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ULTRAVIOLET SPECTRUM OF THE PLANETARY NEBULA NGC 7662. OBSERVATIONS AND MODELS

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RESUMEN

Presentamos observaciones de las líneas en emisión de NGC 7662 en el intervalo espectral 1150-3300 A, tomadas con el satélite *IUE*. Combinando estas observaciones con datos ópticos obtenidos por otros autores, derivamos la composición química de este objeto. Obtuvimos log C = −3.07, log N = −3.73, log O = −3.09 y log Ne = −3.70.

Hemos calculado modelos de estructuras de ionización y equilibrio térmico cuyas predicciones comparamos con los datos observacionales.

ABSTRACT

We present *IUE* observations of emission lines in the spectrum of NGC 7662 in the 1150-3300 A range. Combining these observations with optical data obtained by other authors, we derive the chemical composition for this object. We obtain log C = −3.07, log N = −3.73, log O = −3.09 and log Ne = −3.70.

We compute models of ionization structure and thermal balance to compare with the observed data.

Key words: **ABUNDANCES – NEBULAE-PLANETARY – ULTRAVIOLET-SPECTRA**

I. INTRODUCTION

NGC 7662 has been observed thoroughly in different spectral ranges by a number of authors because of its high surface brightness. From photoelectric observations Peimbert and Torres-Peimbert (1971) derived the abundances of He, N and O. Later Torres-Peimbert and Peimbert (1977, hereinafter TPP77) calculated C abundances for this object from photographic work compiled by Kaler (1976). Ultraviolet observations have been carried out by Bohlin, Harrington, and Stecher (1978) who derived C, N, and O abundances. *IUE* observations have also been carried out by Harrington, Lutz and Seaton (1979, 1981), and Benvenuti and Perinotto (1981) who derive C, N and O abundances.

In §II we describe the observations. In §III we present the derived abundances. We have computed models of ionization structures and compared them to the observations in §IV. Our discussion is given in §V.

II. OBSERVATIONS

We obtained the following *IUE* low dispersion exposures with the large aperture: SWP 3212 (20 min), SWP 3214 (5 min), LWR 2808 (20 min) and with the small aperture: SWP 3214 (5 min). In all cases the star was centered on the entrance aperture. The error in the ITF for the short wavelength spectra was corrected with the 3 Agency 4th File Method (Cassatella, Holm, Ponz, and Schiffer 1980). For calibration the mean *IUE* correction was applied (Bohlin and Snijders 1978). A composite large apertures spectrum of this object is presented in Figure 1.

In Table 1 we present, for each exposure, the observed emission line fluxes, F(λ). The internal errors of the measurements, as estimated from the comparison of different exposures, are <15%. For saturated lines only lower limits are given. Our measurements agree within 15% with those of Harrington *et al.* (1979).

The size of the *IUE* entrance aperture is smaller than the angular diameter of the nebula and, in order to scale our measurements, we have adopted $F(H\beta) = 3.95 \times 10^{-11}$ erg cm^{-2} s^{-1}, as derived from contours by Harrington *et al.* (1979) for the *IUE* large aperture.

The shape of the faint continuum appears compatible with a reddening of $0.15 < C(H\beta) < 0.30$, consistent with the values of $C(H\beta) = 0.20$ by Harrington *et al.*, and $C(H\beta) = 0.16$ by Peimbert and Torres-Peimbert (1971).

We have assumed $C(H\beta) = 0.20$, together with the reddening law f(λ), given in analytical form by Seaton (1979).

