793	3815	3	He I λ3820, O VI
		3835	absent(?)	
Smith (1955)	HD 119078 (WC7)	3809.7	comparable	O VI
		3836.4		O VI
	HD 115473 (WC6)	3811	21.8	O VI
		3834	21.6	O VI
Underhill (1959)	HD 192103	3814.6	medium	He I, He II, O VI
		3833.8	medium	He II, C II, O VI, S III
Aller and Faulkner (1964)	γ_2 Velorum	3811	3.0	O VI
		3835	2.8	O VI

are relatively weak. We must note here, however, one important exception. There is a very interesting WN3 star, HD 104994 ('strangest of all', in the words of Kuhi, 1968), which shows O VI λλ3811, 3834 (Smith, 1955). This star represents the state of highest excitation among the WN stars.

Aller (1948) found O VI emission lines in the spectrum of the central star of NGC 246. Greenstein and Minkowski (1964) investigated the spectra of the central stars of a number of planetary nuclei. They found two of them, A30 and A78 (Abell, 1966), to be of special interest. The O VI doublet is very strong in these stars and two other strong lines are observed, λλ4686 and 4650. The latter line was identified with C IV λ4658 (this is inferred from the fact that they refer the excitation potential for the line to be 58 eV). Also, the intensity of this line was found to be variable. Greenstein and Minkowski (1964) give two spectrograms of A78; on the first one λ4650 is strong, but on the second it is quite faint. These authors also note that 'several plates of Abell 78 fail to show [N II] or even Hα'.

The curious behaviour of the relative intensities of λ4650 and λ4686 in classical Wolf–Rayet spectra has been known for the last 50 years (Plaskett, 1924). Plaskett (1924) was struck by the remarkable variations in the relative intensities of these two lines and noted 'The ratio of 4650 C^+ to 4686 He^+ is also peculiar, as the marked discontinuity at the third group where the ratio abruptly increases tenfold distinctly shows. Examination of the spectra clearly indicates that this is almost entirely due to the sudden increase in the strength of the carbon band. Even supposing the interval between the second and third groups to be greater than between the earlier ones, still the change in the strength of enhanced carbon at 4650 is more abrupt than shown by any other element and there must be some physical reason which makes ionized carbon behave in this unique manner.' Such variations can be readily understood on the basis of laser action (Varshni, 1975a; Varshni and Lam, 1976).

Subsequent investigations by Smith and Aller (1969) showed that in the emission-line spectra of certain planetary nuclei O VI lines attain great strengths, indeed, in some cases these are the strongest lines in the spectrum. These authors classified the emission-line spectra of planetary nuclei in five classes – one of these is called the 'O VI sequence'. The defining characteristic of this class is the presence of emission lines due to the O VI doublet λλ3811, 3834 among the strongest lines in the spectrum. In addition, emission lines C IV λ4658 and He II λ4686 are also present and are usually of comparable intensity to the O VI lines. An infrared photometric survey of 10 of the 12 planetary nebulae in Smith and Aller's list, which have O VI sequence nuclei, has been carried out by Cohen and Barlow (1974). Four of them were found to have an infrared excess.

We list these 12 planetary nuclei in Table II (category A) in order of increasing strength and width of O VI lines (as arranged by Smith and Aller, 1969). The widths of the emission lines range from about 40 Å (e.g., NGC 7026 and NGC 5189) to about 1 Å (NGC 246); when the lines are broad, the two components of the O VI doublet are blended together, as are the He II λ4686 and C IV λ4658 lines. In Table II for each

TABLE II

Data for planetary nuclei, Sanduleak stars, and quasars. In general, the number given in the column for m are the photographic magnitudes, except where indicated otherwise by the following letters: B, B magnitude; E, Estimated; U, Uncertain; V, Johnson-Morgan visual magnitude.

Category	Object	R.A. (1950)	Declination (1950)	$l^{\rm II}$ (degrees)	$b^{\rm II}$ (degrees)	Distance d (kpc)	Apparent magnitude m	Absolute magnitude M	$M(a)$ Eq. (1)
A	NGC 246	$00^{\rm h}44^{\rm m}.5$	−12°09′	118.8	−74.7	0.50	11.2	+2.7	+2.4
	A 78	21 33.4	+31 28	81.3	−14.9	1.83	13.04 B	+1.7	+0.7
	A 30	08 44.0	+18 04	208.6	33.3	1.48	14.23 B	+3.4	+2.9
	IC 2003	03 53.2	+33 43	161.3	−14.9	4.66	17.8	+4.5	+3.4
	IC 1747	01 54.0	+63 05	130.3	1.4	2.11	14.9	+3.3	−0.7
	NGC 1501	04 02.7	+60 47	144.6	6.5	1.20	13.3	+2.9	+0.6
	NGC 2371-2	07 22.4	+29 35	189.2	19.8	1.58	13.2	+2.2	+1.4
	NGC 2452	07 45.4	−27 13	243.4	−1.0	1.71	19.1	+7.9	+4.7
	NGC 2867	09 20.1	−58 06	278.2	−5.9	2.10	14.9	+3.3	+0.7
	NGC 6905	20 20.2	+19 57	61.5	−9.6	1.63	13.9	+2.8	+1.2
	NGC 7026	21 04.6	+47 39	89.0	0.4	1.62	14.8	+3.8	+0.7
	NGC 5189	13 30.2	−65 44	307.2	−3.5	0.60	14.11 B	+5.2	+4.1
B	Sand 1	$01^{\rm h}30^{\rm m}.0$	−73°41′	299.0	−43.4	63(?)	13	−6.0	−6.4
	Sand 2	05 40.0	−68 40	278.9	−31.6	52(?)	∼15	−3.6	−4.1
	Sand 3	16 03.1	−35 37	341.5	12.1		∼13		
	Sand 4	17 42.7	−26 10	2.4	1.4		13.4		
	Sand 5	20 19.8	37 13	75.7	0.3		∼15		
C	DW 0202+31	$02^{\rm h}02^{\rm m}10.0^{\rm s}$	31°57′18″	140.58	−28.14		18.00		
	PKS 2145+06	21 45 36.1	06 43 41	63.66	−34.07				
	PKS 2059+034	20 59 8.8	03 29 49	52.69	−26.65		18 E		
	4C 33.03	01 41 18.0	33 57 00	135.20	−27.41		17.50		
	PKS 0906+01	09 06 35.3	01 33 40	228.95	30.92		17.5 E		
	4C 29.68	23 25 43.0	29 20 00	102.06	−29.87		17.30 V		
	4C 27.38	17 41 57.8	27 54 02	52.41	26.21		17.7 V		
	4C 09.31	08 46 57.3	10 00 42	217.58	30.69		19.2 U		
	3C 48	01 34 49.8	32 54 20	133.96	−28.72		16.20 V		
	4C 37.43	15 12 46.0	37 02 30	59.87	58.32		15.5 U		

