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NEBULAR AND AURORAL TRANSITIONS OF [Ar IV] IN SOME PLANETARY NEBULAE

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ABSTRACT

Measurements of auroral and nebular type transitions in several planetary nebulae of high surface brightness lead to the conclusion that presently available collisional cross sections and transitions probabilities for $3p^3$ configurations in Ar^{+3} may be in error. The observed auroral/nebular line ratio is always larger than the predicted value, and the disagreement is further aggravated if auroral lines are weakened by telluric line absorption.

Subject headings: atomic processes — nebulae: planetary — transition probabilities

I. INTRODUCTION

One of the problems in interpreting forbidden line intensities in gaseous nebulae is that we have had to rely exclusively on theoretical predictions of collisional strengths and *A*-values. Refinements in theory have produced substantial changes in the cross sections and consequently in the derived nebular diagnostics. Observational checks have been mostly indirect; for example, do fine structure line ratios calculated for np^3 configurations give consistent or at least plausible gas densities? Only in a few instances can we compare both auroral (or transauroral) and nebular line intensities in the same ion. One example is [S II] where we can observe the transauroral λλ4068, 4076 and nebular λλ6717, 6731 lines, but here the transauroral lines are often blended with O II features, etc. The results from [S II] are to some extent difficult to interpret, but they actually show some of the same tendencies as we find for [Ar IV]. In [Ar IV] where one can observe both nebular and auroral transitions, we shall show that severe discordances exist between theory and observation.

Argon is represented in the spectra of gaseous nebulae by lines of [Ar III], [Ar IV], and [Ar V]. In H II regions and low excitation planetaries, only the Ar III nebular type transitions (λλ7135, 7751) are observed. Higher excitation planetaries show lines of [Ar IV] and [Ar V]. Here we devote our attentions to [Ar IV].

II. OBSERVATIONAL PROCEDURES

Observations were obtained at the coudé focus of the Mount Wilson 2.5 m telescope with the Shectograph, the Varo-Reticon photon counting detector system, mounted in the coudé spectrograph. Our survey of the spectra of high surface brightness planetaries included spectral regions centered at λ4686 (to measure the [Ar IV] nebular type transitions at λλ4711, 4740 as well as other features) and near λ7135.

This latter region includes [Ar V] λ7005, [Ar III] λ7135, and the auroral type transitions of [Ar IV], λλ7170, 7237, 7262. The system detects the light from two apertures, each 3″.5×0″.5, and separated by 6″ on the sky. Thus we could place a small planetary on one of the slots while the other measured the sky, integrate typically for 1000s, then place the nebula on the other slit, etc. The computer program subtracts the sky from object plus sky. With large objects, both slots would be exposed to the nebular light. Then, one had to integrate first on the nebula, and then for an equal interval of time on the sky. Since cumulative records are displayed on the oscilloscope, the observer can watch the pattern grow and decide when the integration is to be terminated. Individual spectral regions covered about 250 Å in the blue and 400 Å in the red. The "blue" region observations (here defined as the one centered on λ4686) involve lines of C II, C III, N III, O II, [Fe III], He I, and He II as well as the aforementioned [Ar IV] nebular lines, while the "red" region included He I λλ7065, λ7281, He II λ7178, and [O II] λλ7230, 7330. Observations of appropriate comparison stars chosen from the data by Stone (1974) supplied appropriate response function calibrations. In reducing the data it is necessary to apply corrections for nonlinearity of the dispersion, atmospheric extinction, and then apply the response function. In each spectral region, a further

1980ApJ...241..719C

calibration is offered by comparison with spectrophotometric measurements by Peimbert and Torres-Peimbert (1977), Barker (1978), and Aller and Czyzak (1979).