These assumptions yield an excess in He II I(1640)/I(4686) of a factor of 1.53, which is to be expected for a centrally condensed emission. On the other hand, the

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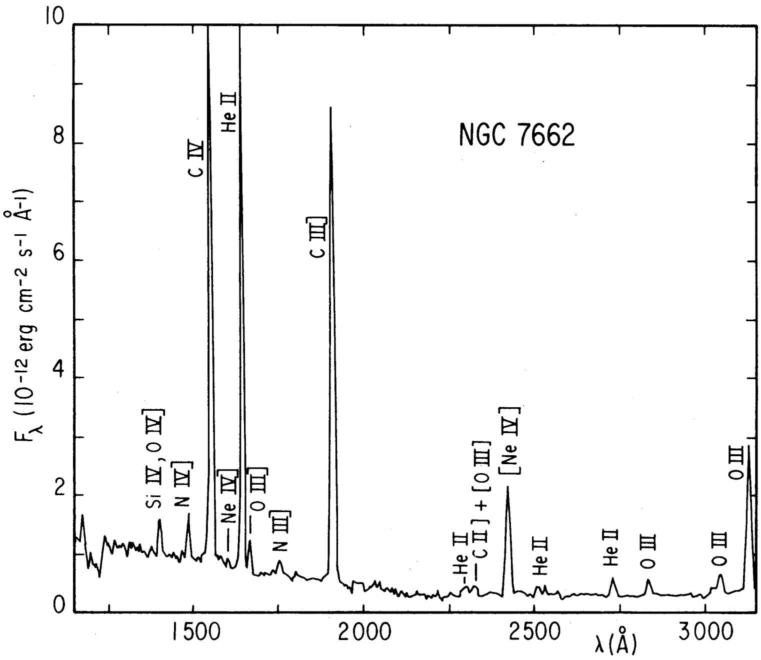

Fig. 1. Composite *IUE* spectrum. Calibrated flux from SWP 3213 and LWR 2808 joined at λ1950 A.

TABLE 1

LINE INTENSITIES

λ	Ion	F(λ)[a] SWP 3213 Large	SWP 3214 Large	SWP 3214 Small	LWR 2808 Large	I(λ)[b]
1176	C III	4.73	4.71	...	...	27.9
1215	H I	...	<8.	...	...	<45.2
1240	N V	<0.80	<0.80	(0.59)	...	< 4.3
1309	Si II	...	...	(0.90)	...	...
1404	O IV]+Si IV	6.90	5.82	(0.70)	...	31.8
1487	N IV]	7.35	8.66	...	...	38.6
1550	C IV	⩾153.9	173.7	6.44	...	758.
1603	Ne IV]	0.38	0.83	...	...	3.6
1640	He II	⩾105.5	90.2	4.14	...	442.
1664	O III]	4.80	3.70	...	...	20.4
1747	N III]	2.77	1.17	...	...	11.7
1909	C III]	⩾112.4	95.9	2.60	95.9	501.
2297	C III+He II	...	...	...	3.01	14.7
2326	C II]+[O III]	...	...	...	3.53	16.7
2424	[Ne IV]	...	...	...	⩾29.1	124.
2512	He II	...	...	...	1.99	7.8
2734	He II	...	...	...	4.84	16.9
2837	O III	...	...	...	3.74	12.6
3024/48	O III	...	...	...	7.39	23.5
3134	O III	...	...	...	40.9	145.
3204	He II	...	...	...	11.5	35.4

a. In units of 10^{-12} erg s^{-1} cm^{-2}.
b. Intensity relative to Hβ, where I(Hβ) = 100, C(Hβ) = 0.20, F(Hβ) = 3.95× 10^{-11} erg cm^{-2} s^{-1}.

I(1664)/I(5007) ratio of [O III] yields $T_e = 11900°K$, consistent with optical observations (§III).

In Table 1 we also present the intrinsic fluxes, I(λ), obtained as

$$\log \frac{I(\lambda)}{I(H\beta)} = \log \frac{F(\lambda)}{F(H\beta)} + C(H\beta)\ f(\lambda) \ .$$

III. IONIC ABUNDANCES

To derive the ionic abundances we need to adopt values for electron density and temperature. A density N_e(O II) = 4000 cm^{-3} has been reported by TPP77, and N_e(Ne IV) = 1.1 × 10^4 cm^{-3} has been found by Lutz and Seaton (1979) from high resolution observations of λλ2421, 2424. For our work we have adopted $N_e = 4000$ cm^{-3} as representative of the whole nebula.

