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The Ionization Structure of Planetary Nebulae

VII. New Observations of the Ring Nebula

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ABSTRACT

New optical spectrophotometric observations of emission-line intensities have been made in eight positions in the Ring Nebula corresponding to those observed previously with the Ultraviolet Explorer satellite; the total coverage is therefore 1400-7200 Å. The intensities are in generally good agreement with those found previously in corresponding positions. The O^{++} and Balmer continuum electron temperatures agree well on the average and, like the N^{+} electron temperatures, decrease with increasing distance from the central star. As found previously for the Ring Nebula and for other planetaries in this series, the λ4267 C II line intensity near the central star implies a C^{++} abundance that is higher than that determined from the λ1906, 1909 C III] lines. The discrepancy again decreases with increasing distance from the central star and vanishes for the outermost positions, again suggesting that the excitation mechanism for the λ4267 line is not understood. Standard equations used to correct for the existence of elements in other than the optically observable ionization stages give results that are

consistent and in approximate agreement with abundances calculated using ultraviolet lines. The logarithmic abundances (relative to H=12.00) are: He=11.04, O=9.05, N=8.36, Ne=8.26, C=9.09, and Ar=6.38. The abundances of He, N, Ne, and Ar are in excellent agreement with the previous study of the Ring Nebula; the abundances of O, and, especially, C, are higher. The measured C/O ratio of 1.1 is now in good agreement with Flower's value of 1.2, which was determined from ultraviolet observations alone. The rather high abundances of O, N, and C, and, to some extent, N, indicate that some mixing of CNO-processed material into the nebular shell may have occurred in the Ring Nebula; it should be interesting to test this hypothesis by measuring abundances in its faint outer halo.

I. INTRODUCTION

The five previous papers in this series (Barker 1980, 1982, 1983, 1984, 1985, and 1986, hereafter Papers I, II, III, IV, V, and VI, respectively) analyzed optical and ultraviolet observations of different positions in the planetary nebulae NGC 6720, NGC 7009, NGC 6853, NGC 3242, and NGC 7662. The purpose of these studies is to measure optical and UV emission-line intensities in the same nebular positions using similar entrance apertures. Since the ionization frequently changes drastically with position in an extended nebula, this procedure is almost essential in order to make a meaningful comparison between UV and optical measurements. The ultimate goals include the following: (1) to observe elements in more stages of ionization than is possible from optical spectra alone; this provides a check on optical ionization correction procedures, which are still useful for nebulae that are too faint to observe with the International Ultraviolet Explorer (IUE) satellite; (2) by averaging measurements made in different parts of the nebula, to get particularly accurate total abundances so that small differences between nebulae will become apparent; such differences can be sensitive tests of theoretical predictions regarding CNO processing and mixing in the progenitors of planetaries; and (3) to further investigate the discrepancies found in the previous papers between optical and UV measurements of the abundance of C^{++}; these discrepancies need to be understood before we can have confidence in optical measurements of that important element.

In several respects, the Ring Nebula, which was the first object studied in this series, has turned out to be the most important. Its large angular size and relatively high surface brightness led to the IUE spectra having the highest signal-to-noise ratio of any planetary and allowed for its ionization stratification to be studied especially well. In addition, the C^{++} discrepancy mentioned above was most clearly demonstrated in this object. Finally, the abundances of both O and C in the Ring Nebula seem to be enhanced with respect to the other nebulae, a particularly important result in view of the fact that I am currently attempting to measure the abundances in its outer halo for comparison. Because of the importance of the Ring Nebula to the conclusions of this series of studies, I believe that a new study is warranted. This study is an improvement over the previous one (Papers I and II) in the following ways: (1) New optical measurements have been made in eight positions in the nebula, twice as many as previously. These positions now correspond precisely to the positions where IUE measurements were made previously; in Paper II, the agreement was less precise because the exact coordinates of the offset star were unavailable at that time. (2) The use of a larger entrance aperture, combined with much longer integration times, has led to optical spectra with a significantly higher signal-to-noise ratio than in Paper I. In particular, the faint C II λ4267 line has been measured in all eight positions, compared to only three in Paper II. (It is important to obtain the intensity of this line because it gives rise to the discrepancy in the measured C^{++} that was described above.) (3) All of the IUE spectra (originally obtained in 1979) have been remeasured using the standard reduction routines now available at the Regional Data Analysis Center at Goddard Spaceflight Center.

