ANALYSIS OF HIGH EXCITATION PLANETARY NEBULAE

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ABSTRACT

Combination of extensive ground-based spectroscopic observation of high excitation planetary with IUE data permit determination not only of improved diagnostics but also better abundances for elements such as C and N that are well-represented in the ultraviolet spectra, and also C, Ar and metals Na, Ca and K whose lines appear in the λ3200-8100Å region. We summarize here some of the principal results from a cooperative program being carried out in collaboration with S. J. Czyzak of Ohio State, G. Shields of the University of Texas, and B. J. O'Mara and J. E. Ross of the University of Queensland.

INTRODUCTION

In our preliminary survey (ref.1), short-wave IUE data were affected by image-processing difficulties that introduced systematic errors. These errors have now been eliminated. Table 1 lists the measured intensities. Successive columns list approximate wavelengths, identifications, and for each nebula (except NGC 6741 and 6886) the logarithm of the flux in ergs $cm^{-2}sec^{-1}$ as received at the top of the earth's atmosphere. Quality is indicated by a, b, c, d, e. Lines indicated by a or b are fairly strong; their accidental errors should be of the order of 10%. Lines of quality c may have errors amounting to 25 - 35%, while those of quality d are seriously affected by noise; errors here can easily amount to 50 - 100%. We use e to indicate that the feature is believed to be present; the tabulated intensity is to be understood as essentially an upper limit. Thus ionic concentrations estimated from lines of quality d are very uncertain; those from e quality lines are upper limits. See Figs. 1,2,3

In principle, objects of small angular size that fit into the large slot present no difficulties for determination of interstellar extinction. Following Seaton (ref.2) one may compare the HeII intensity ratio I(λ1640)/I(λ4686). Although NGC 2440 has some outlying ansae, most of its radiation is accepted. The nebular angular sizes of NGC 2392 and 6302 exceed that of the slot. For NGC 6302 we find an extinction constant C = 1.44 from the HeII λ1640/λ2734 intensity ratio as compared with 1.41 from a comparison of radio and optical data (ref.3). For NGC 2392, C = 0.15 is in accord with the 1640/2734 ratio when account is taken of the λ2734 intensity measurement.

The availability of extensive ground-based data covering a wide gamut of ionization stages (ref.4 and unpublished data for NGC 2867, NGC 2440, NGC 6741, NGC 6302, and Me 2-1) has made possible a more thorough investigation of these objects than otherwise possible. For example, lines of [CℓII], [CℓIII], [CℓIV], [ArIII], [ArIV], and [ArV] but especially [NeIII], [NeIV] λ4724, 25, and [NeV] help bridge the gap from domains of low to those of high excitation. Strata producing these lines overlap those responsible for lines of CIII, CIV, NIII, NIV, NV, and OIV observed with the IUE. If a reasonable estimate of the electron density can be found, we can use the [NeIV] auroral/nebular line ratio to estimate the electron temperature in these hotter, inner regions (eqn.4 of ref. 1).

In our earlier analysis (ref.1) we obtained diagnostics from optical region lines and calculated ionic concentrations from both optical and UV data. We found the ionization correction factors (ICF's) by interpolation in a grid of theoretical models based on Cassinelli's (ref.5) stellar fluxes and a fixed chemical composition. These grid models give a correct general excitation level but did not represent specific line intensities closely.

Our new method is to calculate individualized spherically symmetrical models for each nebula. We iterate an appropriate grid model, modifying the stellar energy distribution and truncation of the nebular radius to fit the observed intensity ratios for HeI/HeII, [OIII]/[OII], and [NeV]/[NeIII]. Lastly individual elemental abundances are adjusted to reproduce the observed optical region line intensities. This objective could be achieved for transitions of ions of He, N, O, and Ne observed with ground-based equipment but our present models are less satisfactory for the forbidden line of S, Cℓ and Ar. Curiously, if the lines of [ArIV] and [ArV] are represented, λ7135 of [ArIII] is too strong. The effect is exactly opposite to that found for our models of low-excitation nebulae. Inclusion of latest available charge exchange cross-sections, recombination coefficients, etc., has had a profound effect on our new series of models.