nuclei we also give its equatorial and galactic coordinates, distance (d), apparent magnitude (m), absolute magnitude (M), and absolute magnitude taking into account space absorption ($M(a)$). Distances are from Cahn and Kaler (1971); where several values were quoted for the same nuclei, an average was taken. Apparent magnitudes are from Smith and Aller (1969). The $M(a)$ values were calculated from the formula

$$M(a) = m + 5 - 5 \log d - A. \tag{1}$$

In order to obtain A it was assumed that the absorption of star light is 1.9 mag kpc^{-1} (Allen, 1973). The scale height for absorption above galactic plane was taken to be 140 pc (Allen, 1973) and the same value was assumed for the scale height of absorption below the galactic plane.

It was pointed out by Sanduleak (1971) that this unusual variety of Wolf–Rayet-like spectrum (O VI sequence) also occurs in stars that do not appear to be planetary nuclei. He provides a list of five such stars. Here we shall label these stars as Sand 1, 2, 3, 4 and 5. Coordinates and magnitudes of these stars are given in Table II (category B).

In Figure 1 we show a diagrammatic representation of the spectra of three of the planetary nuclei namely NGC 6905, NGC 7026, and NGC 5189, and two of the stars, Sand 1 and Sand 4, belonging to the O VI sequence. Only the strong lines have been shown. The sources of data and some additional information about these objects and also Sand 2 are given below.

NGC 6905 and NGC 7026. Emission-line spectra of nuclei of both of these nebulae have been obtained by Smith and Aller (1969). Aller (1968) provides the tracings for the range $\lambda\lambda$3200–4700. Recently, Aller (1976) has observed the central stars of NGC 6905 and NGC 7026 with the Lick Observatory image-tube scanner. He gives scans of NGC 6905 for the ranges $\lambda\lambda$5270–6500 and $\lambda\lambda$6650–8500, and those of NGC 7026 for $\lambda\lambda$5270–8400.

NGC 5189. The spectrum of the central star in NGC 5189 has been reported by Blanco *et al.* (1968a) and by Smith and Aller (1969). Both studies cover the spectral range shortward of $\lambda \sim 5050$ Å. Possible variability in the relative strengths of the two features has been discussed by Sanduleak (1968).

Sand 1. This star was discovered by Miss Cannon (1933) in the vicinity of the Small Magellanic Cloud, and classified as being of O type and having a broad emission feature which apparently she interpreted as He II λ4686. Westerlund (1964) reclassified this star as W–R + O. Sanduleak (1968) obtained a spectrum of this star and found two broad emission bands centred at 4670 ± 5 Å and 3840 ± 5 Å, respectively. He gives a microphotometer tracing of the spectrum for the range $\lambda\lambda$3350–4900.

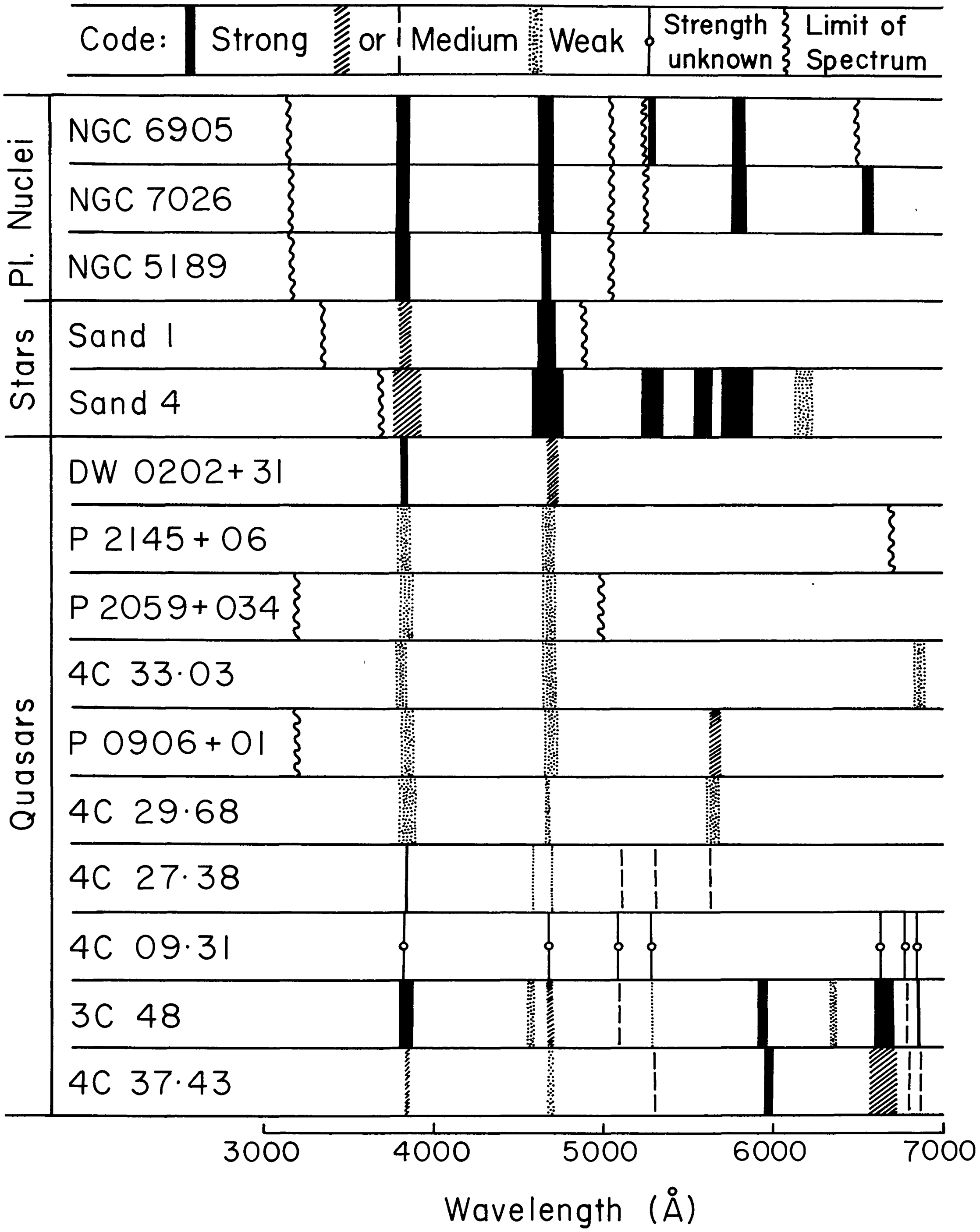

Fig. 1. Diagrammatic representation of the spectra of the following: (A) Central stars of three planetaries, namely, NGC 6905, NGC 7026, and NGC 5189, (B) Stars Sand 1 and Sand 4, and (C) Ten quasars. The code for the strengths of the lines is explained at the top of the diagram. The wavy vertical lines indicate, where known, the limit(s) of the observed spectrum. For the quasar 4C 29.68, the figure shows the set (c) in Table III; for 3C 48, it is a composite figure from the two sets of data, and for 4C 37.43, the set (a) has been shown.