II. OBSERVATIONS

a) Optical and Ultraviolet Observations

The ultraviolet observations were made as described in Paper II using the large oval (21" X 9") entrance aperture of the IUE satellite at a position angle of approximately 112° (not 68° as implied in Paper II). The spectra were measured at the Regional Analysis Data Facility in 1985 July. The spectrum of each of the four observed positions was divided into two parts ("pseudo orders" 20-28 and 28-36), and the line intensities for the resulting eight regions measured separately.

The optical observations were made in photometric conditions at Kitt Peak National Observatory in 1985 July, using the 2.1m telescope and the intensified image dissector scanner (IIDS). Spectra were obtained through a 10.3" diameter aperture using two grating settings covering the range 3400-5100 Å and 4600-7200 Å with resolutions of about 10 Å (FWHM); integration times averaged 40 minutes in each spectral region for each of the eight positions. The offsets with respect to the central star are given in Table 1, although the offsetting with both the IUE and IIDS was actually done using a bright nearby star as described in

Paper II. Note that the centers of optical positions correspond precisely to the centers of the eastern and western halves of the IUE entrance aperture and that the diameter of the IIDS aperture (10.3") is quite close to the width of the IUE aperture (9"). The name given to each position in Paper II is listed in the second row of Table 1; in Paper I, only the eastern positions (labeled positions 2, 3, 5, and 8 in Table 1) were observed.

b) Correction for Interstellar Reddening

The amount of interstellar reddening for each position was measured by comparing the observed and theoretical intensities of the H recombination lines (the "Balmer decrement"). The resulting values of the reddening parameter, c, for each position are listed in the third row of Table 1. The reddening parameters for positions 2, 3, and 5, are quite close to those given in Paper I. For position 8, the value is about half as great as that measured in Paper I. The discrepancy may be due to the faintness of this position and/or to the difficulty of measuring the intensity of $\lambda 6563$ Hα in regions with strong $\lambda 6548$ and $\lambda 6583$ emission. The small scatter in the measured values of c indicates that there is little or no variation in reddening across the Ring Nebula.

The intensities listed in Table 2 have all been calculated by multiplying the observed intensities by $10^{cf(\lambda)}$; the values of $f(\lambda)$ are also listed in Table 2. Note that there is very good agreement between the observed and theoretical (Brocklehurst 1971) intensities of Hα, Hβ, Hγ, Hδ, H9, and H10 (283, 100, 47, 26, 7.4, and 5.3, respectively) for all eight positions. Two other corrections have been applied to the intensities in Table 2: the intensities of Hβ have been corrected for blending with He II emission, and the intensities of the λ3727 [O II] lines have been corrected for blending with other lines as described in Paper III. The latter correction resulted in the observed intensities being multiplied by factors of 0.95, 0.92, 0.96, 0.99, 0.99, 0.99, 0.99, and 1.00 for positions 1-8, respectively.

c) Combining Ultraviolet and Optical Observations

As in all papers in this series, putting the UV and optical observations on the same intensity scale is a difficult task because no emission lines can be observed in common. One method is to directly compare absolute flux measurements, after correcting for the difference in the areas of the entrance apertures. A check on this method is provided by the intensities of the He II lines; for the physical conditions in the Ring Nebula, I(λ1640) should equal 6.25 I(λ4686) (Seaton 1978). The predicted and observed fluxes (uncorrected for interstellar extinction), based on an assumed area of 120 arcsec^2 for the effective IUE aperture, are compared in the last two rows of Table 1. Considering the possible sources of error (in the reddening values, the effective aperture areas, the instrumental sensitivities, and in the line intensities themselves), I believe that the agreement is acceptable. In positions 1-5, however, He II emission is strong, and I decided that the most reliable method for combining the UV and optical observations was to require that I(λ1640) = 6.25 I(λ4686). This method has the advantage of being unaffected by uncertainties in the photometric areas of the apertures, as well as possibly non-photometric conditions when the optical measurements were made, and it is nearly unaffected by errors in the correction for interstellar reddening. For positions 6-8, where the He II emission is much weaker, the normalization was done by comparing absolute fluxes.

