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Wu States and the Absorption Spectra of Quasars

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The plasma-laser star (PLS) model for quasars proposed by the author, is applied to explain the absorption spectra of quasars. The following topics are briefly reviewed (a) Shell stars, especially γ Cas. The role of metastable states. He I λ3889. (b) High Rydberg states. (c) Multiply-excited states of atoms (and ions) which lie above the first ionization potential, especially the Wu states (metastable states which cannot autoionize by Coulomb interactions or decay radiatively. Prototype: $1s2s2p\ ^4P$ state of the Li I sequence). (d) Dielectronic recombination. The expected shell spectrum of a quasar on the basis of the PLS model is compared with the observational data. The absorption lines arising from ordinary excited levels will be very weak as these levels will be strongly underpopulated ($b_n \ll 1$). The populations of metastable levels below the first ionization potential and those of the Wu levels will be enhanced due to the dilution of stellar radiation. Consequently, lines arising from these levels are expected to be prominent. Those arising from the Wu states will be difficult to identify as very few of these have been observed in the laboratory. The difficulties in the identification of observed lines due to the blending of lines and due to the rather large uncertainties in the measured wavelengths are discussed. The presence of He I λ3889 in the spectra of PHL 957, 1331 + 170, 4C 25.05, PHL 5200, PKS 0237-23, and 1158 + 122 is noted. A very reasonable explanation of the absorption "hole" at ~4020 Å in the spectrum of PHL 957 is that it is due to a transition from a Wu level to an autoionizing level. Also, there is no need of assuming redshifts in the spectra of two BL Lac objects, namely, 0725 + 178 and AO 0235 + 164.

1 INTRODUCTION

The conventional interpretation of the spectral lines observed in quasars is based on the red shift hypothesis.[1] However, it has raised many more questions than it has solved. We have proposed an alternative explanation[2–5] 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). 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 time 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. Varshni and Lam[6] have presented model calculations for laser action in He II λ4686 within the framework of the PLS model.

The proposed model resolves many of the enigmas commonly associated with quasars, and is consistent with various pieces of evidence[4,5,7–10]. It is readily seen that if there is no redshift, the difficulties associated with the intrinsic radiation properties and the short-term variability of quasars all disappear. The absence of redshift also readily explains the scatter diagram nature of the apparent magnitude-redshift plot for quasars, and it will also resolve the four paradoxes of Kellermann.[11] We have also shown[12] that there is a continuity in the optical spectra of ten quasars and those of O VI sequence planetary nuclei and stars. A detailed comparison suggests that there is some relationship between quasars and planetary nuclei. This, in turn, suggests that the proper motions of these two types of objects may be comparable. Proper motions of a few quasars have been discussed by Luyten and Smith[13] and Sanders.[14] Luyten[15] has determined the proper motions (absolute) of 951 faint blue stars. We have searched[16] for quasars in Luyten's list and have found that there are 30 quasars, in addition to those considered in Refs. 13 and 14, for which proper motions are known. The proper motions of those 30 quasars were calculated from their component values. There are three quasars which have proper motions comparable to the largest value amongst planetary nuclei. These three quasars and their respective proper motions (in yr^{-1}) are PHL 1033: $0''.049 \pm 0''.013$, LB 8956: $0''.061 \pm 0''.018$, and LB 8991: $0''.050 \pm 0''.018$. These values may be compared with the largest proper motion reported up to now for a planetary nebula, which is $0''.040 \pm 0''.003$ yr^{-1} for NGC 7293 (believed to be the nearest planetary nebula). The distance of NGC 7293 is estimated to be 212 pc;[17] from this it would be reasonable to estimate that the quasars PHL 1033, LB 8956 and LB 8991 lie within a few hundred parsecs from the sun.

It is thus seen that the available evidence clearly substantiates our hypothesis that quasars are stars. In the present paper we wish to consider the absorption spectra of quasars. At present, absorption lines are known to exist in the spectra of some 50 or so quasars. About half of them show a rich absorption line spectrum. Such spectra have been interpreted in the redshift hypothesis by assuming multiple redshifts. Varshni[7,8] has discussed the spectra of the quasar 4C 05.34 in detail and has shown that the number and properties of the proposed absorption redshift systems are insignificantly different from those that would be expected from chance coincidences.

The absorption lines which occur in the spectra of quasars can be conveniently classified in three categories.

a) Sharp and deep absorption lines. These types of lines are the most common ones, especially in the spectra of those quasars which show many absorption lines. Two sample quotations are relevant. Greenstein and Schmidt,[18] for the absorption spectrum of PKS 0237 − 23 note "The lines are sharp and deep, resembling those in a cool or shell star, rather than, say, a B star". Burbridge *et al.*[19] state: "Most of the absorption lines in Ton 1530, PKS 0237 − 23, and PHL 938 are very narrow". The tracings of absorption spectra of quasars, published in more recent investigations, amply confirm the foregoing observations.

b) Very wide (∼30 Å) absorption lines. Two good examples of this category are an absorption line extending approximately from 4000 Å to 4044 Å in PHL 957 (Refs. 20–22) and a very broad line at ∼3370 Å in 1331 + 170 (Refs. 23, 24). There are two other lines which appear to belong to this category. Schmidt[25] has recorded a strong absorption line, about 30 Å wide, at 3585 Å in 1116 + 12. A tracing of the spectrum of this quasar may be found in Bahcall *et al.*[26] Lynds[27] reports a broad, about 20 Å, absorption feature at 5818 Å in PHL 658.

c) P Cygni lines, i.e., emission lines accompanied by shortward displaced absorption lines. Such lines have been found to occur in several quasars. Three lines in PHL 5200 provide beautiful examples; the boundary between the emission and absorption components being rather sharp.[28] The quasar RS 23 also shows three lines with P Cygni profiles.[29]

Our aim in this paper is to provide a broad outline of the type of absorption spectra that we expect from the PLS model for quasars. To prepare the ground work, we shall first briefly review four topics in the next four sections.

II SHELL STARS

Occasionally an early type emission-line star may exhibit a series of strong and sharp absorption lines, such a spectrum is described as a *shell spectrum.*[30] A description of a typical shell spectrum may be found in Merrill.[31] Partial lists of stars with shell spectra have been provided by Merrill[31] and Merrill and Burwell.[32]

Shell absorption spectra have been observed for stars from spectral type A5 III (14 Com) to B0e (γ Cas). There is some evidence for a shell of small extent in an O7f star (9 Sge[33]). Most of the work has been limited to a few shell stars, these include γ Cas, ϕ Per, Pleione, ζ Tau, 17 Lep, β^1 Mon, 14 Com, 48 Lib, and HD 33232.

A summary of the observations on ζ Tau and 48 Lib may be found in Underhill.[34] A review of shell stars has been given by Hack and Struve,[35] who also discuss four of them, namely, γ Cas, Pleione, 48 Lib and ζ Tau, in detail. Merrill and Lowen[36] have made an intercomparison of shell spectra of twenty-one stars. Absorption lines due to metallic ions like Sc II, Ti II, Mn II, Fe II, Cr II, etc, as well as the Balmer Series are known to occur frequently in the spectra of shell stars. But, in general, shell spectra show a gradation in ionization and excitation which are much complex than those in the reversing layer. "Each shell star is different from every other shell star" (Underhill[34]).

