PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
90:39–44, February 1978

IONIZATION AND ABUNDANCES IN THE DUMBBELL NEBULA*

STEVEN A. HAWLEY AND JOSEPH S. MILLER

Lick Observatory, Board of Studies in Astronomy and Astrophysics
University of California, Santa Cruz

Received 1977 August 29

We present line intensities measured at six positions in the Dumbbell nebula exhibiting a wide range of ionization. At each position the electron density, temperatures, and ionic abundances of helium, oxygen, nitrogen, neon, and sulfur are computed. We estimate the total abundances of nitrogen, neon, and sulfur by assuming that the oxygen ionization distribution is a good guide to the ionization distribution of these other elements. The agreement of the total abundances in the six positions indicates that this is a good assumption for nitrogen and sulfur, but not for neon. $I(\lambda3869)$ increases with $I(\lambda3727)$ implying that Ne^{++} evidently coexists with O^+ in the low ionization regions.

Key words: planetary nebula—elemental abundances—temperatures

I. Introduction

Hawley and Miller (1977; hereafter Paper I) recently investigated the physical conditions giving rise to the large ratio of [N II]/Hα seen at the edges of NGC 6720, the Ring nebula. The results of Paper I showed that the strong [N II] lines resulted from nitrogen being predominantly N^+ at the edges of the nebula. We also demonstrated that the ionization correction formulae of Peimbert and collaborators (e.g., Peimbert and Costero 1969; Peimbert and Torres-Peimbert 1971) could satisfactorily account for the unobserved stages of ionization of oxygen and nitrogen.

Several interesting questions remain to be investigated. Will the ionization correction scheme work as well for other objects? Even though the ionization correction factor (i_{cf}) appears to work for the Ring nebula (Paper I) and the Orion nebula (Peimbert and Torres-Peimbert 1977) it is desirable to test the ionization correction scheme in a larger number of nebulae. Aller and Epps (1975) have stated that the total nitrogen abundances they derive within the planetary nebula NGC 7009 varied by almost an order of magnitude as a function of position. However, this result must be viewed with caution because the crucial [O II] $\lambda3727$ line intensity was not measured at the same place and with the same equipment as the other lines.

The total sulfur abundances presented in Paper I are clearly underestimates. However, the constancy of the results for six positions raises the question as to whether S^+/S^{++} is relatively constant independent of i_{cf} and whether the factor i_{cf} gives consistent results for sulfur when S^{++} abundances are available. Observations of [S III] $\lambda6312$ would shed light on this question as well as on the question of what is the total sulfur abundance.

The i_{cf} seriously overestimated the neon abundance in the low ionization regions relative to the high ionization regions in the Ring nebula. This resulted from the unexpected great strength of [Ne III] $\lambda3869$ relative to [O II] $\lambda3727$ at the edge of the nebula. Since this indicates that there may be an ionization process for neon which we do not understand, further observations of [Ne III] in other objects are important. In an attempt to investigate these questions we have obtained high spatial resolution observations of NGC 6853, also known as the Dumbbell nebula, which is well-suited for a study like that of Paper I because of its large angular size, moderate surface brightness, and varying ionization.

II. Observations

The observations presented here were obtained with the image-tube, image-dissector scanner (ITS) (Robinson and Wamper 1972; Miller, Robinson, and Wampler 1976) at the Cassegrain focus of the Lick Observatory 3-m Shane reflector. The observing and reduction procedures were identical to those in Paper I. Six positions were observed and their locations in the nebula are displayed in Figure 1. We attempted to observe in regions showing the widest possible range of ionization. The six positions were chosen by inspecting the color photograph of the Dumbbell nebula published by Miller (1974) and selecting four slit positions which were green (strong [O III]), and two which were red (strong [N II] + Hα).

The line intensities are shown in Table I. The errors associated with these fluxes are roughly 10% for $F(\lambda) \geq 50$, 25% for $10 \leq F(\lambda) < 50$, and 35%–50% for $F(\lambda) < 10$. We also include the flux in Hβ through the $2''.4 \times 4''.0$ entrance slot. The positions are numbered in order of decreasing ionization as inferred from the ratio [O II]/[O III].