Two lines of evidence indicate that the UV and optical intensities have indeed been combined at least approximately correctly. One test is the ratio of the UV and optical O III Bowen lines, I(λ3133)/I(λ3444), which should be 3.33 (Saraph and Seaton, 1980). The observed ratios average 2.62 ± 0.023 for the inner 5 positions, implying a systematic error in intensities between the two wavelength regions of 30% or less. Another check is a comparison between the optical and UV measurements of the O^{++} abundance. As shown in Table 4, these values agree reasonably well (considering the weakness of the intensity of the UV line), except for the outermost position, which is also the faintest.

d) Observational Errors

Aside from possible systematic errors discussed above, the UV intensities are judged to be accurate to within a factor of 2 for the faintest lines (less than 20% of Hβ), to ~40% for those of intermediate intensity (between 20% and 80% of Hβ) and to ~20% for the strongest lines. While these errors may seem high, errors in electron temperatures generally have a greater effect on the accuracy of the abundances determined from collisionally-excited UV lines than do errors in line intensities.

The intensities of the strongest optical lines are judged to be accurate to ~10%, those weaker than half of Hβ to be accurate to ~20%, and even the faintest lines to be accurate to ~30%. The intensities in the outermost position (positions 8) are somewhat more uncertain than the other ones because of the faintness of this position. In addition, the intensities of weak lines in position 1 were hard to measure because of the strong continuum of the central star.

III. TEMPERATURES, DENSITIES, AND IONIC ABUNDANCES

Calculations of the electron temperature (T_e), electron density (N_e), and ionic abundances in the different positions were made using the same methods and atomic constants as in Paper III. The results for N_e and T_e are summarized in Table 3. The values of N_e are in reasonable agreement with those determined previously (eg., Hawley and Miller 1977, Kupferman 1983, and Paper I). The calculated abundances are insensitive to errors in N_e in any event. Adopted values for N_e are listed at the bottom of Table 3.

The ionic abundances are, however, very sensitive to the electron temperature, and the situation is more complex here. I believe that the fact that the N^+ T_e is consistently lower than the O^{++} T_e is significant and implies a systematically lower electron temperature in regions of lower ionization; a corresponding T_e for singly-ionized ions is listed at the bottom of Table 3. For doubly-ionized ions, a T_e corresponding to the O^{++} T_e was adopted. Finally, as discussed in Paper II, the strength of the OIV] emision in the inner regions implies a significantly higher T_e for this ion; this result is not suprising in view of the fact that the [OIII] lines, which are major coolants, are by definition weak here. Using the method described in Paper II gives a T_e of approximately 13,800 K for the O^{3+} region; this value is close to the value of 14,500 K found in Paper II. This higher electron temperature was assumed for ions that are more than doubly-ionized.

The values of the O^{++} and N^+ T_e's, as well as their decrease with increasing distance from the central star, are generally consistent with the results of previous studies (eg., Hawley and Miller 1977, Louise 1981, Paper I, and Kupferman 1983).

The Balmer continuum T_e was measured as explained in Paper V and is subject to greater uncertainties than the O^{++} T_e because of its extreme sensitivity to errors in c, uncertainties in estimating the continuum, and uncertainties in the instrumental calibration at the Balmer limit. For these reasons, this electron temperature was not used to calculate abundances. Note however, that although there is understandably much greater scatter in the values of T_e measured using the Balmer continuum, the average temperature measured this way, 9700 K, is quite close to the average of 10,000 K measured from the [OIII] lines. As for the other planetary nebulae studied in this series, there is no evidence that the T_e's measured from the Balmer continuum are systematically lower than the O^{++} T_e's, as has been claimed for some planetary nebulae (see Barker 1979 for a discussion).

The ionic abundances calculated using the values of T_e and N_e given at the bottom of Table 3 are listed in Table 4.

IV. TOTAL ABUNDANCES

Total abundances may be found by simply adding together all the ionic abundances or by using only optically measured ionic abundances and correcting for the presence of elements in optically unobservable stages of ionization. The former procedure would appear to be the more reliable, but unfortunately relatively small errors in T_e will cause large errors in abundances measured from UV lines. At the very least, however, this method serves as a valuable check on the second procedure, which is commonly used when no UV data are available for a nebula. Both methods were used whenever possible, and the results are summarized in Table 4. The abundances labeled "optical" have been calculated by multiplying the optically measured ionic abundances by the listed values of i_{cf}, the ionization correction factor (the equations used to calculate i_{cf} values are given in Paper III). The abundances labeled "UV + optical" are simple sums of all the ionic abundances.