Sand 2. Discovered by Sanduleak (1969, 1971) and designated as star −68°145 in the catalog of Large Magellanic Cloud members.

Sand 4. Discovered by Blanco *et al.* (1968b). Its spectrum was first discussed by Blanco *et al.* (1968c) and later by Freeman *et al.* (1968), who give an excellent microphotometer record of the spectrum for the range $\sim\lambda\lambda 3700$–7300. Possible variability in the strength of the emission lines has been reported by Johnson and Golson (1968). In some of these references, the star has been referred to as GX3 + 1. Cohen and Barlow (1974) have observed a lower limit of 4.1 for the 10-μ (infrared) magnitude of this star. There is an associated nebula with this star, which, according to Johnson (1975), 'should qualify as a supernova remnant except for the complication that it contains a peculiar, hot star'. The radiofrequency spectrum from the nebula appears to be nonthermal (Johnson, 1973).

The spectrum of the central star of NGC 246 (Heap, 1975) affords an excellent illustration of the O VI lines; the lines are relatively sharp and their relative intensities appear to be close to the theoretical values (see tracing in Heap, 1975). We note that the nebula is so faint that there is practically no interference by nebular lines on the stellar spectrum.

However, in some other cases the situation is not so clearcut. It is observed that in some cases where the lines are broad, $\lambda 3834$ is of comparable intensity to $\lambda 3811$ (e.g., NGC 6905, NGC 7026, see tracings in Aller 1968, also Table I of the present paper). When the lines are so broad that they are completely blended, it seems that $\lambda 3834$ becomes stronger than $\lambda 3811$. This statement is based on the following evidence. Sanduleak (1968) has measured the position of the centre to be 3840 ± 5 Å in Sand 1, and the microphotometer tracing for the spectrum of Sand 4 given by Freeman *et al.* (1968) shows the peak to lie at $\lambda 3850$ Å.

When the O VI lines are strong and broad it would be reasonable to assume that the underlying mechanism is the same as that we have proposed for emission lines in quasar spectra (Varshni, 1974a, 1975a; Varshni and Lam, 1976). To explain the increasing strength of $\lambda 3834$ with the width, the following possibilities are open.

(1) Under non-LTE conditions the populations of $P_{3/2}$ and $P_{1/2}$ levels need not be proportional to their respective statistical weight. It is possible that the population of the $P_{1/2}$ level becomes comparable to, or greater than that of the $P_{3/2}$ level as departure from LTE conditions increases.

(2) There is another line or multiplet at $\sim\lambda 3835$ which undergoes laser action when there is high speed expansion. A possible candidate for this alternative is multiplet 5 of S III ($\lambda\lambda 3832$–3838).

The existing observational data is inadequate to decide (or to favour) between the two possibilities. We would like to stress here, though, that the first possibility appears to be more 'natural' than the second one. Irrespective of what is the correct explanation, the important point to note, for the purpose of our subsequent discussion, is that when the lines are broad, the peak appears to lie at about 3840 Å.

3. O VI Sequence Quasars

3.1. The Data

In the course of our analysis of the spectra of quasars (Varshni, 1973, 1974a, 1975a, 1976b) we have found that there are at least ten quasars whose emission-line spectra (as observed, no red shift) belong to the O VI Sequence; their coordinates and apparent magnitudes (De Veny *et al.*, 1971) are given in Table II (category C).

The spectral data for these ten quasars are summarized in Table III. For each quasar the first row shows the reported wavelengths. Below each wavelength, where known, are indicated the strength and width of the line. The following abbreviations have been used. Strengths: VS = Very Strong, S = Strong, M = Medium, Wk = Weak. Widths: wd = wide (40–100 Å), mwd = medium (20–30 Å), n = narrow (10–15 Å). The quantitative equivalents, shown in parentheses, are from Burbidge and Burbidge (1967).

Wavelengths which are close to each other have been placed in the same vertical column. Lines in each column will be identified by the number at the top. The reported apparent red shift is given in parentheses below the name of each quasar. In addition, in the following, we give some other relevant information on these quasars, together with the sources of data. Where more than one set of data are available, these are labelled (a), (b) etc. and the sources identified below. In those cases where the spectral range observed has been given by investigators, it is noted.

DW 0202+31. The data are due to Burbidge (1970).

PKS 2145+06. We quote verbatim from Kinman and Burbidge (1967) and Burbidge (1968). Kinman and Burbidge (1967): 'Lines at 3824 and 4682 Å were measured in 2145+06, and these are probably Mg II λ2798 and [Ne V] λ3426, with a red shift $z = 0.367$. However, Hβ should then appear at 6643 Å, and we have not seen this line on spectrograms taken in the red with the image-tube spectrograph. This possible red shift needs confirming.' Burbidge (1968): 'Kinman and Burbidge (1967) obtained several spectrograms of this object and measured broad emission features at 3824 and 4682 Å. We tentatively identified these as Mg II λ2798 and [Ne V] λ3426 at $z = 0.367$, but Hβ, which should have appeared at 6643 Å, was absent. Therefore, we did not include this object in our table of red shifts. Two further spectrograms have been obtained, one with each spectrograph. The two lines are less distinct, although λ3824 is certainly still visible, and again no other features can be seen. The red shift is thus still not definitely determined.'

PKS 2059+034. The spectral data are due to Burbidge and Strittmatter (1972). Photographic spectrograph was used which covers the spectral range 3200–5000 Å.

4C 33.03≡3C 48/54. The spectrum of this quasar has been reported by Burbidge (1970).

TABLE III

Emission line data for quasars. Below each wavelength are given, where available, the strength and the width of the line.