The I(4363)/I(5007) ratio yields a temperature of 12500°K. A value of 12000°K is derived from I(1602)/I(2423) of [Ne IV]. By contrast, Benvenuti and Perinotto (1981) obtained a value of 13500°K for the Ne IV region. We do not think justified to use such a high temperature, and we have adopted $T_e = 12\,500°K$ for all regions in the nebula. Since NGC 7662 is highly ionized, the errors introduced by adopting a different temperature for the high ionization region can affect significantly the abundance derived from collisional excitation. However, for C we will use lines formed by recombination processes, which are not temperature dependent.

We derive ionic abundances assuming no temperature variations along the line of sight, $t^2 = 0.0$. The line intensities used for UV lines are those given in Table 1; for optical lines, those obtained from photoelectric photometry by Peimbert and Torres-Peimbert (1971); and for λλ4267 and 4650 those derived from photographic work in the literature (Kaler 1976). Our results are presented in Table 2.

We have determined the C^{++} abundance from λ1909 and from the recombination line λ4267, where the effective recombination coefficients have been taken from Pengelly (1963; also listed in Seaton 1978). We find a C^{++} value a factor of 2.9 lower from λ1909 than from λ4267; this difference can be due to an excess of 1700°K in the adopted temperature, to temperature fluctuations of $t^2 \sim 0.08$, or more likely, to an overestimate of the intensity of λ4267. For the total abundance we will use C^{++} abundance as derived from λ1909. The value listed in Table 2 for λ4267 was obtained by reducing arbitrarily the line intensity by a factor of 2.

The C^{3+} abundance has been computed from the resonance line λ1550, the recombination line λ4650 and the di-electronic recombination lines λλ2297 and 1176. The effective recombination coefficients given by Pen-

TABLE 2

IONIC ABUNDANCES[a]

Ion	λ	$\log N(X^{+m})/N(H^+)$	Notes
C^+	2326	−4.40	...
C^{++}	1909	−3.57	...
C^{++}	4267	−3.41	b
C^{3+}	1550	⩾−3.52	...
C^{3+}	4650	{ −3.04	c
		{ −3.85	d
C^{3+}	2297	−3.38	e
C^{3+}	1176	−3.15	f
N^+	6584	−6.00	...
N^{++}	1784	−4.48	...
N^{3+}	1487	−3.92	...
N^{4+}	1245	(−4.96)	g
O^+	3727	−5.02	...
O^{++}	1664	−3.82	...
O^{++}	5007	−3.72	...
O^{3+}	1404	−3.32	...
O^{5+}	1371	<−4.11	h
Ne^{3+}	2421	−4.11	...

a. UV lines from this paper; optical lines from Torres-Peimbert and Peimbert (1977); λλ4267 and 4650 from Kaler (1976).
b. Radiative recombination, line reduced by 0.50.
c. Radiative recombination, case A; line reduced by 0.50.
d. Radiative recombination, case B; line reduced by 0.50.
e. Di-electronic recombination, He II subtracted.
f. Di-electronic recombination.
g. Line was not observed.
h. Di-electronic recombination; line was not observed.

gelly for λ4650, yield C^{3+}, a factor of 6 and 38 times lower (cases A and B, respectively) than those given by Bednarek and Clarke (see Aller and Czyzak 1973), which were used by TPP77 and led them to very high values of C for several nebulae. In Table 2 we present those abundances computed with Pengelly's values; the intensities have been reduced by a factor of 2.

The C^{3+} value derived from λ1550 can be considered a lower limit to the true abundance because dust absorption makes the observed resonance line intensities lower than predicted (§IV).

The effective di-electronic recombination coefficients have been computed by Storey (1981) for several ions; we have used his computations for this work. The C^{3+} value from λ1176 appears a factor of 1.7 higher than that from λ2297; however the lack of sensitivity of the detector at λ1176 makes the value from λ2297 more dependable. We will adopt the C^{3+} abundance as obtained from λ2297, corrected for the contribution of λ2303 of He II, for the computation of total abundance.