Most shell stars show marked changes in intervals not exceeding a few years in the appearance or the position of the lines (Merrill[37]). Only a few of them (e.g., HD 193182, HD 195325, HD 54858) have stable shells.[36,37]

It was noted by Struve and Swings[38] "that all known absorption shells form a more or less uniform spectral sequence, which runs parallel to the usual sequence, with the shell nearly always showing a lower degree of ionization than the exciting star."

A more detailed study of the systematics of shell spectra was made by Baldwin.[39] He compared the shell spectra of γ Cas, ζ Tau, ε Cap, β Mon, Pleione, HR 8731, and ψ Per and found that they can be arranged, as above, in order of decreasing excitation conditions in the shell. If the state of excitation shown by the shell is high, the chances are that the photospheric spectral class is an early B. As the shell excitation conditions decrease from star to star, the photospheric spectral type becomes later.

Probably the shell of highest excitation ever observed was that of γ Cas during its shell episode of June 1939–October 1940. Baldwin[40] reports measurements on three spectrograms of γ Cas taken during this period; in the wavelength interval $\lambda\lambda$3065 to 6563 he measured a total of 289 lines, of these only 145 could be identified. Most of the identified lines were due to Fe III, He I and the Balmer series.

Merrill[41] records three B-type stars, HD 172694, HD 184279, and HD 195407 which have sometimes shell spectra marked by absorption lines from metastable levels of the neutral helium atom and the metallic lines are absent or weak presumably because the excitation required for the helium lines is sufficient to remove a second electron from the metallic atoms. These features appear to indicate that the shells are of high excitation; the description of the spectra of these three stars, provided by Merrill,[41] is rather brief and we do not know if any unidentified lines were noted.

It is well known that in the spectra of shell stars, absorption lines for which the lower level is metastable, are unusually strong. The explanation of this phenomenon was furnished by Struve and Wurm.[42] In the shell the dilution of the stellar radiation is quite pronounced and the Rosseland cycle goes into operation leading to large populations in metastable levels. The original calculations of Struve and Wurm[42] were carried out for He I taking into consideration six states of this atom. Subsequent calculations by Goldberg[43] and Wellmann[44]—on this atom, taking into account a large number of levels, have fully substantiated the conclusions of Struve and Wurm.[42] It would be safe to assume that the over population of metastable states in the presence of a dilute radiation field is a fairly general phenomenon and, unless there is evidence to the contrary, can be expected to occur for any atom or ion. A metastable excited state is often defined[45] as one whose natural lifetime is greater than 10^{-6} seconds, and we shall also adopt this definition here. Departures of the energy-curve of the exciting radiation from that of a black body could also lead to departures from the Boltzmann formula.[46]

The principal questions concerning the structure of shells were formulated by Struve[47] as follows:

1) Why do some stars possess tenuous outer atmospheres or shells, while other stars, apparently of identical physical characteristics, do not have such shells?

2) What is the origin of a shell and how is it supported, in apparent violation of the laws of mechanics?

3) How can we account for the remarkable tendency of nearly all shells to vary either periodically or, more often, in an irregular manner?

4) Why do some shells expand, while others are stationary?

Struve[47] presented a very penetrating analysis of the problems posed by these questions. Even today our understanding of these problems is very incomplete.

III HIGH RYDBERG STATES

It is known[48] that the lifetimes T_{nl} of the quantum states of the hydrogen atom increase with increase of the principal quantum number n. For a fixed azimuthal quantum number l, we have $T_{nl} \propto n^3$, and the average lifetime T_n of the n-th quantum state increases with n much faster: $T_n \propto n^{4 \cdot 5}$. From this, we can expect that all the highly excited quantum states of hydrogenic atoms are long lived. Such states are known as "high Rydberg" states.[49] For sufficiently large principal quantum number n, a high Rydberg atom (or ion) consists of a single excited electron moving in a distant orbit in a near-Coulomb field. Such atoms are therefore expected to be near hydrogenic in character. Early observations of such ions were made by Kupriyanov *et al.*[50,51] Experimental studies for sodium[52] with $7 \leq n \leq 13$, for xenon[53] with $25 \leq n \leq 40$, and for rubidium[54] with $12 \leq n \leq 22$ demonstrate that the lifetimes increase approximately as (n^*),[3] where n^* is the effective quantum number, in agreement with hydrogenic theory. We note here that for a fixed value of n the lifetime of the component levels depends strongly on the orbital quantum number l. Except for s states, the lifetimes increase with increase in l. It is obvious that, in practical terms, high Rydberg states with long lifetimes will behave as metastable states.

IV MULTIPLY-EXCITED STATES

An atom or ion has excited states which lie above the first ionization potential. Such states can arise in two ways, either by excitation of two or more electrons or by the excitation of a single inner-shell electron. It has become customary[55] to refer to both these types as multiply-excited states and we shall also follow this nomenclature here. We give here a summary of the important properties of these states and we shall illustrate the categories by giving examples of different types of such states for Li I, which is the best studied system so far for such states. For further details, reference may be made to review articles by Martinson and Gaupp[56] and by Berry.[55]

Multiply-excited states can be conveniently divided in two broad categories:

I) States which are subject to auto-ionization via the Coulomb interaction into the adjacent continua. The *lifetime* of such a state is of the order of 10^{-14} to 10^{-15} sec.

II) States for which autoionization via the Coulomb interaction is forbidden due to the selection rules (see Table I, pure LS coupling is assumed[57]). However, these states can undergo autoionization through some other channel, provided appropriate selection rules are satisfied. Such channels are identified in Table I. The life times for autoionization through these modes are much longer than those for the Coulomb interaction and this circumstance makes these states rather sharp and quite interesting.

These states can be divided into two categories.

IIa) Those which cannot decay radiatively to the ground state or an excited state lying below the first ionization potential. In Li I, examples of such states are $1s2snp\ ^4P$, $1s2sns\ (n > 3)\ ^4S$, $1s2snd\ ^4D$, $1s2pnp\ ^4P$ etc. These states are frequently referred to as the quartet states of Li I. These states can decay radiatively and will, in general, cascade to the lowest state amongst them. Figure 1, which is reproduced from a review article by Berry,[55] shows

TABLE I.

Selection rules for auto-ionization (Feldman and Novick[57]).