Quasar (red shift)	Set	1 λ (Å)	2 λ (Å)	3 λ (Å)	4 λ (Å)	5 λ (Å)	6 λ (Å)	7 λ (Å)	8 λ (Å)	9 λ (Å)	10 λ (Å)	11 λ (Å)
DW 0202+31		3823		4708								
(1.466)		S, mwd		M, wd								
PKS 2145+06		3824		4682								
(0.367?)		Wk, wd		Wk, wd								
PKS 2059+034		3840		4686								
(0.370)		M, wd		Wk, wd								
4C 33.03		3808		4687								6861
(1.455)		Wk, wd		Wk, wd								Wk, wd
PKS 0906+01		3843		4695			5662					
(1.018)		Wk, wd		Wk, wd			M, wd					
4C 29.68	(a)	3846					5639					
(1.015)		M, 35 Å					Wk, 35 Å					
	(b)	3834					5625					
(1.009)												
	(c)	3841		4675			5645					
(1.013)		Wk, 95 Å		Wk, mwd			Wk, wd					
4C 27.38		3837	4591	4700	5114	5310	5631					
(0.372)		S, 10 Å	Wk, 10 Å	Wk, 10 Å	M, 10 Å	M, 10 Å	M, 10 Å					
4C 09.31		3822		4681	5088	5285				6628	6774	6841
(0.366)		20 Å										
3C 48	(a)	3832.3	4575	4685	5097	5288		5935	6349	6646		
(0.3675)		S, 70 Å	Wk, mwd	M, mwd	M, n	Wk, n		S, mwd	Wk, mwd	VS, wd		
	(b)				5099.4						6781.7	6849.6
(0.3679)												
4C 37.43	(a)	3837		4691		5301		5969		6640	6799	6862
(0.370)		M, mwd		Wk, mwd		M, mwd		S, wd		M, 160 Å	M, n	M, n
	(b)	3833		4704		5301				6638	6800	6862
(0.371)		M, 50 Å		Wk		Wk				M, 100 Å	10 Å	M, 10 Å

PKS 0906+01≡4C 1.24. Data are due to Burbidge and Strittmatter (1972). Both the photographic spectrograph (spectral range 3200–5000 Å) and the Carnegie image-tube spectrograph (spectral range 4000–7200 Å, low resolution) were used.

4C 29.68≡CTD 141. Three sets of data are available. (a) Schmidt (1966) observed it in the spectral region 3200–6200 Å. (b) Lynds' (1967) spectroscopic material was obtained with the Cassegrain spectrograph of the Kitt Peak 84-inch telescope. (c) The third set is due to Kinman and Burbidge (1967), who note that the line seen by them at 4675 Å was not measured by either Schmidt or Lynds.

4C 27.38. The data are due to Schmidt (1974). This quasar is one of 39 investigated by Schmidt (1974), and he states 'The spectra usually cover the range 3200–6700 Å for each object'. He also states that for this quasar 'All the lines are unresolved, i.e., less than 10 Å wide'. If this finding is confirmed by independent observations, the spectrum of this quasar could be used for accurate determinations of the emission line wavelengths, which would be of considerable value in their identification.

4C 09.31. The spectrum of this quasar was obtained by Lynds and Wills (1972) at the Kitt Peak National Observatory. The wavelength region covered is not given, nor are the intensities and widths of lines, except in one case where the width is noted. The wavelength values given in Table III are the calculated ones obtained from their supposed red-shifted identifications and the apparent red shift.

3C 48. Preliminary observations of the spectrum of this quasar were reported by Greenstein and Münch (1961) and by Matthews and Sandage (1963). Greenstein and Matthews (1963) interpreted the spectral lines on the red-shift hypothesis and a detailed study was made by Greenstein and Schmidt (1964). The first set of data given in Table III are from the last named source. Greenstein and Schmidt (1964) have given numerical estimates (on a relative scale) for the intensities of emission lines. For comparative purposes we have converted them into qualitative measures like 'strong', 'medium' etc. In addition to the lines recorded in Table III, three very weak lines at 4065.7, 4205.3 and 5136 Å, respectively, are also present. Ford and Rubin (1965) obtained the spectrum of 3C 48 with the aid of a cascaded-image tube using the Perkins 69-inch telescope at Lowell Observatory. They give a tracing of the spectrum for the range 4200–7500 Å, however, no measured wavelengths are given. Wampler *et al.* (1975) have carried out observations of the nucleus of 3C 48 and also that of the nebulosity surrounding it, using the image-tube scanner (Robinson and Wampler, 1972) at the Cassegrain focus of the Lick 120-inch telescope. Their observations cover the spectral range $\lambda\lambda$4800–7000. In addition to the three lines listed in the row labelled (b) of Table III, there are features in their scan of the nucleus corresponding to line nos. 5, 7 and 9; however, their wavelengths have not been given by Wampler *et al.* (1975).

4C 37.43. Two sets of data are available: (a) Burbidge (1968) obtained the spectrogram(s) at the prime focus of the 120-inch telescope at Lick Observatory. (b) Schmidt (1974), who has reported on 39 quasars in his paper, states 'The spectra usually cover the range 3200–6700 Å for each object'. It is interesting to note that a strong line at 5969 Å reported by Burbidge (1968) was not observed by Schmidt (1974), though obviously the latter's observations (Table III) cover this region. We note that this line is quite close to the night sky line λ5893 and probably this fact has some bearing on the difference between Burbidge (1968) and Schmidt (1974).

The spectra of these ten quasars are represented diagrammatically in Figure 1.

3.2. Accuracy of the Data

For the purposes of identifying lines and interpreting other features in a spectrum it is of vital importance to know the accuracy of the reported data. The accuracy of the data depends on a number of factors, of which the two most important are the size of the telescope and the methods employed to obtain a spectrum. Besides the conventional direct spectrograph, spectrographs incorporating image tubes have also been used to study the spectra of quasars. The performances of different image tubes vary considerably and the technique has developed considerably over the last few years. The accuracy of the data obtained with some of the early models is difficult to assess. The data due to Burbidge and collaborators were obtained with the 120-inch telescope at Lick Observatory. Some of the data quoted above were obtained by them using a spectrograph that incorporates an RCA image tube. For this image tube Wampler (1974) makes the following comment 'The poor contrast performance of the C33011 that Lick Observatory owns is very striking'. Livingston (1967) has also commented on this problem and gives a quantitative comparison (in his Figure 6) of spectra obtained by direct photography and those obtained using the image tube.