Lick Observatory Bulletin No. 785.

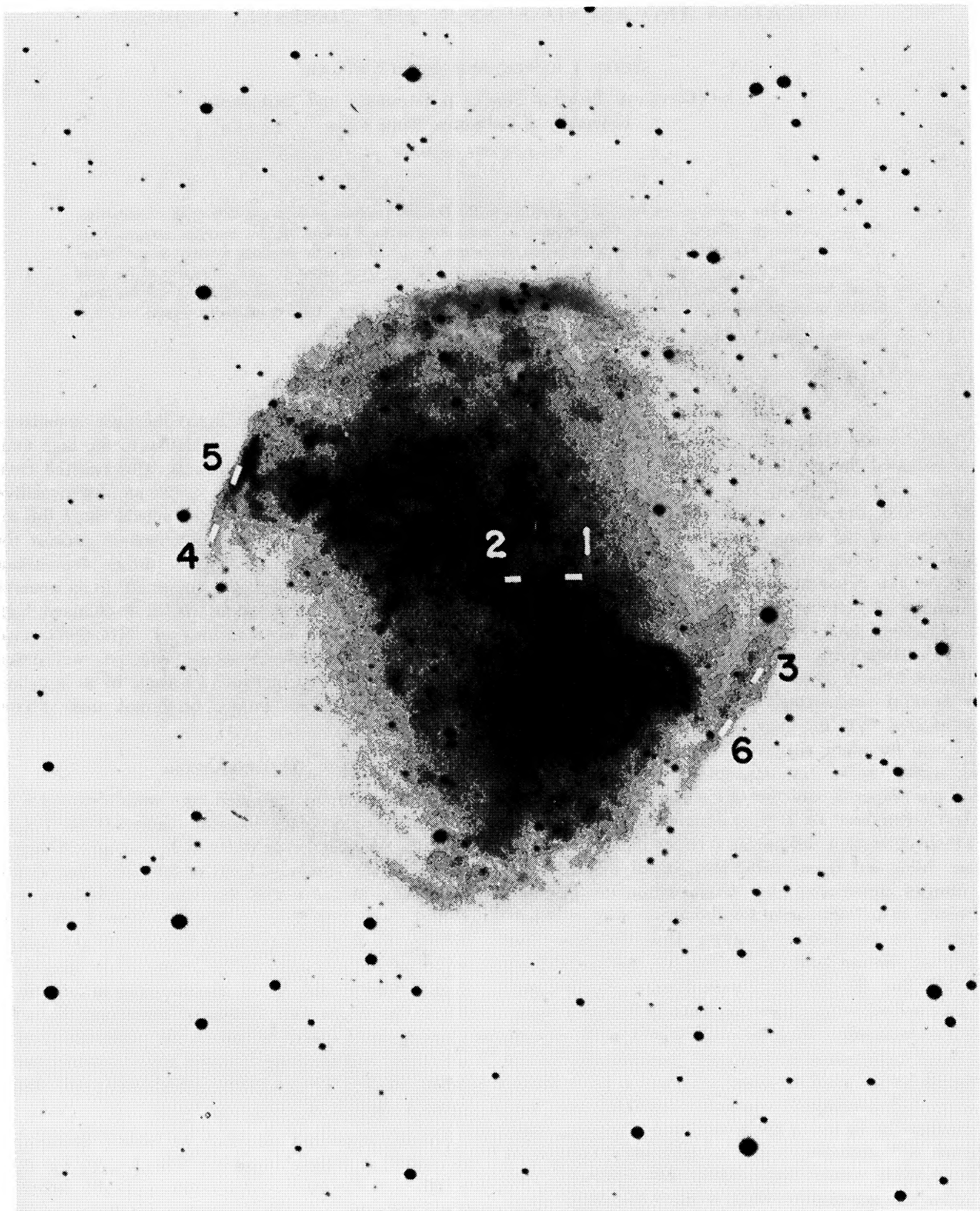

FIG. 1—Observing positions in the Dumbbell nebula. North is at the top and east is at the left. The slits are shown twice actual size of 2.″4 × 4.″0 for the purpose of illustration.