Table 1 gives the wavelength of each line (Bowen 1960), the ion responsible, the A-values according to Czyzak and Krueger (1963), and the spectroscopic designation for the transition. Table 2 lists the observed and corrected nebular line intensities for seven planetaries of relatively high surface brightness. Here I_0 denotes the observed intensity and I_c the intensity corrected for interstellar extinction, using the Whitford (1958) extinction function. The extinction constants are adopted from other sources (Kaler *et al.* 1976; Aller and Czyzak 1979). All intensities are referred to $I(\mathrm{H}\beta) = 100$. We also indicate those lines for which some telluric line absorption is expected: footnote b denotes a small to moderate effect, footnote a indicates a possible serious effect. Depending on the combined Doppler effect of the nebular radial velocity and the projection of the Earth's orbital motion, nebular lines in the red spectral regions occasionally can be shifted behind telluric (mostly water vapor) absorption features. For example, although [Ar iii] λ7135 appears to be unaffected, [Ar v] λ7005.67 can be perturbed by atmospheric λ7004.31, λ7004.75, λ7005.12, λ7005.61, and a few other weaker features. Among the [Ar iv] transitions, λ7237.26 is generally unaffected, λ7262.76 can be weakened by λ7261.5, λ7262.0, λ7262.97 (water vapor), while λ7170.62 can be attenuated by a host of telluric lines at λ7169.9, λ7170.09, λ7170.33, λ7170.57, λ7170.87, λ7170.04, and λ7192.95. Furthermore, in low-dispersion scans such as those obtained with the image dissector scanner (Aller and Czyzak 1979), λ7170.6 is blended with He ii λ7177.8. The λ7332 $^2D_{5/2}-{}^2P_{1/2}$ transition is lost beneath the strong [O ii] auroral lines. We estimated the influence of the telluric lines by calculating the expected positions of the nebular lines at the epoch of each observation. For this purpose we adopted the radial velocity of the object from the compilation of Perek and Kohoutek (1967). Then we calculated the sum reduction by standard procedures and derived the momentary radial velocity of the nebula with respect to the observer. With the aid of the Minnaert solar spectrum atlas, we could readily verify if telluric absorption was likely to be important. A quantitative assessment of the effect was not possible since we had no measurement of the water vapor absorption at the time of observation, other than a rough check provided by the underlying nebular continuous spectrum, if present, and by the comparison star. Water vapor attenuation, although present in some lines, apparently is not significant, except in a few instances as noted in Table 2.

III. INTERPRETATION OF THE DATA

One of the popular electron density diagnostics is the [Ar iv] λ4711/4740 ratio (Krueger, Aller, and Czyzak 1970; Czyzak, Krueger, and Aller 1970; Saraph and Seaton 1970). In practice, it is often not possible to use this ratio because λ4711 is blended with λ4713 in the low dispersions customarily used except in high-excitation planetaries where λ4713 is weak. By taking advantage of the high dispersion offered by the coudé and the efficiency of the Shectograph, the two lines are separated.

TABLE 1

Transition Probabilities of Ar iii, Ar iv, and Ar v

λ	Ion	A	Transition
4711.34 ...	Ar iv	0.00961	$^4S_{3/2}-{}^2D_{5/2}$
4740.20 ...	Ar iv	0.0768	$^4S_{3/2}-{}^2D_{3/2}$
7005.67 ...	Ar v	0.514	$^3P_2-{}^1D_2$
7135.80 ...	Ar iii	0.321	$^3P_2-{}^1D_2$
7170.62 ...	Ar iv	0.912	$^2D_{3/2}-{}^2P_{3/2}$
7137.26 ...	Ar iv	0.670	$^2D_{5/2}-{}^2P_{3/2}$
7262.76 ...	Ar iv	0.678	$^2D_{3/2}-{}^2P_{1/2}$

From our present data, we can calculate a number of auroral line ratios and auroral/nebular line ratios. For example, the theoretical ratio, $I(\lambda 7237/I(\lambda 7171) = 0.73$, is fixed. It depends only on the ratio of transition probabilities. The observed ratio (from data in Table 2) exceeds unity, possibly because λ7171 is so frequently weakened by telluric lines. If we use $b(J)$ to denote the factor by which the population of a given level, J, deviates from the thermodynamic equilibrium value appropriate to the ambient electron temperature, T_e, we find, e.g., that

$$\frac{I(\lambda 7262)}{I(\lambda 7237)} = 0.504\,\frac{b(^2P_{1/2})}{b(^2P_{3/2})}$$

varies from 1.18($\log x = -2$) to 1.04($\log x = +2$) at $T = 17{,}500$ K. Only at very high densities would it approach the asymptotic values of 0.504. The observed ratios (see Table 3) fall between 0.5 and 1.0, which would imply very high densities in the Ar^{+3} region, or effects of telluric extinction, or inaccuracies in the collision strengths. The required densities are so high that we would be forced to conclude that all [Ar iv] lines originate in unique pockets, which seems improbable. Telluric extinction cannot account for the effect, and we suspect that inaccuracies in the atomic parameters are responsible.