Lynds (1967) has used an English Electric Valve P829 D image intensifier in conjunction with the Cassegrain spectrograph of the Kitt Peak 84-inch telescope. The good points and limitations of the image tube used by Lynds and coworkers are summarized by Livingston *et al.* (1966). For one of the quasars, 0122-00, Lynds' results can be compared with the more recent ones obtained by Browne *et al.* (1975) using an image-tube scanner (Robinson and Wampler, 1972) at the Cassegrain focus of the Anglo-Australian 3.9-m telescope. Lynds (1967) gives the wavelengths as 3210, 3947 (strong), and 5797 Å, respectively. The observations of Browne *et al.* covered the region 3573–6133 Å, and they give the wavelengths as 3968 (Line/Continuum ratio = 0.4) and 5848 Å (Line/Continuum ratio = 0.6). They also state that λ5848 appears to be asymmetric, suggesting self-absorption in the blue wing. It will be noticed that there are large discrepancies between the two sets of wavelengths. Also, from the data given by Browne *et al.* it would appear that λ5848 is stronger than λ3968, while Lynds' data would appear to imply the reverse. Did the strength of one or both of the lines change during the interval between Lynds' and Browne *et al.*'s observations? What is the accuracy of Lynds' observations? Obviously some light could have been thrown on these questions if microphotometer tracings were published. Unfortunately, microphotometer tracings of the emission spectra of only a few quasars (out of about 400 for which data are now available) have been published.

The quasar spectra share with the Wolf–Rayet spectra the common property of having wide emission lines. We consider it appropriate to quote Edlén's (1956) opinion on this point: 'It may be remarked, by the way, that it is practically impossible to describe a Wolf–Rayet spectrum properly by means of a wavelengths list alone. An exhaustive description of a spectrum of this kind would require, in addition to the table, a spectrum reproduction and a photometer tracing of the same magnification, which should be large enough for reading off details on an adjoined wavelength scale. The reproduction of HD 192103 published by Swings (1942) sets an excellent standard with regard to magnification and gradation.' Edlén's comments about Wolf–Rayet spectra are applicable, if anything, to a greater degree, for quasar spectra.

As another example of the difficulties in assessing the accuracy and reliability of the published data, we quote the case of the quasar 2136+14 (≡OX 161). Two investigations on this quasar were published in the same month, one by Wills and Wills (1974) and the other by Strittmatter *et al.* (1974). Both groups used image-tube spectrographs. Their data are given in the following, labelled I and II, respectively,

I 4167 Å (Strong), 4794 Å, 5303 Å
II 4165 Å (Very strong, wide), 4260 Å (Medium, wide), 4820 Å (Weak, wide, possibly confused with night sky), 5302 Å (Medium, medium wide).

Clearly the reality of λ4260 and λ4794 (or λ4820) as being due to the quasar is in doubt. Again, microphotometer tracings of the spectra of quasar and night sky would have been helpful.

Comparisons such as the ones given above, for quasars for which two or more sets of data are available, show that:

(a) Wavelengths of lines described as very strong or strong agree to ±3 Å, unless the line is very wide, in which case the difference can be larger.

(b) Wavelengths of lines described as medium often differ by ±10 Å, differences as large as ±20 Å are not uncommon.

(c) Weak lines reported by one observer are often not reported by another observer at all. Differences in the reported wavelengths are frequently very large. For very weak lines the situation is even worse.

A subjective factor in the reported wavelengths may also be noted. It is human nature to prefer the data which fits theory, which in the present context is the red-shift hypothesis. Knowing that there are large uncertainties in the measured wavelengths, an investigator may tend to unconsciously favour the wavelength which fits the red-shift hypothesis.

Night sky lines and lines from city mercury-vapour lights also create problems. If a quasar line falls near any of these lines, it is obvious that there can be considerable uncertainties in the wavelength and strength of the quasar line, especially if its strength is only medium or weak (see also Roeder and Dyer, 1972).

Allowing for the uncertainties present in the reported data that we have discussed above, the wavelengths in each vertical column in Table III may be considered to be more or less the same.

3.3. Spectral Classification of Quasars

We have shown in a previous paper (Varshni, 1975a) that the PLS model for quasars predicts large variations in the relative intensities of lines which are undergoing laser action, and that such variations have been observed in the spectra of related quasars. The emission-line region of a quasar can be defined by a certain electron density (n_e) and electron temperature (T_e). (These values are, of course, some sort of an average over the emission region, because the emission line region has a certain thickness and it is reasonable to expect that n_e and T_e will be a function of the distance from the star.) These variations in relative intensities, however, create problems in the spectral classification of quasars. Suppose there are some quasars which show emission lines at wavelengths λ_1, λ_2, and λ_3, some which show emission at λ_1, λ_2, some which show λ_1 and λ_3, and some others which show λ_2 and λ_3. It is readily seen that all these four groups have neighbourly positions on the n_e, T_e diagram. But in the spectral classification of astronomical objects, usually some criteria are adopted for membership in any spectral class. What do we do in the example that we have given? Should we say that at least one wavelength, say λ_1 (arising from a certain transition in a certain ion) must be present in all the quasars? That will leave out the group which shows λ_2 and λ_3, though it might be as close to the λ_1, λ_2 group as is the λ_1, λ_3 group. There is, however, a difficulty if we require only one wavelength to be the defining characteristic of a spectral class. There are quite often large uncertainties in the wavelengths of medium and weak lines. It is possible that two or more different transitions (in different ions) may give laser lines whose wavelengths are close and observationally difficult to distinguish. Suppose λ_1 and λ_1' are two such close wavelengths belonging to two different ions, and let the optimum conditions for laser action in these lines be given by n_e, T_e and n_e', T_e' respectively. Generally speaking, n_e and T_e will be different from n_e' and T_e'. Because $\lambda_1 \simeq \lambda_1'$, we will not be certain whether we are dealing with the n_e, T_e region or n_e', T_e' region. However, if we decide to make the classification on the basis of two lines, we avoid this difficulty, because it is very unlikely that in two completely different environments we will find two different pairs of ions undergoing laser action at the same two wavelengths. In the example given above suppose we require that λ_1 and λ_2 should be present in all quasars belonging to a spectral class. This will then leave out yet another group – the λ_1, λ_3 group. It is thus seen that there are problems in the spectral classification of quasars. But we must make a start somewhere. We have chosen the requirement that at least two wavelengths must be common in quasars belonging to the same spectral class. In due course, these different spectral classes can be juxtaposed.

In the present instance we require that two emission lines at about 3820 and 4686 Å respectively be present in a quasar if it is to be a member of the O VI sequence. It will be noticed from Table III and Figure 1 that the spectra of the ten quasars therein satisfy this requirement. A scrutiny of Table III indicates that in some cases the peak of the O VI emission lies at about 3840 Å – we have earlier drawn attention to a similar situation in the spectra of the stars Sand 1 and Sand 4. It will also be noticed that these quasars can be divided into three groups according to their red shifts. These occur at $z \simeq 0.37$, 1.015, and 1.46. We have noted in a previous paper (Varshni, 1976b) that some quasars with very different red shifts belong to the same spectral class; the present example illustrates that point. We may also note here that probably there are a few other quasars, which belong to the O VI sequence; however, the available data for these quasars are either incomplete or not accurate enough, or both.