TABLE I

LINE INTENSITIES IN THE DUMBBELL NEBULA

λ	ID	1 F(λ)	1 I(λ)	2 F(λ)	2 I(λ)	3 F(λ)	3 I(λ)	4 F(λ)	4 I(λ)	5 F(λ)	5 I(λ)	6 F(λ)	6 I(λ)
3727	[O II]	228	252	345	366	474	548	538	632	1629	1938	1602	1934
3869	[Ne III]	134	147	116	122	141	155	139	160	142	165	150	177
4071	[S II]	-	-	6.7	7.0	4.9:	5.3:	6.6	7.4	13.5	15.3	6.6:	7.6:
4101	Hδ	29.0	31.1	25.1	26.1	28.1	30.2	28.8	32.2	29.0	32.7	21.8	24.8
4340	Hγ	46.9	49.5	54.0	55.7	54.7	57.8	55.4	60.3	50.6	55.4	48.9	54.0
4363	[O III]	13.7	14.4	11.8	12.2	4.6	4.9	14.1	15.3	4.3	4.7	5.4	5.9
4471	He I	2.2	2.3	4.7	4.8	2.7	2.8	5.1	5.4	6.2	6.6	5.3	5.7
4686	He II	58.5	59.5	57.6	58.2	8.7	8.9	12.8	13.2	2.4	2.5	5.0	5.2
4861	Hβ	100	100	100	100	100	100	100	100	100	100	100	100
4959	[O III]	421	417	379	381	408	404	392	386	104	102	83.4	82.0
5007	[O III]	1373	1355	1205	1196	1282	1265	1242	1216	325	319	252	246
5755	[N II]	3.9	3.7	4.8	4.6	4.3	4.0	6.1	5.5	15.3	13.6	16.7	13.6
5876	He I	10.0	9.1	9.2	8.8	14.8	13.6	13.5	11.9	16.0	14.0	18.7	16.2
6300	[O I]	-	-	12.8	12.0	-	-	-	-	78.5	65.8	93.3	77.0
6312	[S III]	2.1	1.9	1.5	1.5	$\lesssim$1.2	$\lesssim$1.1	2.9	2.5	-	-	$\lesssim$1.1	$\lesssim$0.9
6363	[O I]	-	-	3.6	3.4	-	-	-	-	24.8	20.7	32.1	26.3
6548	[N II]	66.2	58.9	81.1	75.9	162	144	167	139	421	345	428	345
6563	Hα	323	287	307	287	324	287	346	287	351	287	357	287
6583	[N II]	201	178	277	259	420	475	520	431	1339	1093	1379	1107
6678	He I	3.7	3.3	3.3	3.1	4.4	3.9	6.0	4.9	5.0	4.1	6.1	4.9
6717	[S II]	18.3	16.1	23.9	22.3	36.5	32.1	44.4	36.4	129	104	151	120
6731	[S II]	14.1	12.4	19.7	18.3	29.9	26.3	35.3	28.9	116	93.5	125	99.0
F(Hβ) (erg cm^{-2} s^{-1})		8.85×10^{-14}		1.03×10^{-13}		3.71×10^{-14}		2.31×10^{-14}		4.84×10^{-14}		2.98×10^{-14}	

III. Discussion of the Observations

The observed ratio $H\alpha/H\beta$ is slightly greater than is predicted by recombination theory (Brocklehurst 1971). We attribute this steeper Balmer decrement to interstellar reddening and have corrected the observed fluxes by calculating the Balmer line color excess $E(\beta-\alpha)$ and adopting the reddening curve given by Miller and Mathews (1972). Miller (1973) has shown that the Dumbbell nebula is only slightly reddened ($H\alpha/H\beta = 2.90$) and so there may be some unknown systematic error in these observations at the $\sim$ 10% level which mimics reddening. An error this small has little effect on the subsequent discussion and will be ignored in this paper. The reddening-corrected fluxes are presented in Table I as $I(\lambda)$.