From Table 2, it can be derived that λ4650 is probably produced in NGC 7662 under intermediate conditions between cases A and B. It should be noted that assuming an abundance of $N(C^{3+})/N(H^+) = 4.2 \times 10^{-4}$ (derived from λ2297), the predicted intensity from di-electronic recombination of λ1909 is only 5% of the observed intensity. Thus the C^+ abundance derived from λ1909 by considering collisional excitation is valid. By contrast the predicted intensity for λ1335 of C^{++} is a factor of 10 higher than the detection limit but the line is not observed. It is likely that λ1335 is also reduced by dust absorption. The lines λλ1245 and 1371 were not detected and the abundances of N^{4+} and O^{5+} given in Table 2 correspond to the detection limit.

Total abundances were derived from ionic abundances and are presented in Table 3. For carbon, total abundance was derived by adding directly the observed ions and assuming that the contribution of C^{4+} is given by Model C presented in Table 4. Therefore

$$\frac{N(C)}{N(H)} = 1.17 \frac{N(C^+ + C^{++} + C^{3+})}{N(H^+)} .$$

For nitrogen and oxygen the procedure is similar since we observe all ions but N^{4+} and O^{4+} which are expected to be present. We have adopted

$$\frac{N(N)}{N(H)} = 1.19 \frac{N(N^+ + N^{++} + N^{3+})}{N(H^+)} , \quad \text{and}$$

$$\frac{N(O)}{N(H)} = 1.18 \frac{N(O^+ + O^{++} + O^{3+})}{N(H^+)} ;$$

for neon we have used

$$\frac{N(Ne)}{N(H)} = 2.57 \frac{N(Ne^{3+})}{N(H^+)} ,$$

from Model C in Table 4

In Table 3 we also present total abundances obtained by other authors.

IV. MODEL COMPUTATIONS

We have computed spherically symmetric models of ionization structure assuming thermal balance, which predict line intensities, temperature and relative volumes for ions of C, N, O, Ne, Si and S. Details about our models will be given elsewhere (Torres-Peimbert and Peña 1981). We include charge exchange reactions with H^+ of O^+, O^{++}, C^{++}, N^{3+} and N^+, taking the rate coefficients from Dalgarno and Butler (1978). We have not included di-electronic recombinations that are important for C^+, C^{++}, N^{++} and O^{4+} (Storey 1981).

TABLE 3

COMPARISON OF TOTAL ABUNDANCES DERIVED FOR NGC 7662

Author	log N(X)/N(H)			
	C	N	O	Ne
This paper	−3.07	−3.73	−3.09	−3.70
Harrington *et al.* 1981	−3.22	...	...	...
Harrington *et al.* 1979	−3.49	−3.96	−3.42	−4.15
Bohlin *et al.* 1978	−3.43	−4.10	−3.43	−4.20
Benvenuti and Perinotto 1981	−3.32	−4.37	−3.28	−4.05
Torres-Peimbert and Peimbert 1977	−2.20	−4.37	−3.35	...
Sun[a]	−3.43	−3.94	−3.17	−3.96

a. Given by Withbroe (1971) and Bertsch, Fichtel, and Reames (1972).

TABLE 4

COMPARISON OF MODELS WITH OBSERVATIONS.