4. Line Identifications and Comparison of Spectra

4.1. General Remarks

The identification of a spectral line from an astronomical source, at any given point in time, is a function of a number of factors:

(1) Accuracy of the observed wavelength. When a line is broad, one naturally has to allow a certain amount of uncertainty in its wavelength.

(2) Extent of the available laboratory data at that time.

(3) A reasonable guess as to the composition of the emission region in the astronomical source and the conditions of excitation in it.

(4) Self consistency in the proposed identifications for various lines.

In actual practice, tradition has also played an important part. As our knowledge of factors (1)–(4) improves with time, the identification of a spectral line goes through a process of evolution, gradually (or sometimes by a big quantum jump) reaching a state of almost certainty. Perhaps those who are familiar with the history of the identification of the D_3 line, 'nebulium' lines and 'coronium' lines will be able to appreciate these remarks better.

When the emission lines from an astronomical source are broad, their identification poses especially difficult problems. The centre of the line is difficult to determine, and if the profile is asymmetrical this difficulty is further compounded. In addition the lines are sometimes blended, further confusing the picture.

The history of the identification of λ4650 in Wolf–Rayet spectra may be given here as an illustration. Plaskett (1924) thought this line was due to C II, Beals (1930) attributed it to C III. Edlén (1956) considers it to be a blend of C III and C IV. Smith and Aller (1969) identify it with C IV λ4658.

4.2. Line Identifications and Discussion

It would obviously be of interest to compare the spectra of O VI sequence planetary nuclei, Sanduleak stars, and quasars in the high wavelength region. However, amongst planetary nuclei there are only two nuclei (NGC 6905 and NGC 7026) and amongst

Sanduleak stars, there is only one star (Sand 4) for which spectra are available for the long wavelength region; there are no published data for other objects for $\lambda > 5050$ Å. We shall compare the spectra of these three stars with the spectra of the ten quasars shown in Figure 1, in the context of line identifications which we now consider.

Line no. 1. O VI doublet.

Line no. 2. It occurs only as a weak line in two quasars. Lines at about this wavelength have been known in classical W–R spectra for many years. We divide these lines in three groups according to their wavelengths. Some of the reported wavelengths and assignments of lines in these three groups are: (i) 4577, 4581 Å, Si III (Beals, 1930), 4572.8 Å, Si III (Swings, 1942), 4575.2 Å, O III, O IV (Underhill, 1959), (ii) 4585.2 Å, C III (Underhill, 1959), (iii) 4592 Å (Campbell, 1894), 4593 Å (Wright, 1918), 4593 Å (Beals, 1930), 4593.6 Å, C III (Underhill, 1962).

Line no. 3. He II λ4686 and another line, which very likely is C IV λ4658. We have noted earlier the large variations in the intensity of the latter line. It seems that in most of the quasars considered here the contribution due to C IV λ4658 is not very significant.

Line no. 4. A weak line at about 5090 Å occurs in Sand 4, which Freeman *et al.* (1968) have attributed to C IV λ5093. In classical W–R spectra, Swings (1942) has reported a line at 5092.9 Å, and Underhill (1959) at 5090.8 Å. Underhill (1959) also attributes this line to C IV. However, Moore (1970) does not list any line at about this wavelength for C IV.

Line no. 5. There is a strong line in NGC 6905 and a medium strength line in NGC 7026 at about 5292 Å, which Aller (1976) identifies with O VI λ5292. There is a strong, wide line at 5293 Å in Sand 4. Freeman *et al.* (1968) consider the contributors to be C III λ5273, O IV λ5305, and O VI λ5291. A line at about this wavelength has been known in W–R spectra since the work of Wright (1918), some of the reported wavelengths and assignments are: 5305 Å (Wright, 1918), 5304.67 Å, O IV (Swings, 1942), 5303.7 Å, C III, O IV (Underhill, 1959).

Line no. 6. Swings (1942) has reported a line at 5650.8 Å, and Underhill (1959), at 5651.3 Å in W–R spectra. The emitter is believed to be C II.

Line no. 7. A tracing for 3C 48 given by Greenstein and Schmidt (1964) shows this line as a bump in the shoulder of the strong night sky line λ5893. It seems that the wavelength and other characteristics of this line are not well determined, being dependent on the accurate subtraction of the night sky line contribution. We have noted earlier that while Burbidge (1968) has reported this line in the spectrum of 4C 37.43, Schmidt (1974) has not.

Line no. 8. It has been reported in only one quasar, 3C 48. Underhill (1959) has reported a weak line at 6350.7 Å in the W–R star HD 192103, and she attributes it to C III.

Line no. 9. A weak line in W–R spectra has been reported at 6632 Å and attributed to O IV (Meinel *et al.*, 1975).

Line no. 10. In W–R spectra a blend of lines due to C II, multiplet 14, having a strong component at 6784 Å has been reported. There is also a line at 6804 Å, which has been attributed to C III (Meinel *et al.*, 1975).

Line no. 11. Lines at 6857, 6863 and 6872 Å due to C III, multiplet 19, have been observed in the W–R spectra (Meinel *et al.*, 1975).

Thus it is seen that three of the lines which have been observed in quasars have also been observed in NGC 6905 and NGC 7026. Sand 4 has several lines common with quasar lines. Also, practically for all the quasar lines, corresponding lines have been observed in the W–R spectra. The difficulties encountered in the identification of broad emission lines are well known. In the case of quasars one is further handicapped by the lack of microphotometer tracings and the uncertainties in the reported data. For line numbers 1 and 3 the identifications are reasonably secure. For others, we have noted the suggested identifications for the corresponding W–R lines. These could serve as a good starting point at a later date. Laser action is possible in numerous spectral lines under appropriate conditions. At the present time we consider it is important to know first the wavelengths and other characteristics (strength, width, profile) as accurately as possible. A comparative study of the spectra of the ten quasars considered in this paper, over a wide wavelength interval, with the aim of obtaining the highest possible accuracy in the data, preferably using the same telescope, would be of considerable importance. It would greatly help the task of identification of the spectral lines, enable us to find interrelations amongst these quasars, and improve our understanding of the conditions in the emission-line region. We appeal to the astronomers who have access to large telescopes to undertake such a study.