Normally we are concerned with the diagnostic ratios

$$\frac{I(\lambda 4711)}{I(\lambda 4740)} = 0.119\,\frac{b(^2D_{5/2})}{b(^2D_{3/2})}$$

which depends strongly on x and slowly on t. We may now also compare the auroral and nebular transitions, viz.,

$$\frac{I(\lambda 7237)}{I(\lambda 4740)} = 15.51\,\frac{b(^2P_{3/2})}{b(^2D_{3/2})}\,10^{-0.86/t} = A(x,t)10^{-0.86/t}.$$

1980ApJ...241..719C

TABLE 2

OBSERVED AND CORRECTED NEBULAR LINE INTENSITIES

NEBULA	λ (Å) 4711	4740	7005	7135	7170	7237	7262	
NGC 7027:								
I_0..........	1.36	6.15	13.6	84	2.0[a]	3.06	1.54	$C=1.37$
I_c..........	1.55	6.87	4.0	23.5	0.54[a]	0.81	0.41	
NGC 7662:								
I_0:								
I........	5.05	4.0	1.49	6.25	0.43	0.55	0.38	$C=0.16$
II........	6.72	5.67	1.35	11.0	0.37	0.55	0.31	
I_c:								
I........	5.13	4.05	1.29[a]	5.4	0.37	0.47	0.33[b]	
II........	6.83	5.74	1.17[a]	9.47	0.32	0.47	0.26[b]	
86° −8.1:								
I_0..........	5.3	4.76	[8.7]	9.9	0.21	[0.4]	0.41	$C=0.5$
I_c..........	5.5	4.9	[5.7]	6.2	0.13	[0.24]	0.25	
IC 2165:								
I_0..........	5.41	6.0	1.77[b]	11.0	0.34	0.51	0.34	$C=0.62$
I_c..........	5.74	6.3	1.01[b]	6.14	0.19	0.30	0.19	
NGC 2440:								
I_0:								
a........	6.26	7.2	5.55	36.8	0.64	0.76	0.54	$C=0.64$
b........	6.3	6.9	6.26	42.0	0.82	0.76	0.75	
I_c:								
a........	6.6	7.5	3.1	20.2	0.35[b]	0.41[b]	0.29	
b........	6.7	7.2	3.5	23.0	0.45[b]	0.41[b]	0.40	
NGC 6572:								
I_0..........	...	...	...	28.2	0.165[a]	0.465	0.09	$C=0.5$
I_c..........	1.72	2.02	...	17.7	0.103[a]	0.29	(0.55)	
IC 4997:								
I_0..........	0.046	0.46	...	4.3	0.32	0.20	0.13	$C=0.5$
I_c..........	0.048	0.48	...	2.7	0.20	0.12	0.08	

[a] Strongly affected by telluric lines.

[b] Slightly affected by telluric lines.

TABLE 3

COMPARISON OF THE AURORAL AND NEBULAR LINE DENSITY RATIOS

Nebula (1)	t (2)	$\log x$ (3)	$\frac{\lambda 4711}{\lambda 4740}$ (4)	Derived $\log x$ (5)	$\frac{\lambda 7263}{\lambda 7237}$ (6)	$\frac{\lambda 7237}{\lambda 4740}$ (7)	$\log x$ (8)
IC 2165......	1.35	−0.4	0.91	+0.30	0.61	0.048	+1.4
NGC 2440...	0.97	−0.15	0.86	+0.38	0.7	0.054	1.46
	1.35	+0.1	0.93	+0.281	1.0	0.056	1.50
NGC 6572...	1.0	−0.05	0.85	+0.43	...	0.141	2.5
NGC 7027...	1.15	+1.0	0.23	(1.5)	0.50	0.12	2.16
IC 4997......	1.86:	+1.0	1.10	>2	0.65	0.25	2.26
	1.6	−0.10	1.17	−0.20	(1.0)	0.05	1.22
NGC 7662...	1.3	−0.40	1.27	−0.38	0.69	0.12	2.05
			1.18	−0.10	0.46	0.082	1.82

Here $A(x, t)$ depends slowly on t, but steeply on x, for $x > 1$; see Table 4.