LINE INTENSITIES[a], TEMPERATURES, RELATIVE VOLUMES AND GENERAL CHARACTERISTICS

	λ	Observed	Model A	Model B	Model C
He I	4471	3.0:	2.6	2.4	2.6
He II	4686	44.	52.0	56.6	52.2
C II	2326	16.7	4.2	5.7	10.5
C III]	1909	501.	383.	389.	644.
C IV	1549	758.	1767.	1884.	1646.
N II]	6584	4.2	3.3	4.1	7.1
N III]	1749	11.7	20.9	23.9	32.9
N IV]	1488	38.6	78.0	73.5	64.0
N V	1240	<4.3	163.	135.	53.8
[O II]	3727	13.2	20.7	26.0	48.7
[O III]	5007	1157.	1644.	1384.	1505.
O IV	1401	31.8	37.6	33.	29.4
[Ne IV]	2424	124.	125.	140.	146.
$T(C^+)$	...	...	12604	12746	12820
$T(C^{++})$	...	...	12896	13026	13053
$T(C^{3+})$	...	...	13913	13933	13791
$T(N^+)$	...	...	12590	12743	12840
$T(O^+)$	...	...	12500	12616	12702
$T(O^{++})$	...	12500	12818	12937	12962
$T(Ne^{3+})$	...	12000	14262	14088	13886
$x(C^+)$	...	0.047	0.003	0.003	0.006
$x(C^{++})$	...	0.317	0.204	0.223	0.312
$x(C^{3+})$	...	0.491	0.533	0.521	0.516
$x(N^+)$	...	0.005	0.002	0.002	0.004
$x(N^{++})$	...	0.181	0.253	0.274	0.381
$x(N^{3+})$	...	0.656	0.450	0.439	0.427
$x(O^+)$	...	0.012	0.009	0.010	0.019
$x(O^{++})$	...	0.238	0.447	0.416	0.463
$x(O^{3+})$	...	0.598	0.273	0.310	0.340
$x(Ne^{3+})$	...	(0.389)	0.299	0.343	0.389
$N(cm^{-3})$	...	4000	6000	3000	3000
ϵ^b	...	0.42	1.0	1.0	1.0
log O/H	...	−3.09	−3.30	−3.25	−3.25
log C/O	...	0.02	0.0	0.10	0.10
log N/O	...	−0.64	−0.45	−0.40	−0.40
log Ne/O	...	−0.61	−0.54	−0.49	−0.49
$R_i(pc)^c$	...	...	0.001	0.001	0.039
$R_o(pc)^c$	...	0.078	0.040	0.062	0.068

a. Intensities relative to Hβ, where I(Hβ) = 100.
b. ε is filling factor.
c. R_i R_o are inner and outer nebular radii.

From the models we derive a temperature and a relative volume for each ionic species, X^{+m}, from

$$T(X^{+m}) = \frac{\int N_e N(X^{+m}) T_e dV}{\int N_e N(X)\, dV} ,$$

and

$$x(X^{+m}) = \frac{\int N_e N(X^{+m})\, dV}{\int N_e N(X)\, dV} .$$

In order to try to adjust the He II lines and the forbidden lines it was necessary to select a relatively hot exciting star and to cut off the nebula at intermediate positions (optically thin nebula). The models presented were computed from a central star flux of $T_* = 125000$ K° and log g = 5.5 (Model 225 by Hummer and Mihalas 1970). In Table 4 we present the comparison between the observed line fluxes and the predicted ones. In all cases the predicted intensities for the resonance lines of C IV and N V are much higher than the observed intensities. This effect has been interpreted as due to absorption by dust particles.

V. DISCUSSION

The carbon abundance derived in this work is similar to that by Harrington *et al.* (1981) obtained from models to fit λλ2297, 1909 and 2326. The abundances derived for NGC 7662 by Harrington *et al.* (1979) and Bohlin *et al.* (1978), obtained from fits to models, and Benvenuti and Perinotto (1981), based on higher temperatures, are also presented in Table 3.

TPP77 gave a value of log C/O = 1.1; this value was obtained from λλ4267 and 4650. The latter had been reduced with the effective recombination coefficients from Bednarek and Clarke which yield a C^{3+} abundance a factor of 10 higher than the prediction from the di-electronic recombination line λ2297.

We have obtained for this object log O/H and log C/O larger than solar (from Table 3 log C/O = 0.02). Other planetary nebulae have shown a large C/O ratio; namely, those in the halo have a mean ratio log C/O = 1.1 (Torres-Peimbert, Rayo and Peimbert 1981).

The enrichment of the ejected nebula is probably showing the effects of the internal evolution of the progenitor star. A discussion of the comparison of observations with models of stellar evolution has been made by Peimbert (1981).

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