Some interesting differences between the spectra of some of the objects considered here may be noted. Hα appears with great strength in NGC 7026 but is completely absent in A 78 (Greenstein and Minkowski, 1964). This is obviously connected with the fact that many of the planetary nuclei are known to be deficient in hydrogen. Sand 4 also does not show Hα (there is only a small spike on the tracing of the spectrum due to the nebula). The blend of C IV $\lambda\lambda$5801, 5812 appears with great strength in NGC 6905, NGC 7026 and Sand 4, but none of the ten quasars appear to have this. It may be noted, however, that some of the quasars have not been investigated in this region. Also, these lines are not far from the night sky line λ5893 and could have been confused with it.

From our discussion of the spectra of O VI sequence planetary nuclei, Sanduleak stars, and quasars we are led to infer that these are related objects. However, their family relationship is far from clear. As far as the spectra are concerned, Sand 1, Sand 2, Sand 3, and Sand 5 appear to be indistinguishable from quasars. Sand 4 has associated with it what Johnson (1975) calls a 'counterfeit' supernova remnant. Some questions naturally present themselves. Is there a genetic relationship between quasars and planetary nuclei? Is a quasar an evolutionary stage of a star preceding the formation of a nebula or does it represent the stage when the nebula has completely dissipated? It is worth noting that 3C 48 has a nebulosity associated with it, which would appear to suggest that perhaps the first possibility is more likely. Could it be that some quasars may have extended nebulae (or perhaps H II regions) of such low surface brightness that they are undetectable? We note that A 30 and A 78 have just such extended and faint nebulae (Greenstein and Minkowski, 1964; Abell, 1966).

It is known that planetary nuclei show emission-line spectra in many cases, and these are of varied types, with certain features having no equivalent among spectra of Population I stars (Vorontsov-Velyaminov, 1962; Smith and Aller, 1969). In view of what we have said earlier, it is not surprising to find that quasars show such richness of variety in their spectra.

5. Other Properties

Having established the spectral continuity between O VI sequence planetary nuclei, Sanduleak stars and ten quasars, we can now attempt to guess some other properties of quasars belonging to this sequence. Quite often similarities in the spectra of two or more stars also imply similarities in some of their other properties, e.g., absolute magnitude, temperature and mass; but it is well to bear in mind that it is not necessarily always so. For example, Smith and Aller (1971) have shown that the spectra of a planetary nucleus, BD+30°3639 (Campbell's hydrogen-envelope star), and a classical Wolf–Rayet star, HD 164270, are very similar, though the two stars are apparently of different masses, luminosities, and population types.

5.1. Magnitudes

It will be noticed from Table II that the apparent magnitudes of O VI sequence planetary nuclei (category A in Table II) are spread over the range 11.2 to 19.1 – a dispersion of 7.9 magnitudes. And this is not all due to their different distances as can be seen from the absolute magnitudes which range from +1.7 to +7.9 (dispersion of 6.2 magnitudes). This dispersion is somewhat further reduced if we allow for the space absorption. The spread in $M(a)$ values is of 5.4 magnitudes.

When we consider the two stars Sand 1 and Sand 2, we are, however, faced with a puzzle. The apparent magnitudes of these two stars are similar to those in category A, but if we consider absolute magnitudes (which are calculated assuming that these are associated with the Small and Large Magellanic Clouds, respectively) we find that Sand 1 and Sand 2 are brighter than the brightest category A star by 7.7 and 5.3 magnitudes, respectively. These figures are changed to 5.7 and 3.4 magnitudes if space absorption is allowed for. Two possibilities exist; we shall discuss the pros and cons of both. 1. These are indeed bright objects. The example of BD+30°3639 and HD 164270 quoted earlier will support this hypothesis. One may raise the question as to why such objects have not been found in our galaxy. It is possible that Sand 3, Sand 4, and Sand 5 belong to this category, but their distances are not known. 2. The possibility exists that Sand 1 and Sand 2 might be foreground stars and not belong to the Small and Large Magellanic Clouds, respectively, as radial-velocity confirmation is lacking (Sanduleak, 1971). In that case these stars can be expected to have the same sort of distances as category A stars and consequently their absolute magnitudes will also lie in the same range of values as those of category A stars. Clearly, an unequivocal decision is not possible with the presently available evidence. By analogy we estimate that the absolute magnitudes of quasars are fainter than $M \simeq -6$ or $\simeq +1$, depending on the two possibilities.

5.2. Distribution in Galactic Coordinates

If we exclude stars in categories A and B which lie between $b^{\text{II}} = +10°$ and $-10°$, we find that the angular distribution of the ten quasars in category C is not unlike these stars. This exception of the zone between $b^{\text{II}} = +10°$ and $-10°$ has to be considered in the broader context of quasars in general.

In Figure 2 we show the distribution of about 400 quasars in galactic coordinates. It will be noticed that only two quasars have been reported between $b^{\text{II}} = +10°$ and $-10°$, and in general there is a scarcity of quasars at low galactic latitudes. We believe the reasons for this sparseness are the following. A strong belief amongst quasar investigators that these are extra-galactic objects and so they should be searched for outside the 'zone of avoidance' for galaxies, which is roughly between $b^{\text{II}} = +10°$ and $-10°$. Some of the existing catalogues which are used as a starting point for quasar searches are confined to high galactic latitude objects. For example, LB and PHL catalogues are especially devoted to faint blue stars at high galactic latitudes. Similarly, the Parkes catalogue excludes the regions near the galactic plane, except those between $l^{\text{II}} \simeq 165°$ and $210°$.

It is known that there is a moderate crowding of planetaries towards the plane of the Galaxy (Perek and Kohoutek, 1967). From the similarities that we have drawn between planetary nuclei and quasars, we are led to expect that quasars should also occur near the galactic plane.

The average apparent magnitude of the twelve planetary nuclei in Table II is 14.5, and that of the nine quasars is 17.4. Thus the number of quasars that we can expect to observe in the zone $b^{\text{II}} = +10°$ to $-10°$ will not be very large.