Electron densities from [S II] and temperatures from [N II], [O III], and in some cases [S II] were derived in the manner described in Paper I. These results are shown in Table II. The uncertainty associated with the electron density determination is $\pm$ 100 cm^{-3}, and that with the [O III] and [N II] temperatures is $\pm$ 1000 K. The error in the [S II] temperature is somewhat higher because $\lambda\lambda$4069, 4076 are weak and possibly contaminated by λ4078 of Hg in the night sky

TABLE II

TEMPERATURES, DENSITIES AND ABUNDANCES

	1	2	3	4	5	6
T_e [O III] °K	11,500	11,500	8,500	12,450	13,200	-
T_e [N II] °K	11,250	10,600	8,000	9,200	9,150	9,100
T_e [S II] °K	-	-	10,000	11,000	8,150	5,750
N_e [S II] cm^{-3}	250	450	450	300	800	500
He^+	0.070	0.066	0.095	0.086	0.101	0.117
He^{++}	0.051	0.051	0.007	0.012	0.002	0.004
He	0.121	0.116	0.102	0.098	0.103	0.121
O^+	$5.3x10^{-5}$	$1.0x10^{-4}$	$5.8x10^{-4}$	$3.2x10^{-4}$	$1.2x10^{-3}$	$1.1x10^{-3}$
O^{++}	$2.9x10^{-4}$	$2.5x10^{-4}$	$7.3x10^{-4}$	$1.0x10^{-4}$	$4.5x10^{-5}$	$4.6x10^{-5}$
i_{cf}	1.74	1.76	1.08	1.13	1.02	1.04
O	$5.9x10^{-4}$	$6.3x10^{-4}$	$1.4x10^{-3}$	$5.8x10^{-4}$	$1.2x10^{-3}$	$1.2x10^{-3}$
N^+	$2.6x10^{-5}$	$4.2x10^{-5}$	$1.7x10^{-4}$	$1.0x10^{-4}$	$2.5x10^{-4}$	$2.8x10^{-4}$
i_{cf}	11.2	6.07	2.45	1.85	1.06	1.08
N	$2.9x10^{-4}$	$2.5x10^{-4}$	$4.2x10^{-4}$	$1.9x10^{-4}$	$2.7x10^{-4}$	$3.0x10^{-4}$
Ne^{++}	$8.2x10^{-5}$	$6.8x10^{-5}$	$3.0x10^{-4}$	$6.7x10^{-5}$	$5.8x10^{-5}$	$8.5x10^{-5}$
i_{cf}	2.06	2.48	1.92	2.91	27.3	25.5
Ne	$1.7x10^{-4}$	$1.7x10^{-4}$	$5.7x10^{-4}$	$2.0x10^{-4}$	$1.6x10^{-3}$	$2.2x10^{-3}$
S^+	$5.7x10^{-7}$	$1.0x10^{-6}$	$2.2x10^{-6}$	$2.3x10^{-6}$	$1.1x10^{-5}$	$3.3x10^{-5}$
S^{++}	$5.0x10^{-6}$	$5.0x10^{-6}$	$1.1x10^{-5}$	$1.3x10^{-5}$	-	$<5x10^{-6}$
i_{cf}	11.2	6.07	2.45	1.85	1.06	1.08
S	$6.3x10^{-5}$	$3.6x10^{-5}$	$3.1x10^{-5}$	$2.8x10^{-5}$	$1.2x10^{-5}$	$4.1x10^{-5}$

even though this line is much weaker than λ4358. Also, at a given temperature $I(\lambda\lambda4069, 4076)/I(\lambda\lambda6717, 6731)$ is more sensitive to the electron density than $I(\lambda4363)/I(\lambda5007)$ or $I(\lambda5755)/I(\lambda6583)$. We estimate that the [S II] temperatures are good to ± 2000 K.