Spherically symmetrical shells or constant density models cannot predict successfully all nebular line intensities. By representing certain excitation ratios we hope that the general ionization pattern is adequately predicted. We then use the models to derive the ICF's and to estimate the electron temperature in the hotter inner regions. The [NeIV] aur/neb ratios support these estimates, although because of the high excitation potentials, the hottest portions of Ne^{+++} zones tend to be favored. We can derive the chemical composition by a best fit of the predicted intensities or by calculating ionic concentrations in the usual way and then using the models to derive the ICF's. We prefer the latter method, although both procedures agree reasonably well for most elements. The discordances tend to be larger for the clumpy nebulae, NGC 2392 and NGC 2440, particularly for nitrogen when the model representation was based on fitting the [NII] lines.

Although a reasonably good representation is found for visual region lines, agreement is less satisfactory in the ultraviolet. Many lines are weak and accidental errors are large which makes comparison difficult. The predicted NV 1239/41 intensities exceed the observed values which suggests the models predict too high a level of ionization for nitrogen. The predicted CIII/CIV intensity ratio always exceeds the observed one, presumably because of optical depth effects (ref.6). The predicted OIV 1403/09 intensity, however, tends to be less than the observed one. Theoretical predictions of the OIII 1661/66 feature tend to agree with the observed values, thus providing an independent check on the calibration and on the interstellar extinction. Although theoretical and observed [NeIV] aur/neb ratios tend to agree, when differences occur, they suggest that the electron temperature exceeds model predictions. Curiously, although a condition of acceptance of a model is that the [NeIII]/[NeV] line ratios are correctly represented, predicted [NeIV] intensities are too weak. Possibly a modification of the assumed stellar energy flux or an improvement in the cross-sections would remove this discordance.

The theoretical models suffer from simplistic assumptions about geometry and density. Obviously, they are poor approximations for NGC 2440 and NGC 2392; no such model can predict even approximately a satisfactory spectrum for NGC 6302. For this nebula, only approximate ICF's can be found.

Table 2 compares abundance estimates with those of a previous survey based exclusively on ground-based data (ref.7) and solar values (ref.8). Shields, Czyzak, and Aller are carrying out an analysis of NGC 2440 in which the straightjacket of a constant density structure is no longer imposed. (For consistency we treat NGC 2440 here on the same basis as the other nebulae). Note that low carbon abundances are found in the clumpy planetaries, NGC 2392, 2440, and especially 6302 which are not well represented in the constant density approximation. All of these nebulae appear to be nitrogen rich. Perhaps high-excitation planetaries originate exclusively from relatively massive stars in which nitrogen building has been prominent. Furthermore, the relatively small departures of the abundances of S, C, Ar, and K from solar values suggest that these nebulae, particularly, came from stars that did not differ greatly from a solar-type composition.

Becker and Iben (ref.9) have calculated asymptotic giant branch evolution of intermediate mass stars. They discuss abundance modifications for stars of different mass and composition for the first dredge-up phase on the red giant branch and for the second dredge-up phase on the asymptotic giant branch. The depletion of C and O and the enrichment of He and N depends on mass and initial composition, being the more marked the greater the mass and the initial He and/or heavy metal content. For massive (5-11 solar mass) progenitor stars, our observed abundance modifications agree qualitatively with their results (cf. their table 6) but the predicted helium enhancement is greater than the observed. Probably few planetaries have progenitor stars as massive as five solar masses.

Alternately, following Scalo, Despain, and Ulrich (ref.10) we can consider highly evolved stars with double shells which develop high temperatures ($50 - 80 \times 10^6$ ^{o}K) at the bottom of their convective envelopes between shell flashes. Near the upper end of this temperature range, full CNO processing can occur; carbon will be destroyed, and nitrogen will be enhanced. Helium will not be produced in excessive amounts. Stars down to a lower limit of 1.5 solar masses can be involved.

In summary, use of IUE data helps enormously in our understanding of the spectra of gaseous nebulae and enables us to handle the problem of chemical compositions more accurately. Curiously, in a number of instances the simple extrapolation methods suggested by Seaton, Peimbert and Costero, and others for N, O, and Ne seem to work rather well.