An underexposed spectrogram (which will suppress the nebular lines) of an O VI sequence planetary nucleus whose spectrum exhibits broad emission lines will be difficult to distinguish from a quasar spectrum. Indeed, as far as the spectra of stars like Sand 1, Sand 2, Sand 3 and Sand 5 are concerned, these stars can be considered as quasars, and can be assigned 'red shifts' of $\simeq 1.46$ or $\simeq 1.015$ following the usual

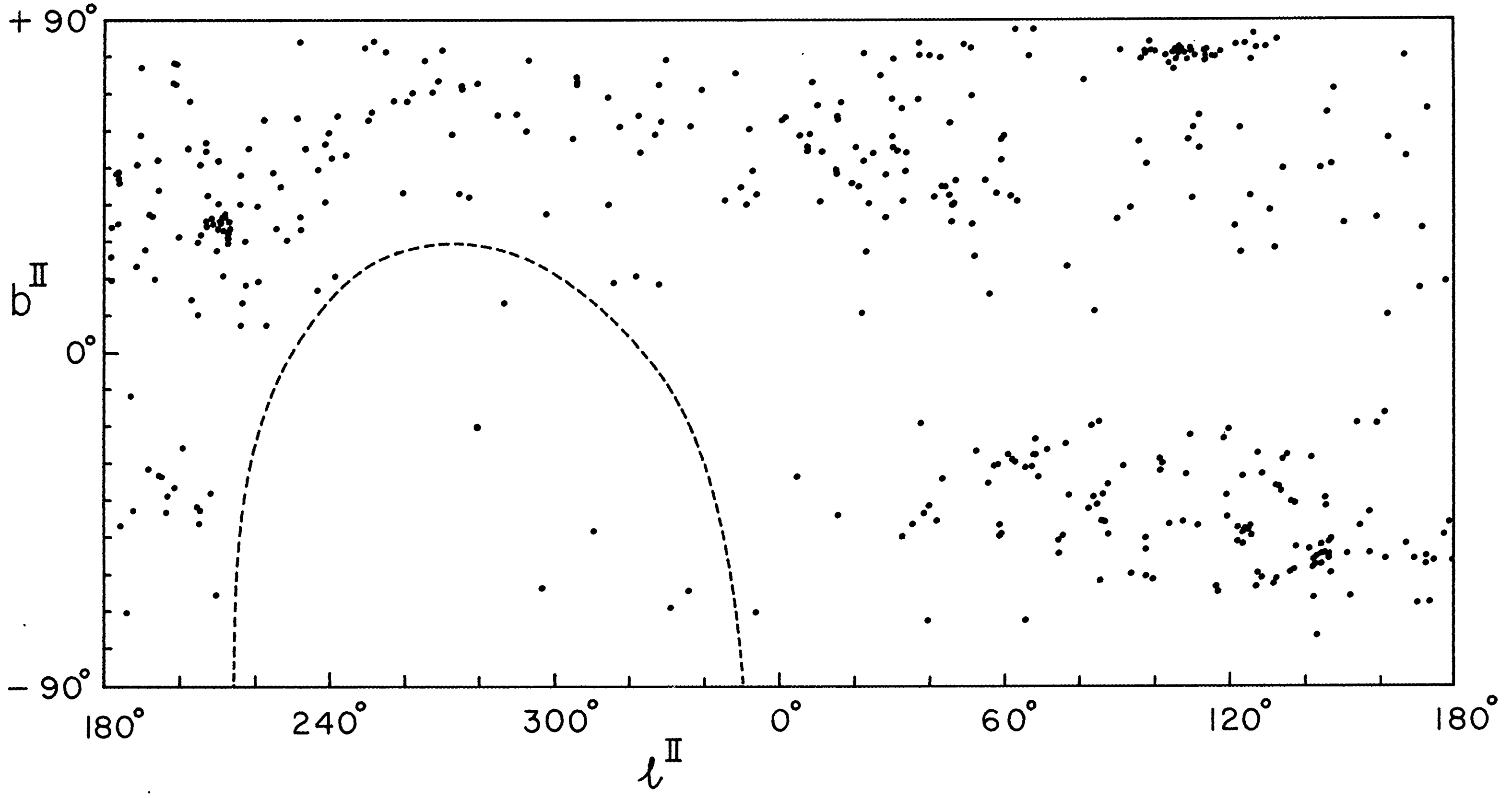

Fig. 2. Distribution, in galactic coordinates, of about 400 quasars. In some of the crowded fields, all quasars have not been shown. The region enclosed by the dashed curve represents approximately the part of the sky which is inaccessible to telescopes based in California and Tucson, where most of the spectral work on quasars has been carried out.

procedures of red shift determination (Schmidt, 1965). Sand 4 exhibits very faint nebular lines and if we ignore them, its spectrum becomes just like a quasar spectrum. Sand 5 has $b^{\text{II}} = 0\overset{\circ}{.}3$ and it can be considered to belong to the population of quasars in the zone $b^{\text{II}} = +10°$ to $-10°$ that we have predicted earlier.

5.3. Temperatures, Masses

All available estimates (Seaton, 1966; Capriotti and Kovach, 1967; Lang, 1974; Heap, 1975) of the temperatures of O VI sequence planetary nuclei indicate that these have very high temperatures, approximately in the range 70 000–200 000 K. By analogy, it would be reasonable to infer that the O VI sequence quasars have the same sort of temperatures. These estimates of temperature are consistent with the model results for laser action in He II λ4686 (Varshni and Lam, 1976) and with the fact that quasars are blue in colour.

The masses of most of the planetary nuclei are believed to lie in the range of about 1 to 1.5 $M_{\odot}$, though some might have their mass as low as 0.85 $M_{\odot}$ and some as high as 4 $M_{\odot}$ (Salpeter, 1971). In general, similar values can be anticipated for the masses of quasars.

6. Predictions

Finally, on the basis of our study, we venture to make the following predictions.

(1) Most of the quasars in our list should show the resonance line He II λ303.8.

(2) The line He II λ3203 should be observable (though weak as compared to He II λ4686) in some of the quasars considered in this paper. The reasons are as follows. We have carried out calculations (similar to those of Varshni and Lam, 1976) for the occurrence of laser action in He II λ3203. The results suggest that over certain regions in the n_e, T_e diagram, laser action in He II λ4686 should be accompanied with laser action in He II λ3203. Also, the central stars of NGC 6905 and NGC 7026 both show He II λ3203 (Aller, 1968).

(3) A good number of quasars should be observable in the zone $b^{\text{II}} = +10°$ to $-10°$.

Acknowledgements

The author wishes to thank Dr L. H. Aller (Los Angeles) for making available his scans of the central stars of NGC 6905 and NGC 7026 prior to publication, Professor T.-Y. Wu (Buffalo) for helpful discussions and correspondence, and Dr B. A. Logan for improving the manuscript. The work was supported in part by a research grant from the National Research Council of Canada.

Note added in proof. It is of interest to note that recently A. Stockton (1976, *Astrophys. J. Letters* **205**, L113) has reported the existence of a nebulosity surrounding the quasar 4C 37.43. Also, the distribution of the nebulosity around 4C 37.43 is similar to that of the nebulosity around 3C 48, both in extent and in general appearance.

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