Columns (2) and (3) of Table 3 list, for each object, values of $t = T_e/10{,}000$ and $x = 10^{-4}N_e/\sqrt{t}$ as obtained from previous analyses (see Kaler *et al.* 1976; Aller and Czyzak 1979; Shields, Aller, and Czyzak 1980). Column (5) then lists values of $\log x$ from the λ4711/λ4740 ratio. In most instances the resultant densities are larger than those obtained by other diagnostics. Column (6) gives the observed value of the λ7263/λ7237 ratio which again would imply high densities (as noted above). Column (7) gives λ7237/λ4740 ratio. If we adopt t from column (2), we derive the $\log x$ values as shown in column (8). If we take higher temperatures in the Ar^{+3} zone, values of $\log x$ will be decreased, but no reasonable value of t will give x-values

TABLE 4

DEPENDENCE OF $A(x, t)$ ON THE TEMPERATURE AND ELECTRON DENSITY $A_2(x, t) = 15.5b(^2P_{3/2})/b(^2D_{3/2})$

log x	−2	−1.0	−0.5	0	+0.5	+1.0	+1.5	+2	+2.5
t=1.0	0.076	0.078	0.081	0.089	0.108	0.142	0.248	0.505	1.26
t=1.75	0.072	0.074	0.077	0.085	0.101	0.133	0.227	0.473	1.21

that can be reconciled with other independent data. Thus, again, unless one is prepared to believe that Ar^{+3} ions are concentrated uniquely in very dense blobs, the only conclusion that can be drawn is that the cross sections and perhaps also the A-values are in error. This question was raised by Kaler *et al.* (1976) in a discussion of NGC 7027. In other words, if one accepts the presently available collision strengths and A-values, the observed auroral [Ar IV] lines are systematically *too strong* with respect to the nebular type transitions. Any systematic errors caused by inadequate allowance for telluric line absorption would only further aggravate the situation.

We may mention another, independent approach that illustrates the problems involved. Theoretical models have been calculated for a number of medium excitation planetaries. In one set of models, hereafter denoted (I), the charge exchange reaction $O^{++} + H^0 \rightarrow O^+ + H^+$ is neglected (Aller *et al.* 1979). In a second set of models, denoted (II) (Keyes and Aller 1980), this reaction is included, as are others given by Butler, Bender, and Dalgarno (1979), together with additional values kindly supplied by Dalgarno in advance of publication. These include: $Ar^{+3} + H^0 \rightarrow Ar^{+2} + H^+ (\sigma = 4.4 \times 10^{-9})$; $Ar^{+4} + H^0 \rightarrow Ar^{+3} + H^+ (\sigma = 6.5 \times 10^{-9})$; $Ar^{+4} + He^0 \rightarrow Ar^{+3} + He^+ (\sigma = 9.8 \times 10^{-10})$; $Ar^{+2} + He^0 \rightarrow Ar^+ + He^+ (\sigma = 1.3 \times 10^{-10})$. In each instance the observed intensities of He I, [N II], [O II], [O III], [Ne III], [S III], and a few other ionic lines are represented by the models to within observational error. If we fit the [Ar III] λ7135 intensities, then (except in NGC 6790) the [Ar IV] lines are predicted too strong. See Table 5. Inclusion of charge exchange can have pronounced effects on the ionization balance. Suppose, for example, we use the observed λ3727/λ5007 intensity ratio as a parameter to define an acceptable model. If a given nebula is represented by model (I), then in order to recover this same ratio in a type (II) model, we have to raise the temperature of the central star (in order to increase the number of photons capable of ionizing O^+ to O^{++}) and also truncate the outer lower ionization zone more severely in order to cut down the volume emitting [O II]. This effect would tend to favor Ar^{+3} over Ar^{+2}.

Péquignot (1978) emphasized the importance of charge-exchange reactions and has attempted to adjust the rates to fit the line intensities. Our point of view is that physical reaction rates should be obtained from laboratory experiments or theory; model data in themselves do not establish a quantitative basis for cross section and transition probability corrections.