Interaction	ΔL	ΔS	ΔJ	Parity change	Relative transition rate[a]
Coulomb	0	0	0	No	1
Spin-orbit / Spin-other-orbit	0, ± 1	0, ± 1	0	No	α^4
Spin-spin	0, ± 1, ± 2	0, ± 1, ± 2	0	No	α^4
Hyperfine	0, ± 1, ± 2	0, ± 1	0, ± 1	No	$\alpha^4(m/M)^2$

[a] Here α is the Sommerfeld fine-structure constant, m is the mass of the electron, and M is the proton mass.

the presently known quartet levels in Li I and the transitions between them. In the present case the lowest state is $1s2s2p\ ^4$P and it is radiatively metastable because of the spin selection rule. Calculations on this state were first made by Professor Wu[58] and this state serves as the prototype of such states in various atoms and ions. We shall refer to such states as the Wu states. It should be noted that there are states of higher multiplicity, arising from the simultaneous excitation of two or more inner-shell electrons (excepting lithium, of course) which are metastable against auto-ionization as well as radiative decay. All such states are included in the definition of the Wu states.

The experimental confirmation of Wu states in alkalies was first obtained by Feldman and Novick[57] who found the following lifetimes (in μsec) for the quartet Wu levels: Li (5.1 ± 1.0), K(90 ± 20), Rb(75 ± 20). There are three fine-structure levels of $1s2s2p\ ^4$P, viz. $^4P_{1/2}$, $^4P_{3/2}$, and $^4P_{5/2}$. In Li I, $^4P_{3/2}$ lies the lowest, followed by $^4P_{5/2}$ and $^4P_{1/2}$. The energy differences are as follows: $E_{5/2} - E_{3/2} \simeq 0.997\ \text{cm}^{-1}$, $E_{1/2} - E_{5/2} \simeq 1.725\ \text{cm}^{-1}$ (Levitt, Novick and Feldman[59]). In He^- the energy differences[60] are much smaller.

The three fine-structure levels of $1s2s2p\ ^4$P, have different lifetimes since the $J = \frac{1}{2}$ and $J = \frac{3}{2}$ states decay both by spin-orbit and spin-spin interaction whereas $J = \frac{5}{2}$ only auto-ionizes via the spin-spin interaction. The $^4P_{5/2}$ state has thus a markedly longer lifetime. For Li I the following lifetimes were obtained by Levitt *et al.*[59] who used the Zeeman-quenching atomic beam method, $^4P_{5/2}$ ($\tau = 5.8 \pm 1.2\ \mu$s), $^4P_{3/2}$ ($\tau = 0.46 \pm 0.10\ \mu$s) and $^4P_{1/2}$ ($\tau = 0.14 \pm 0.07\ \mu$s).

IIb) Those which can decay radiatively directly to the singly excited states lying below the first ionization potential. In Li I, there are some doublet states belonging to this category. A prominent transition involving such a state, $1s^22p\ ^2P^0 - 1s2p^2\ ^2$P has been identified by Buchet *et al.*[61]

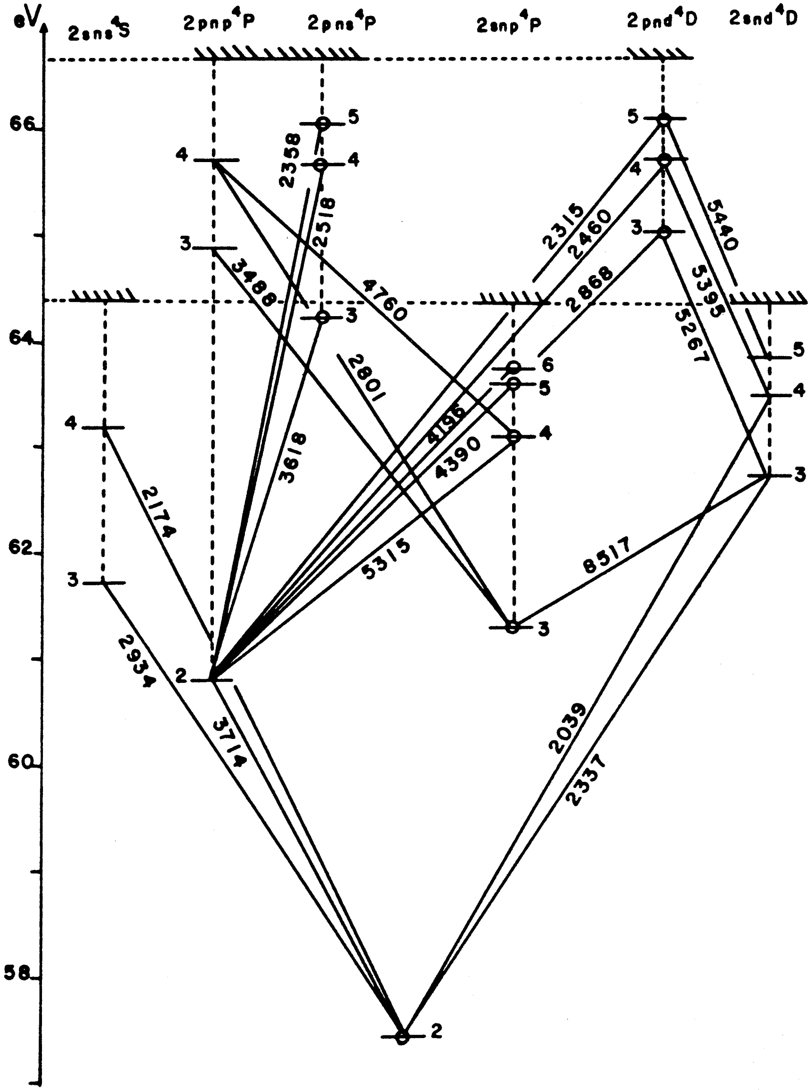

FIGURE 1 Term scheme for the Li I quartet system (Berry[55]). The lowest state is $1s2s2p\ ^4P^0$.

V DIELECTRONIC RECOMBINATION

A complex atom has a series of levels with excitation potentials converging on the ionization potentials corresponding to the different levels of the ion X^+. This is illustrated in Figure 2 for $I_i < I_j$, where I_i and I_j represent the two ionization potentials. As an example, I_i may refer to one-electron excitation and I_j, to two-electron excitation. Suppose that one of the levels f of the series of X associated with the ionization potential I_j lies within the continuum of the system composed of X^+ in level i, and a free electron. Subject to certain selection rules[62] an electron with kinetic energy E (in a plasma) may undergo a radiationless transition to an autoionizing level of the same total energy:

$$X_i^+ + e \rightarrow X_f. \tag{1}$$

The doubly excited state X_f thus formed may revert to the ionic state X_i^+ by the process of autoionization. However, it is possible that before this reversal occurs, the doubly excited atom X_f may undergo a radiative transition and drop to some state X_b which is not subject to autoionization:

$$X_i^+ + e \rightarrow X_f \rightarrow X_b + h\nu. \tag{2}$$

This process is known as dielectronic recombination.[63,64]

The lifetime associated with emission of the line $f \rightarrow b$ is in general much longer than the lifetime for autoionization, which may be of the order of 10^{-13} sec or even less. Thus the rate of dielectronic recombination will

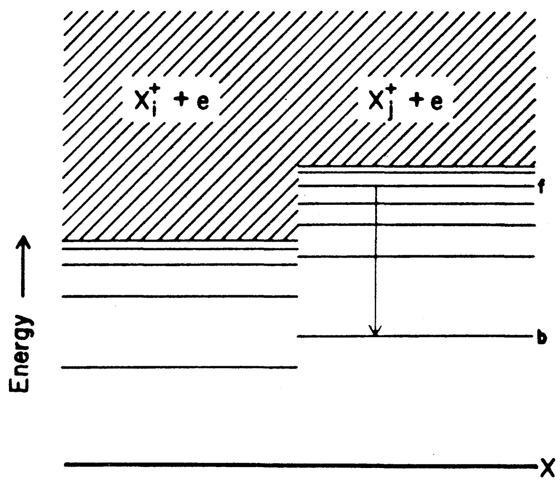

FIGURE 2 Schematic energy-level diagram illustrating process of dielectronic recombination.

usually be small because of the relative inefficiency of the second step of the reaction (2) compared with the inverse of the first. However, it was shown by Burgess[65] that for complex ions at fairly high temperatures and low densities dielectronic recombination will be the most important process by which an electron can recombine with an ion.