TABLE 1.-LOGARITHM OF INTENSITIES OF NEBULAR LINES

λ	iden	NGC 2392	NGC 2440	NGC 2867	Me 2-1	NGC 6302
1239/41	NV	-11.96b	-11.45a	-12.5:e	-12.1 e	-12.09b
1335	CII	-11.98 c		-12.15d	-12.45e	
1391	SiIV"					
1403, 1409	OIV	-11.53b	-11.60b	-12.64d	-11.79 c	-12.38b
1487	NIV	-11.49b	-10.95a	-11.90c	-11.99d	-11.66a
1548/50	CIV	-11.06a	-10.56a	-10.81a	-10.62a	-11.65a
1640	HeII	-10.72a	-10.57a	-10.79b	-10.90a	-11.80a
1661/66	OIII	-11.34b	-11.52a	-11.98c	-12.06e	-12.33b
1747	NIV	-11.23a	-11.08a	-12.06c	-12.21d	-11.68a
1892	SiIII	-11.48c	-11.76b			-12.70c
1906/09	CIII	-10.69b	-10.37a	-10.38a	-10.80a	-11.83a
2326/28	CII	-11.76c	-11.46a	-11.25a	-12.10c	
2422	[NeIV]	-11.17b	-11.06a	-11.71b	-11.26a	-11.87a
2470	OII		-11.84c	-12.16d		-12.64d
2511	HeII		-11.88c	-12.1 e	-12.30c	-12.73d
2734	HeII	-12.08c	-11.87c	-12.13c	-12.27c	-12.66c
2798/2800	MgII			-12.12d		
2830	HeI		-12.05c	-12.14c	-12.62d	-12.75d
3024	OIII			-12.4:c		-12.8:d
3047	OIII		-12.14d	-12.05c	-12.42d	-12.32d
3133	OIII	-11.71b	-11.04c	-11.16a	-12.39a	-11.52b
3187	HeI			-11.96c		
3204	HeII		-11.45b	-11.76c	-11.89b	-11.92c

TABLE 2.-SUMMARY OF ABUNDANCE ESTIMATES

	NGC 2392	NGC 2440	NGC 2867	Me 2-1	NGC 6302	NGC 6741	NGC 6886	mean	mean ref.7	Solar ref.8
He	10.96	11.08	11.05	11.01	11.27	11.04	11.01	11.03	11.02	11.08
C	8.35	8.37	9.03	8.88	8.04	9.01	8.83	8.77	9.10	8.62
N	8.32	8.78	8.13	8.23	8.96	8.4	8.8	8.58	7.97	7.94
O	8.56	8.61	8.65	8.73	8.71	8.74	8.63	8.67	8.66	8.84
Ne	7.69	8.03	7.91	8.20	8.02	8.34	8.21	8.11	8.02	8.1
Na		6.26					6.29	6.27	6.23	6.28
S	6.78	6.43	6.75	7.13	6.81	6.91	6.48	6.82	6.97	7.2
Cℓ	5.11	5.28	5.20	5.29	5.56	5.36	5.39	5.34	5.26	5.5
Ar	6.12	6.47	6.25	6.41	6.93	6.63	6.51	6.55	6.38	6.0
K	4.75	4.64		5.38	5.48	4.68	5.18	5.15	4.90	5.16
Ca	4.80	4.90		5.03	5.37	5.38	4.87	5.12	5.10	6.35
Extinct. Coeff.	0.15	0.67	0.52	0.28	1.44	1.30	1.09			

Extinct. Coeff. = $\log[F_T(H\beta)/F_O(H\beta)]$

where $F_O(H\beta)$ = observed Hβ flux.

$F_T(H\beta)$ = Hβ flux corrected for interstellar extinction.