At the positions where the ionization is low, the [S II] temperature seems to be less than either the [N II] or the [O III] temperature. The accuracy of the [O III] temperature for position 5 is somewhat less than quoted above for positions 1 through 4 because, where λ4363 is weak, the strong contamination by Hg λ4358 causes more uncertainty in the sky subtraction. The three temperatures would not necessarily be expected to be the same since the ionization potentials of S^+, N^+, and O^{++}, so the emission lines arise in different regions possibly characterized by different physical conditions.

The calculation of ionic abundances from the line intensities in Table I was carried out in the manner described in Paper I. We used T_e([O III]) for the O^{++} and Ne^{++} abundances, T_e([N II]) for the N^+, S^{++}, and O^+ abundances, and T_e([S II]) for S^+ when it was available and T_e([N II]) otherwise. For position 6 we adopted T_e([O III]) = 12,000 K. To compute the helium ionic abundances we used T_e([O III]) for He^{++} and T_e([N II]) for He^+. The helium ionic abundances are not sensitive to the electron temperature. Uncertainties in the electron temperatures result in errors of roughly 50% in the ionic abundances derived from the forbidden lines.

A modification to the procedure outlined in Paper I which we have made here is to replace equation (4) with

$$\frac{N(S)}{N(H)} = \frac{N(S^+ + S^{++})}{N(H^+)} \frac{N(O)}{N(O^+)}$$

(Peimbert and Costero 1969) since we have a measurement of λ6312 of [S III] in several positions. This formula should accurately correct for unobserved ionization stages in sulfur since the ionization potentials of O^+ and S^{++} are nearly identical.

The ionic and total abundances along with the values of i_{cf} are shown in Table II. Since λ4686 of He^{++} was observed in every position we have assumed that no neutral helium is present (Harman and Seaton 1966). The total helium abundances show the same scatter as in the Ring nebula. The range of the i_{cf}'s is not so great as in the Ring nebula but for nitrogen still encompasses an order of magnitude. The derived total oxygen and nitrogen abundances are consistent to a factor of 2 independent of ionization. Evidently the ionization correction scheme works well for nitrogen and oxygen in the Dumbbell nebula. The i_{cf} also seems to work well for sulfur since the total sulfur abundances show roughly the same scatter as do the nitrogen abundances.

The neon situation is still not understood. The behavior seen in the Ring nebula is evident here; i.e., the i_{cf} greatly overestimates the total neon abundance in the low ionization regions relative to the high ionization regions. This difference amounts to more than an order of magnitude between position 1 and position 6. Inspection of Table I shows that $F(\lambda3869)$ generally increases with decreasing ionization. In Figure 2 we have plotted $\log I(\lambda3727)$ versus $\log I(\lambda3869)$ including the data from Paper I. There is an evident correlation between [O II] and [Ne III] which is unexpected since the ionization potential of Ne^+ (41 eV) is greater than that of O^+ (35 eV). We currently have no explanation for this observation, but it must result from the physics of the ionization equilibrium of neon in the outer low ionization regions.