Gabriel[66] has pointed out that in plasmas the contribution to the production of core-excited states through the process of dielectronic recombination can be important.

VI THE EXPECTED SHELL SPECTRUM OF A QUASAR

Let us now consider the expected shell spectrum of a quasar on the basis of the PLS model and the aspects in which this will be similar to or different from, "classical" shell spectra. We have a high temperature star which is undergoing a mass loss, the rapidly expanding plasma undergoes cooling and gives rise to population inversion and laser action in some of the atomic species. We do not here consider the various mechanisms which may be responsible for the mass loss. As the plasma continues to expand further, if appropriate conditions are satisfied, an absorption shell may be formed. We show, in Table II, atoms and ions up to $Z = 28$ in an increasing order of their ionization potentials. Two elements, Li and Be, have been omitted as their stellar abundances are less than 20 (scale $N(\mathrm{Si}) = 10^6$); the cut-off point was determined by Sc, which frequently shows up in shell spectra and which has an abundance of 23. Lines due to metallic ions like Sc II, Ti II, Mn II, Fe II, Cr II etc. are known to occur frequently in the spectra of "classical" shell stars. In addition, He I and Fe III lines in some shells in which the ionization level is higher. Extrapolating, we can expect the presence of He I, Fe III, Ti III, O II, Mn III, Ar II, Si III, Cr III, Al III etc in the shells of quasars. For quasars with still higher excitation, we can go further down in the list. It must be remembered that Table II provides only a *very* approximate and rough way of looking at the problem. The intensity (equivalent width) of an absorption line depends on the number of atoms in the lower state of the transition and the oscillator strength, f, of the transition in question. The absorption lines arising from ordinary excited levels will be very weak as these levels will be strongly underpopulated.[67,68] The Collisional-Radiative model leads to this result; in addition, the effect of the dilute stellar radiation will also act in the same direction. On the other hand, the populations of metastable levels below the first ionization potential, of high Rydberg states and those of the Wu levels will be enhanced due to the dilution of stellar radiation. Thus, we expect that the lines arising from such levels will be strong.

TABLE II

Atoms and ions arranged in an increasing order of their ionization potentials. The list is limited to ionization potentials below 80 eV.

Atom or Ion	Ionization potential (eV)	Atom or Ion	Ionization potential (eV)
K I	4.341	Cr III	30.96
Na I	5.139	K II	31.63
Al I	5.986	Si III	33.492
Ca I	6.113	Co III	33.50
Sc I	6.54	Mn III	33.67
V I	6.74	S III	34.83
Cr I	6.766	F II	34.970
Ti I	6.82	O II	35.117
Mn I	7.435	Ni III	35.17
Ni I	7.635	B III	37.930
Mg I	7.646	Cl III	39.61
Co I	7.86	Ar III	40.74
Fe I	7.870	Ne II	40.962
Si I	8.151	Ti IV	43.26
B I	8.298	Si IV	45.141
S I	10.360	K III	45.72
P I	10.486	V IV	46.71
C I	11.260	Na II	47.286
Ca II	11.871	S IV	47.30
Sc II	12.80	N III	47.448
Cl I	12.967	C III	47.887
Ti II	13.58	Cr IV	49.1
H I	13.598	Ca III	50.91
O I	13.618	Co IV	51.3
N I	14.534	Mn IV	51.4
V II	14.65	P IV	51.42
Mg II	15.035	Cl IV	53.46
Mn II	15.640	He II	54.416
Ar I	15.759	Fe IV	54.8
Fe II	16.16	Ni IV	54.9
Si II	16.345	O III	54.934
Cr II	16.50	Ar IV	59.81
Co II	17.06	K IV	60.92
F I	17.422	F III	62.707
Ni II	18.168	Ne III	63.45
Al II	18.826	C IV	64.492
P II	19.725	P V	65.02
Ne I	21.564	V V	65.23
S II	23.33	Ca IV	67.15
Cl II	23.81	Cl V	67.7
C II	24.383	Cr V	70.2
He I	24.587	Na III	71.64
Sc III	24.76	S V	72.68
B II	25.155	Mn V	73.0
Ti III	27.49	Sc IV	73.7
Ar II	27.629	Ar V	75.04
Al III	28.448	Fe V	75.5
V III	29.31	Ni V	75.5
N II	29.601	O IV	77.413
P III	30.18	N IV	77.472
Fe III	30.651	Co V	79.5

At a given electron density and electron temperature, usually, no more than two ionization stages occurs simultaneously to a significant degree. This rule of thumb can be followed here also for levels which lie below the first ionization potential. But for the Wu levels, one has to be careful. As a first approximation, one may expect that Wu levels for a z-times ionized atom X^{z+}, will co-exist with ordinary levels for the ion $X^{(z+1)+}$.

VII IDENTIFICATION OF ABSORPTION LINES IN THE SPECTRA OF QUASARS

For identifying spectral lines, one would like to have an accuracy of 0.1 Å or better in the observed wavelengths, a moderate accuracy in their intensities and to have these data over a wide wavelength interval. However, most of the reported data are of poor accuracy—the claimed accuracy varies between 1 Å and 2 Å. When interpreting these data on the redshift hypothesis, usually most authors allow a discrepancy of ± 2 Å and it would appear that most of the data have this sort of uncertainty. Also, in several cases, the mutual blending of lines is very severe. As an illustration, we quote here from Baldwin *et al.*:[69] "In addition to possible errors arising from the wavelength calibration, many if not most of the measured features are blends of two or more lines. Consequently, the tabulated wavelengths are only mean values for the "center of gravity" of the blend. This propensity for the absorption features in OQ 172 to be blended at 3.5 Å resolution has caused severe difficulty in interpreting the spectrum." The spectra of some of the quasars have been obtained only at low dispersion and only the strong lines have been recorded; it is not clear whether these lines are single or blends of two or more lines. In such cases where quasar spectra have been obtained both under low and high dispersions, it has frequently been found that what appeared to be a single line on the low dispersion spectrum turned out to consist of two or more lines on the high dispersion spectrum. Also a high dispersion spectrogram is able to reveal weak lines which are not visible on a low dispersion spectrogram. An instrumentation problem may also be noted here. Many of the spectra have been obtained by spectrographs which incorporate an image tube. This affects the contrast performance. Figure 3, which is reproduced from Livingston,[70] compares the tracings of two spectra, one obtained by direct photography and the other by using an image tube. It will be noticed that the resolution is very much poorer in the image-tube spectrum and also the weaker lines have been rather "washed out." Bearing these limitations of the reported data in mind, we consider the lines which will arise from the different types of levels.