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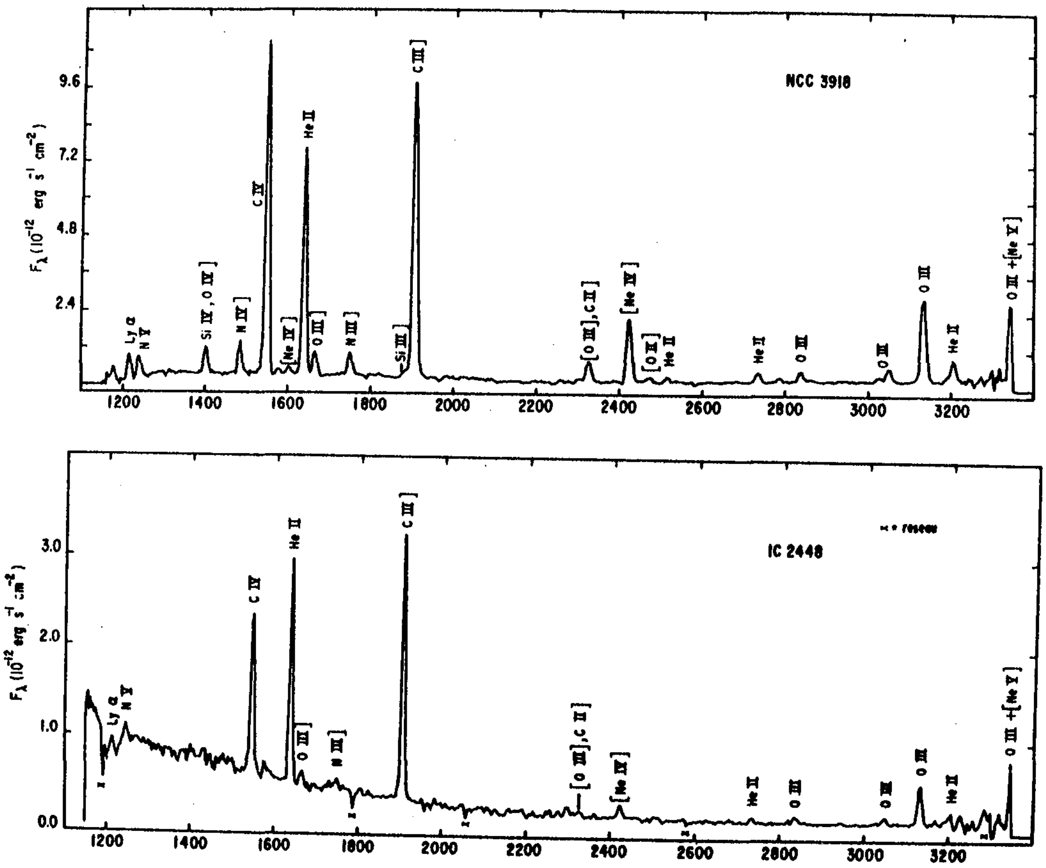

Figure 1. Calibrated IUE spectra. (a) For NGC 3918 we have added SWP 1906 and SWP 3192 for λ< 1950 A and all available large aperture spectrograms for longer wavelengths. (b) For IC 2448 we have combined SWP 3194 and LWR 2756.

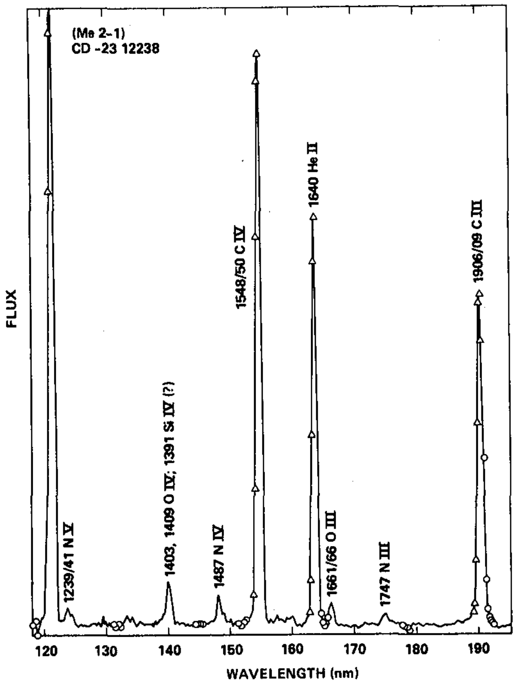

Fig. 1 Far Ultraviolet Spectrum of CD-2312238

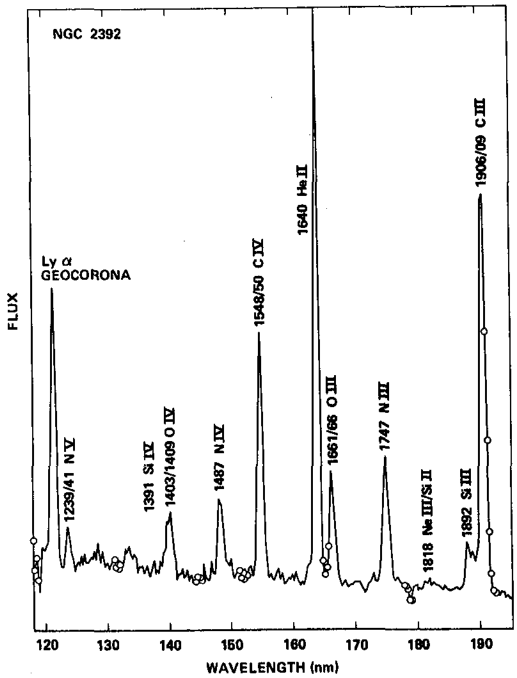

Fig. 2. Far Ultraviolet Spectrum of NGC2392