In Table III we present the total abundances derived

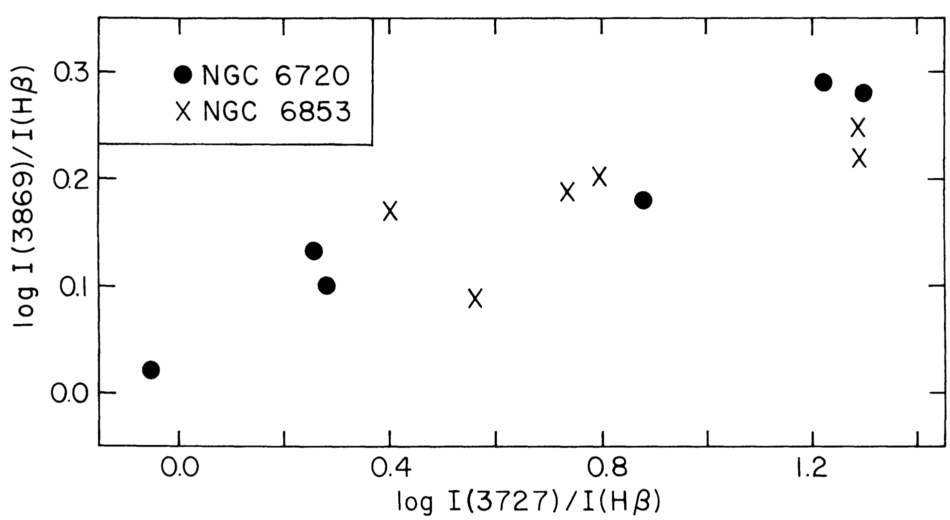

FIG. 2—Log $I(\lambda3869)/H\beta$ versus log $I(\lambda3727)/H\beta$. Filled circles are Ring nebula data; crosses are Dumbbell nebula data.

TABLE III

COMPARISON OF ABUNDANCES RELATIVE TO HYDROGEN BY NUMBER

	DUMBBELL	RING NEBULA	PLANETARIES	HII REGIONS
He	0.110	0.115	0.110	0.115
O	9.3×10^{-4}	9.4×10^{-4}	7.4×10^{-4}	4.0×10^{-4}
N	2.9×10^{-4}	2.5×10^{-4}	2.1×10^{-4}	3.9×10^{-5}
Ne	2.8×10^{-4}	2.5×10^{-4}	1.9×10^{-4}	1.3×10^{-4}
S	3.5×10^{-5}	-	4×10^{-5}	1.8×10^{-5}

for the Dumbbell nebula along with the results for the Ring nebula from Paper I, the average abundances for planetaries from Torres-Peimbert and Peimbert (1977), and for galactic H II regions from Hawley (1977). The neon abundances for the Dumbbell and Ring nebulae are the average of positions 1 through 4 only. The agreement of the different abundances among the various objects is good, implying that for the cases of oxygen, nitrogen, and sulfur in the Dumbbell nebula, the i_{cf}'s give consistent total abundances which are typical of the abundances in gaseous nebulae.

IV. Summary

In section III we concluded that the ionization correction scheme works well for oxygen and nitrogen in the Dumbbell nebula. As in the Ring nebula the regions of strong [N II] emission are regions where the nitrogen is predominantly N^+. Neon is still a problem, since $I(\lambda3869)$ correlates with $I(\lambda3727)$. The i_{cf} adequately corrects for unobserved stages of ionization of sulfur as evidenced by the consistent total sulfur abundances for six positions and an average abundance which agrees with the sulfur abundances in other planetaries.

REFERENCES

Aller, L., and Epps, H. 1975, *Ap. J.* **197**, 175.
Brocklehurst, M. 1971, *M.N.R.A.S.* **153**, 471.
Harman, R. J., and Seaton, M. J. 1966, *M.N.R.A.S.* **132**, 15.
Hawley, S. A. 1978 *Ap. J.* (in press).
Hawley, S. A., and Miller, J. S. 1977, *Ap. J.* **212**, 94.
Miller, J. S. 1973, *Mém. Soc. Roy. des Sci. de Liège*, 6e série, tome V, 57.
——— 1974, *Sci. Am.* **231**, 34.
Miller, J. S., and Mathews, W. G. 1972, *Ap. J.* **172**, 593.
Miller, J. S., Robinson, L. B., and Wampler, E. J. 1976, *Advances in Electronics and Electron Physics* (New York: Academic Press).
Peimbert, M., and Costero, R. 1969, *Bol. Obs. Tonantzintla y Tacubaya*, **5**, 3.
Peimbert, M., and Torres-Peimbert, S. 1971, *Ap. J.* **168**, 413.
——— 1977, *M.N.R.A.S.* **179**, 217.
Robinson, L. B., and Wampler, E. J. 1972, *Pub. A.S.P.* **84**, 161.