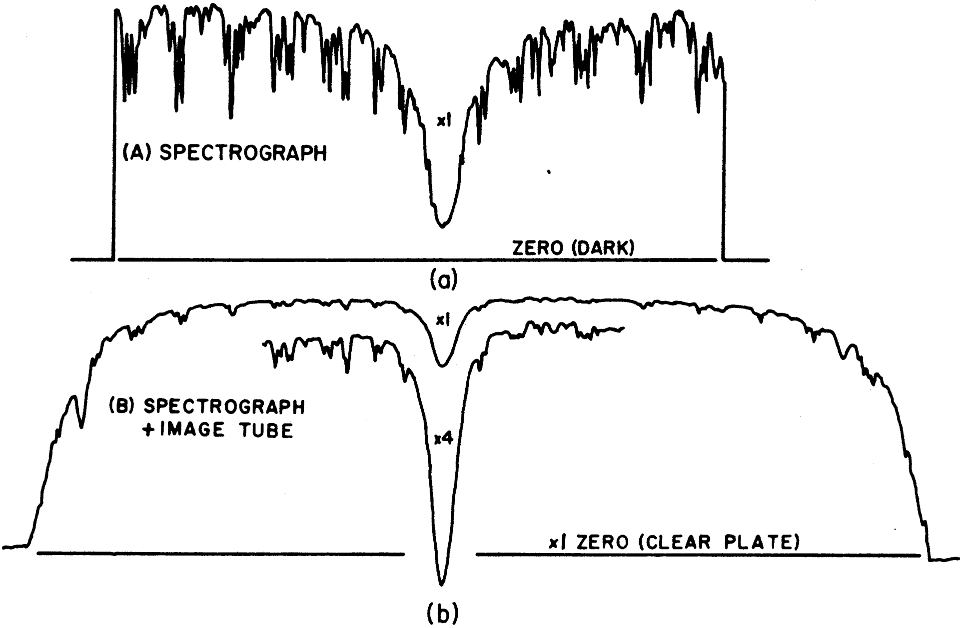

FIGURE 3 Photometric response of an image tube system in the case of absorption lines. Source is the sun and an iodine absorption tube at 5890 Å and a dispersion of 4 mm Å. (a) Image slicer + spectrograph. (b) Same as (a) + cylindrical lens + C 33011 tube + F2 transfer lens + IIa–0 plate exposed to density 0.95 (Livingston[70]).

A Ordinary excited levels

We have noted earlier that the ordinary excited states of ions in the shell of a quasar will be greatly underpopulated and consequently the lines arising from these levels will be weak. These lines would be the easiest to identify, but unfortunately the present observational techniques do not permit clear recognition of such lines above the "noise." A quotation from Coleman *et al.*[22] is illustrative of the situation: "There are, however, many other weak features that may be real but are not listed."

One could expect to observe lines arising from the ground state, but except for Ca II, such lines for ions which may be expected in quasar shells, (e.g., Mg II $\lambda\lambda$2796, 2803, Al III $\lambda\lambda$1855, 1863, Si III λ1206) lie in the ultraviolet. The resonance lines of Ca II, $\lambda\lambda$3934, 3968 can be identified in the spectra of some of the quasars, e.g. 3C 191, PKS 0237 – 23, and PHL 957. However, from the available data it is not possible to say how much contribution is from the circumstellar shell and how much from the interstellar material.

B Metastable levels lying below the first ionization potential

It is well known that the line $\lambda 3889$ arising from the ^3S metastable level of He I is an important line in the spectra of shells of medium and high excitation. A line at 3889 Å (or very close to it) is indeed observed in the absorption spectra of the quasars PHL 957, 1331 + 170, 4C 25.05, PHL 5200, PKS 0237 − 23, and 1158 + 122. He I $\lambda 3187$, which arises from the same level, is also present in the spectrum of PHL 957. It would be interesting to look for this line in the other five quasars.

As noted earlier the shell spectra (June 1939–Oct. 1940) of γ Cas is a sort of last "outpost" in the high excitation region. One could turn to it for some guidance. Fe III was quite prominent in the shell of γ Cas. Fe III has many

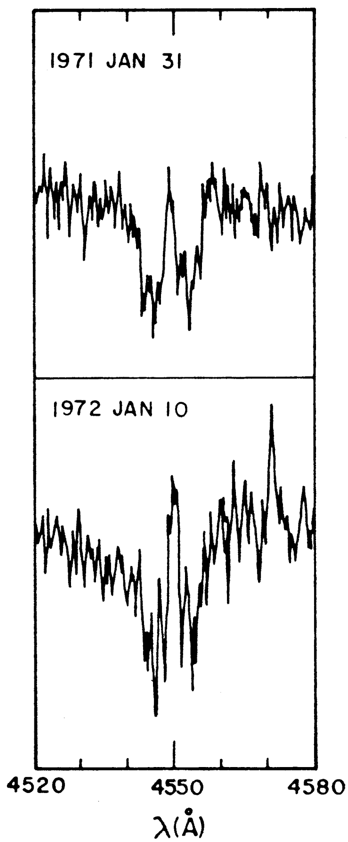

FIGURE 4 Relative intensity traces of a feature in the spectrum of Ton 1530, on two different dates. The spectra were obtained with the Princeton integrating television system by Morton and Morton.[71] (By permission of the University of Chicago Press. © by the American Astronomical Society.)

lines. As many of the lines in the spectra of quasars are blended, it makes it difficult to pick out Fe III lines clearly. We must also recall here that practically half of the lines in the shell spectra of γ Cas have not yet been identified.

C Wu levels

Very few lines involving Wu states have been observed experimentally in the laboratory. This places a serious limitation on their identification in the spectra of quasars.

We list in Table III, for atomic systems having between 3 and 26 electrons, the multiplicities of possible Wu states. A minimum of at least one Wu state of a given multiplicity is expected to occur in any of these atomic systems; there could be several in favourable circumstances. From practical considerations, in the shells of quasars, one could restrict oneself to the first three multiplicities listed against any atom. We notice from Table III that Wu states have high multiplicities. This provides us with the "signature" of lines arising from Wu states—they will have several components, with fine-structure splittings ranging from a few cm^{-1} to a few hundred cm^{-1}.