Inclusion of the new argon charge-exchange cross sections makes an impressive difference. Keyes and Aller calculated a number of models without them. The

TABLE 5

EFFECT OF INCLUDING CHARGE-EXCHANGE REACTIONS IN THEORETICAL MODEL CALCULATIONS

Nebula and Ionization State	Ar III λ7135	Ar IV λ4740
NGC 6543:		
0	13.8	0.66
I	17.2	2.6
II	13.2	2.7
NGC 6826:		
0	5.7	0.5
I	5.8	5.7
II	5.0	1.7
MI-74:		
0	27.7	1.1
I	27.7	14.8
II	28.0	6.7
IC 4856:		
0	8.2	1.05
I	8.0	2.6
II	8.0	2.3
NGC 6790:		
0	4.8	2.4
I	4.8	4.0
II	4.4	1.8

1980ApJ...241..719C

TABLE 6

f-VALUES FOR C III, N IV, O V, AND Sr I

Ion	λ(Å)	Transition	f_{exp}	f_{th}
C III . . .	2297	$2s2p\ ^1P^o$–$2p^2\ ^1D$	0.187	0.47[a]
				0.27[b]
				0.19[c]
N IV . . .	1718	$2s2p\ ^1P^o$–$2p^2\ ^1D$	0.157	0.38[a]
O V	1371	$2s2p\ ^1P^o$–$2p^2\ ^1D$	0.147	0.32[a]
				0.18[b]
				0.15[c]
Sr I	4608	$5s5p\ ^1P^o$–$5s^2\ ^1S$	1.84	2.46[a]
				1.84[b]

[a] Coulomb type wave functions.
[b] Hartree-Fock wave functions.
[c] Hartree-Fock with superposition of configurations.

predicted value of the intensity of λ4740 ranged from 5.5 to 8.4 times greater than the values found in Table 5 for model II.

Improvement in the transition probability values is not likely to be significant. These calculations have been made with Hartree-Fock (HF) wave functions. The configuration interactions were taken into account in the intermediate coupling calculations in the determination of the transition probability values. Thus, these determinations were made with the most accurate wave functions available. Any improvement in HF calculations would include configuration interaction. For example, consider the transitions in Table 6 for several ions. Here we see that even when using Hartree-Fock wave functions the matter of configuration interaction can not be ignored. However, since configuration interactions have been included in the earlier transition probability calculations, the use of improved Hartree-Fock configuration interaction (HFCI) wave functions is not likely to alter the earlier results significantly.

Insofar as the collision strengths are concerned, the possibility that these values need improvement seems reasonable. The earlier results of Krueger and Czyzak (1970) were made with the best available wave functions, namely, HF and HFCI, but the distorted wave (DW) and exact resonance (ER) methods for calculating the collision strengths have since been modified by Seaton and his coworkers who also have used other means of calculating the collision strengths, e.g., close-coupling method. Thus the new values for waves of the np^3 configuration differ from the earlier ones at the threshold energy by approximately 25%. In view of this fact, one can also expect that the ions of np^2 and np^4 may, as well, differ by an equivalent amount. This would affect the ionic concentrations, electron temperatures, etc., attained from the [Ar III] and [Ar V] collision strengths.

In addition, it is necessary to consider the fact that while the newer calculations of the collision strengths, (Pradhan 1976, 1978), which represent an improvement over the older formalism, employed Fermi-Thomas-Dirac (FTD) wave functions, these functions unfortunately represent a lower order of accuracy than the HFCI.

In the FTD method, scaling factors are employed to try to ensure that wave functions are the result of the minimum energy. There are two ways of approaching the minimum energy, namely, (*a*) choose λ to obtain agreement between calculated and observed quantities, and (*b*) use the variational principle for minimizing the energy which gives the minimum variational energy. With reference to (*a*), this requires considerable patchwork and is a semiempirical procedure that is of questionable value. As for (*b*), this procedure does what one does with the HF method, *but* the potential used is *limited*. Thus in the FTD method one has a particular potential with *one* adjustable parameter, and within these limitations or constraints one can find a certain minimum energy.

Now the HF method has no such constraints. The potential one obtains is that which gives the minimum energy. Thus one is not limited to a particular function, and with no constraints a lower energy is obtained. The optimum value of a self-consistent field is that which gives the lowest energy. The best one can hope for in the FTD method is to approach the HF result, provided one happens to have a fortuitous situation. A comparison of the FTD versus HF and FTD versus HFCI shows a significant difference in the wave function pattern. The higher order effects may also play an important role in the Ω calculations because when one compares the HF versus HFCI a difference between these two wave functions is observed. Thus even with an improved collision strength formalism one still must resolve the wave function difference. Another matter which may affect the Ω calculations is the autoionization resonances. Whether or not it increases or decreases along the isoelectronic sequence will determine the significance of such a contribution in the calculations. For example, if it should increase, then the present computed [Ar IV] Ω's could be in error by a large factor. On the other hand, if it decreases, then the present [Ar IV] Ω's probably would not be altered significantly.

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