Strong absorption lines with several components have indeed been observed in the spectra of quasars. We show, in Figures 3–6, tracings[71–74] of a

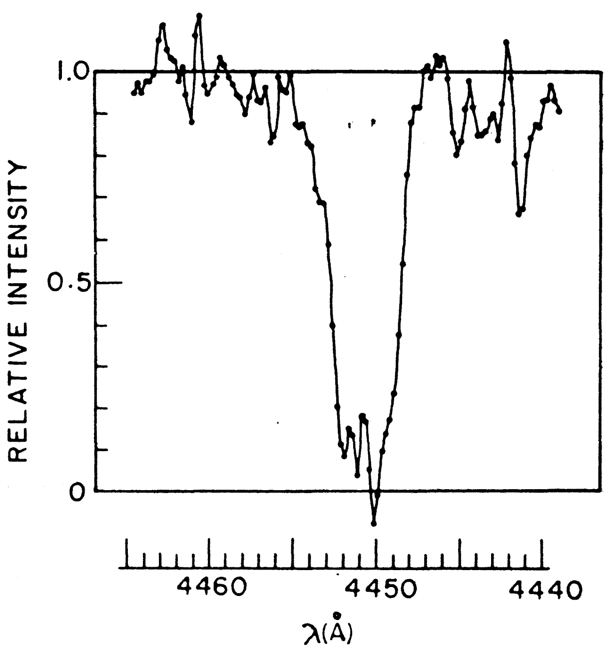

FIGURE 5 Profile of a cluster of lines at ~4450 Å in the spectrum of PHL 957 obtained by Morton and Morton[72] with the Princeton integrating television system. (By permission of the University of Chicago Press. © by the American Astronomical Society.)

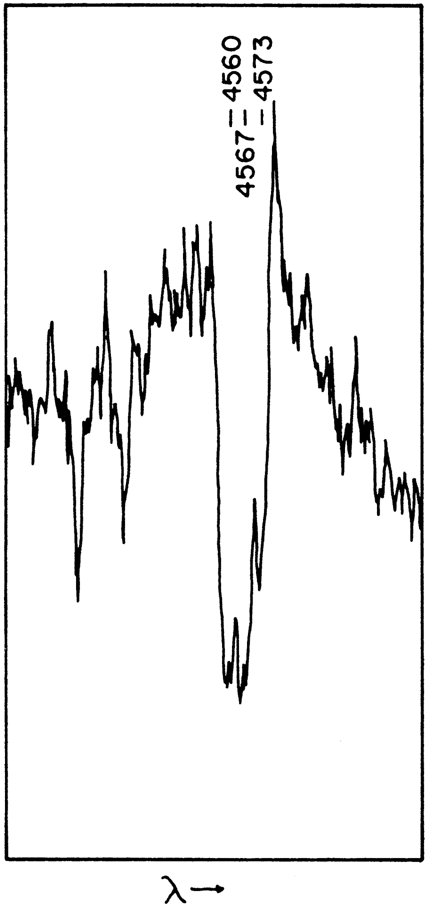

FIGURE 6 Intensity tracing of a portion of a spectrogram of 3C 191 showing a strong line with several components at ~4565 Å (after Williams *et al.*[73]). (By permission of the University of Chicago Press. © by the American Astronomical Society.)

few such lines. It would be reasonable to surmise that such lines are arising from Wu levels.

The spectrum of PHL 957 shows a very broad, strong absorption feature extending from 4000 Å to 4044 Å. Perhaps it is better described as an absorption "hole," see Figure 8. A more detailed view of this feature, obtained by Beaver *et al.*, by Digican spectrophotometry, is shown in Figure 9. A very reasonable explanation of this "hole" is that it is due to a transition from a Wu level to an autoionizing level. It is well known that autoionizing

TABLE III

Multiplicities of the possible Wu states

Prototype atom	Isoelectronic ions	Multiplicities of the possible Wu states
Li I	B III, C IV	4 (quartet)
Be I	B II, C III, N IV	5
B I	C II, N III, O IV	6
C I	N II, O III	7
N I	O II, F III	8
O I	F II, Ne III	7, 9
F I	Ne II, Na III	6, 8, 10
Ne I	Na II	5, 7, 9, 11
Na I	Mg II, Al III, Si IV	4, 6, 8, 10, 12
Mg I	Al II, Si III, P IV	5, 7, 9, 11, 13
Al I	Si II, P III, S IV	6, 8, 10, 12, 14
Si I	P II, S III, Cl IV	7, 9, 11, 13, 15
P I	S II, Cl III, Ar IV	6, 8, 10, 12, 14, 16
S I	Cl II, Ar III, K IV	7, 9, 11, 13, 15, 17
Cl I	Ar II, K III, Ca IV	6, 8, 10, . . . , 18
Ar I	K II, Ca III, Sc IV	5, 7, 9, . . . , 19
K I	Ca II, Sc III, Ti IV	4, 6, 8, . . . , 20
Ca I	Sc II, Ti III, V IV	5, 7, 9, . . . , 21
Sc I	Ti II, V III, Cr IV	6, 8, 10, . . . , 22
Ti I	V II, Cr III, Mn IV	7, 9, 11, . . . , 23
V I	Cr II, Mn III, Fe IV	8, 10, 12, . . . , 24
Cr I	Mn II, Fe III, Co IV	9, 11, 13, . . . , 25
Mn I	Fe II, Co III, Ni IV	10, 12, 14, . . . , 26
Fe I	Co II, Ni III	9, 11, 13, . . . , 27

levels are extremely efficient absorbers of radiation.[75] (For the same number of absorbing atoms, the strength of an autoionizing line may exceed that of an ordinary line by two or three orders of magnitude.) The great width of the "line" in question indicates that the lifetime of the involved autoionizing level is very short.

VIII BL LAC OBJECTS

BL Lacertae objects are characterised by a star-like appearance, continuous optical spectrum, and rapid and large amplitude variability at optical, infrared and radio wavelengths. Two of the BL Lac objects, namely 0735 + 178[76] and AO 0235 + 164.[77,78] have been found to show sharp lines in their spectra. These lines have been interpreted on the conventional redshift hypothesis. From our discussion of the absorption spectra of quasars on the PLS model, it is obvious that there is no need of assuming redshifts in the spectra of 0735 + 178 and AO 0235 + 164.

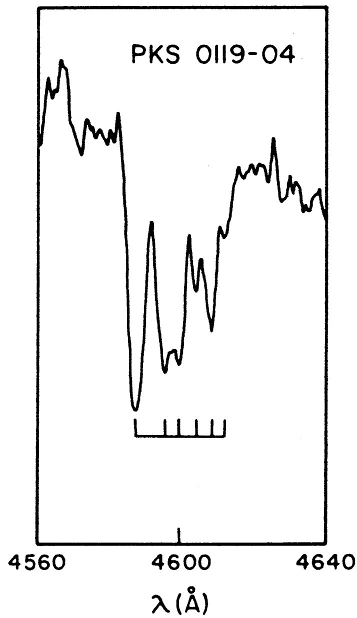

FIGURE 7 Density tracing of a portion of image-tube spectrum of PKS 0119 − 04 at 47 Å mm^{-1} showing a strong line with several components at ~4600 Å (after Weymann *et al.*[74]). (By permission of the University of Chicago Press. © by the American Astronomical Society.)

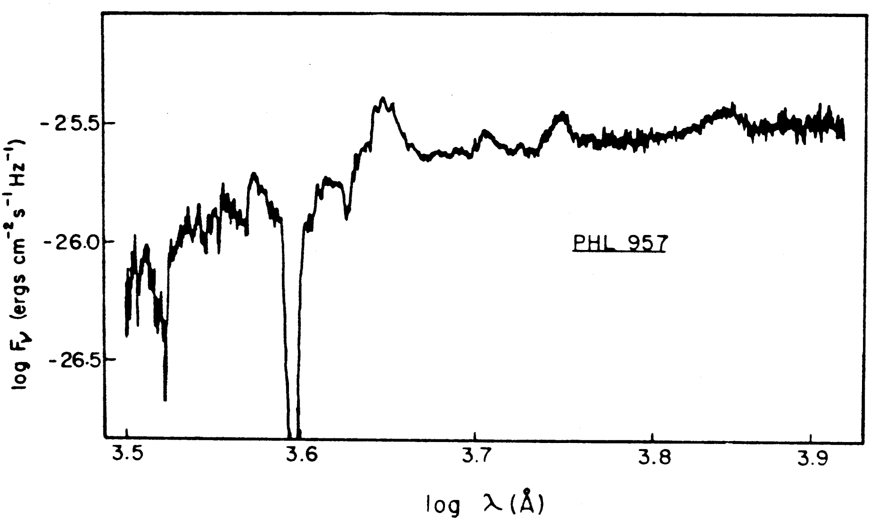

FIGURE 8 Sum of low resolution scans of PHL 957 (Coleman *et al.*[22]). (By permission of the University of Chicago Press. © by the American Astronomical Society.)

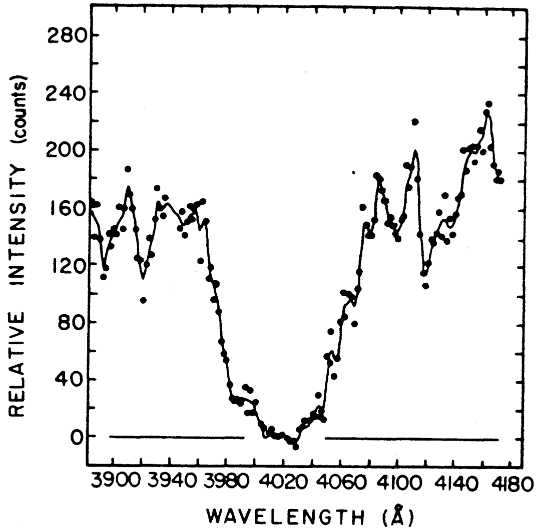

FIGURE 9 Digicon measurements of PHL 957. Note the extremely low intensity in the central 30 Å of the absorption "hole". (Beaver *et al.*[21]) (By permission of the University of Chicago Press. © by the American Astronomical Society.)

IX RADIO ABSORPTION LINES

Single radio absorption lines have been detected in three quasars, 3C 286,[79] 4C 32.33[80] and 3C 232,[81] and a BL Lac object, AO 0235 + 164.[82] There are four possibilities to explain such lines on the PLS model: (a) Transitions between high Rydberg levels (see also Shaver[83]), (b) Transitions between hyperfine structure components of the ground state and also those of metastable states lying below the first ionization potential, (c) Transitions between fine structure components of Wu levels of such ions as He^-, Mg^- and Ca^-, and (d) Transitions between hyperfine structure components of Wu levels. It should also be noted that the observed radio lines may be due to as yet unknown interstellar molecules.

X TRIBUTE

In conclusion, I wish to express my great pleasure in presenting this paper as a contribution to the book dedicated to Professor Ta-You Wu, to whom I will add my very best personal greetings and wishes for continued good health through many years to come.

References

1. M. Schmidt, *Astrophys. J.*, **141**, 1295 (1965).
2. Y. P. Varshni, *Bull. Am. Phys. Soc.*, **18**, 1384 (1973).
3. Y. P. Varshni, *Bull. Am. Astron. Soc.*, **6**, 213 (1974).
4. Y. P. Varshni, *Bull. Am. Astron. Soc.*, **6**, 308 (1974).
5. Y. P. Varshni, *Astrophys. Space Sci.*, **37**, L1 (1975).
6. Y. P. Varshni and C. S. Lam, *Astrophys. Space Sci.*, **45**, 87 (1976).
7. Y. P. Varshni, *Astrophys. J., Lett.*, **193**, L5 (1974).
8. Y. P. Varshni, *Astrophys. J.*, **201**, 547 (1975).
9. Y. P. Varshni, *Astrophys. Space Sci.*, **42**, 369 (1976).
10. Y. P. Varshni, *Astrophys. Space Sci.*, **43**, 3 (1976); *Astrophys. Space Sci.*, **51**, 121 (1977).
11. K. I. Kellermann, *Astron.. J.*, **77**, 531 (1972).
12. Y. P. Varshni, *Astrophys. Space Sci.*, **46**, 443 (1977).
13. W. J. Luyten and J. A. Smith, *Astrophys. J.*, **145**, 366 (1966).
14. W. L. Sanders, *Astrophys. J.*, **146**, 609 (1966).
15. W. J. Luyten, *A Search for Faint Blue Stars*, University of Minnesota Observatory, Minneapolis, Paper 50 (1969).
16. Y. P. Varshni, *Bull. Am. Astron. Soc.*, **9**, 578 (1977).
17. K. M. Cudworth, *Astron. J.*, **79**, 1384 (1974).
18. J. L. Greenstein and M. Schmidt, *Astrophys. J. Lett.*, **148**, L13 (1967).
19. E. M. Burbidge, C. R. Lynds, and A. N. Stockton, *Astrophys. J.*, **152**, 1077 (1968).
20. J. L. Lowrance, D. C. Morton, P. Zucchino, J. B. Oke, and M. Schmidt, *Astrophys. J.*, **171**, 233 (1972).
21. E. A. Beaver, E. M. Burbidge, C. E. McIlwain, H. W. Epps, and P. A. Strittmatter, *Astrophys. J.*, **178**, 95 (1972).
22. G. Coleman, R. F. Carswell, P. A. Strittmatter, R. E. Williams, J. Baldwin, L. B. Robinson, and E. J. Wampler, *Astrophys. J.*, **207**, 1 (1976).
23. P. A. Strittmatter, R. F. Carswell, E. M. Burbidge, C. Hazard, J. A. Baldwin, L. Robinson, and E. J. Wampler, *Astrophys. J.*, **183**, 767 (1973).
24. R. F. Carswell, R. L. Hilliard, P. A. Strittmatter, D. J. Taylor, and R. J. Weymann, *Astrophys. J.*, **196**, 351 (1975).
25. M. Schmidt, *Astrophys. J.*, **144**, 443 (1966).
26. J. N. Bahcall, B. A. Peterson, and M. Schmidt, *Astrophys. J.*, **145**, 369 (1966).
27. C. R. Lynds, *Astrophys. J.*, **147**, 837 (1967).
28. C. R. Lynds, *Astrophys. J.*, **147**, 396 (1967).
29. E. M. Burbidge, *Astrophys. J. Lett.*, **160**, L33 (1970).
30. O. Struve, *Astrophysics*, 85, J. A. Hynek (Ed.), McGraw-Hill Book Co. (1951).
31. P. W. Merrill, *Publ. Astron. Soc. Pacific*, **61**, 38 (1949).
32. P. W. Merrill and C. G. Burwell, *Astrophys. J.*, **110**, 387 (1949).
33. A. B. Underhill, *Publ. Dominion Astrophys. Obs. Victoria* **9**, 143 (1958).
34. A. B. Underhill, *The Early Type Stars*, D. Reidel Publishing Co., Dordrecht (1966).
35. M. Hack and O. Struve, *Stellar Spectroscopy II. Peculiar Stars*, Observatorio Astronomico di Trieste, Trieste (1970).
36. P. W. Merrill and A. L. Lowen, *Astrophys. J.*, **118**, 18 (1953).
37. P. W. Merrill, *Astrophys. J.*, **115**, 42 (1952).
38. O. Struve and P. Swings, *Astrophys. J.*, **93**, 446 (1941).
39. R. B. Baldwin, *Astrophys. J.*, **97**, 388 (1943).
40. R. B. Baldwin, *Astrophys. J.*, **93**, 333 (1941).
41. P. W. Merrill, *Astrophys. J.*, **115**, 47 (1952).
42. O. Struve and K. Wurm, *Astrophys. J.*, **88**, 84 (1938).
43. L. Goldberg, *Astrophys. J.*, **93**, 244 (1941).
44. P. Wellmann, *Z. Astrophysik*, **30**, 71 (1952). See also A. A. Nikitin, *Dokl. Akad. Nauk SSSR*, **85**, 285 (1952).
45. R. D. Rundel and R. F. Stebbings, *Case Studies in Atomic Collision Physics*, 549, E. W. McDaniel and M. R. C. McDowell (Eds.), North-Holland (1972).

46. O. Struve, *Publ. Astron. Soc. Pacific*, **54**, 11 (1942).
47. O. Struve, *Astrophys. J.*, **95**, 134 (1942).
48. H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms*, Springer-Verlag, Berlin (1957).
49. R. F. Stebbings, *Science*, **193**, 537 (1976).
50. S. E. Kupriyanov, Z. Z. Latypov, and A. A. Perov, *Zhur. Eksper. Teor. Fiz.*, **47**, 21 (1964).
51. S. E. Kupriyanov and Z. Z. Latypov, *Zhur. Eksper. Teor. Fiz.*, **47**, 52 (1964).
52. T. F. Gallagher, S. A. Edelstein, and R. M. Hill, *Phys. Rev.*, **A11**, 1504 (1975).
53. R. F. Stebbings, C. J. Latimer, W. P. West, F. B. Dunning, and T. B. Cook, *Phys. Rev.*, **A12**, 1453 (1975).
54. F. Gounand, P. R. Fournier, J. Cuvellier, and J. Berlande, *Phys. Letters*, **A59**, 23 (1976).
55. H. G. Berry, *Physica Scripta*, **12**, 5 (1975).
56. I. Martinson and A. Gaupp, *Phys. Letters*, **C15**, 113 (1974).
57. P. Feldman and R. Novick, *Phys. Rev.*, **160**, 143 (1967).
58. T.-Y. Wu, *Phys. Rev.*, **58**, 1114 (1940); T.-Y. Wu and S. T. Shen, *Chinese J. Phys.*, **5**, 150 (1944).
59. M. Levitt, R. Novick, and P. D. Feldman, *Phys. Rev.*, **A3**, 130 (1971).
60. S. T. Manson, *Phys. Rev.*, **A3**, 147 (1971). D. L. Mader and R. Novick, in *Atomic Physics* **3**, 169, S. J. Smith and G. K. Walters (Eds.) Plenum (1973).
61. J. P. Buchet, M. C. Buchet-Poulizac, H. G. Berry, and G. W. F. Drake, *Phys. Rev.*, **A7**, 922 (1973).
62. E. U. Condon and G. H. Shortley, *The Theory of Atomic Spectra*, Cambridge University Press, Cambridge (1959).
63. H. S. W. Massey and D. R. Bates, *Rept. Prog. Phys.*, **9**, 62 (1942).
64. D. R. Bates and A. Dalgarno, *Atomic and Molecular Processes*, Chap. 7, D. R. Bates (Ed.), Academic Press (1962).
65. A. Burgess, *Astrophys. J.*, **139**, 776 (1964).
66. A. H. Gabriel, *Mon. Not. Roy. Astron. Soc.*, **160**, 99 (1972).
67. S. Suckewer, *Phys. Rev.*, **170**, 239 (1968).
68. J. Richter, *Tenth Internat. Conf. on Phenomena in Ionized Gases*, Invited Papers, **37**, Donald Parsons & Co. Ltd., Oxford (1971).
69. J. A. Baldwin, E. M. Burbidge, G. R. Burbidge, C. Hazard, L. B. Robinson, and E. J. Wampler, *Astrophys. J.*, **193**, 513 (1974).
70. W. C. Livingston, *Advances in Electronics and Electron Physics*, **23**, 347 (1967).
71. W. A. Morton and D. C. Morton, *Astrophys. J.*, **178**, 607 (1972).
72. D. C. Morton and W. A. Morton, *Astrophys. J.*, **174**, 237 (1972).
73. R. E. Williams, P. A. Strittmatter, R. F. Carswell, and E. R. Craine, *Astrophys. J.*, **202**, 296 (1975).
74. R. J. Weymann, R. E. Williams, E. A. Beaver, and J. S. Miller, *Astrophys. J.*, **213**, 619 (1977).
75. L. Goldberg, in *Autoionization*, I. A. Temkin (Ed.), Mono Book Corp., Baltimore (1966).
76. R. F. Carswell, P. A. Strittmatter, R. E. Williams, T. D. Kinman, and K. Serkowski, *Astrophys. J., Lett.*, **190**, L101 (1974).
77. G. H. Rieke, G. L. Grasdalen, T. D. Kinman, P. Hintzen, B. J. Wills, and D. Wills, *Nature*, **260**, 754 (1976).
78. E. M. Burbidge, R. D. Caldwell, H. E. Smith, J. Liebert, and H. Spinrad, *Astrophys. J., Lett*, **205**, L117 (1976).
79. R. L. Brown and M. S. R. Roberts, *Astrophys. J., Lett.*, **184**, L7 (1973).
80. A. D. Haschick and B. F. Burke, *Astrophys. J., Lett.*, **200**, L137 (1975).
81. M. Grewing and U. Mebold, *Astron. & Astrophys.*, **42**, 119 (1975).
82. M. S. Roberts, R. L. Brown, W. D. Brundage, A. H. Rots, M. P. Haynes, and A. M. Wolfe, *Astrophys. J.*, **81**, 293 (1976).
83. P. A. Shaver, *Astron. & Astrophys.*, **46**, 127 (1976).