Except for He, the errors assigned to the abundances are based on the errors estimated for T_e, N_e, and the line intensities. In most cases, the errors in T_e dominate over the other sources.

The average abundances and errors are given in the first row of Table 5. For comparison, abundances for the Ring Nebula from Papers I and II and Hawley and Miller (1977) are also given. Abundances measured in the four other planetaries studied in this series are also listed, together with determinations for H II regions and the sun. The slightly higher heavy element abundances found in the Ring Nebula from the present study are primarily a result of the electron temperature determinations being somewhat lower than in Paper I; since the current observations have a much higher signal-to-noise ratio, I believe that they are more reliable. In general, however, the three different studies agree rather well; a detailed discussion is given below.

a) Helium

The three different He I lines agree very well (except for position 8, which is much fainter than the others and will be excluded from the rest of this discussion), and the average He^+/H^+ abundance given in Table 4 for each position is an unweighted sum of the three measurements. The total

He abundance is the sum of the He^+ and He^{++} abundances. The fact that the calculated He abundances are in close agreement for the different positions suggests that little if any He in the Ring Nebula is in the form of He^0, consistent with the results of Paper I. The average He abundance (see Table 5) is close to that found in other studies.

b) Oxygen

Although the O abundances calculated for the different positions generally agree to within the error estimates, there is a slight systematic trend toward higher calculated abundances in the outer regions. It appears possible that the i_{cf}'s for O are too small in the inner regions. Such a possibility was discussed in Paper I, where the evidence was weaker because of the smaller number of positions observed. Interestingly, however, this trend is definitely not evident in any of the other planetary nebulae observed in this series. The possibility of an actual O abundance gradient in the Ring Nebula cannot be completely ruled out, although one would expect material in the inner region, which presumably comes from a deeper layer in the star, to be more enriched in O, rather than less. Because of the possibility that the ionization correction procedure for O is inappropriate for the inner positions, however, only the outer five positions were included for the average O abundance given in Table 5. Because of this, and because the T_e's measured in the current study average somewhat lower than those in Paper I, the O abundance given in Table 5 is significantly higher than that from Paper I. Note, however, that it is closer to the value measured by Hawley and Miller (1977).

c) Nitrogen

Across the large range of ionization found in the Ring Nebula, the optically-measured abundances of N are quite consistent with each other and with those measured using UV lines as well (see Table 4). This result was also found in Papers I and II and for the other planetaries observed in this series. There is substantial evidence, then, that N abundances in planetary nebulae can be determined from optical measurements using the simple ionization-correction procedure. The average abundance listed in Table 5 is quite close to previous determinations.

d) Neon

The Ne^{4+} abundance was calculated after first correcting for blending of the λ3426 [Ne V] line with λ3429 O III, taking I (λ3429) = 0.33 I (λ3444) (Saraph and Seaton 1980). In the inner positions, the total Ne abundance inferred from the Ne^{++} abundance is in reasonable agreement with that found by summing the Ne^{++}, Ne^{3+} and Ne^{4+} abundances. The total measured Ne abundance in the outer positions, however, is systematically larger than in the inner ones. This result is consistent with that found by Hawley and Miller (1977) and in Papers I and II, and in NGC 6853 (Paper IV) and is attributable to the inapplicability of the ionization correction formula for Ne under low-ionization conditions (see Papers II and IV and references therein and Harrington, 1983). Because of this difficulty, only the inner three positions were used for the calculation of the average Ne abundance given in Table 5.

e) Carbon

As found previously in NGC 6720, as well as in NGC 7009, NGC 6853, NGC 3242, and NGC 7662, the C^{3+} abundance in the inner positions inferred from the λ4267 line is larger than that found using the UV 1906, 1909 lines. The ratio of the two measurements is 1.77, 6.70, 2.14, 1.19, 1.38, 0.62, 0.98, and 1.08, for positions 1-8, respectively, so the discrepancy again decreases approximately monotonically with increasing distance from the central star. (The relatively good ageement in the innermost position may be due to contamination by the stellar continuum there; the λ4267 emission line has an "equivalent width" of only 0.6 Å, and even a weak absorption line in the spectrum of the central star at this wavelength would cause a large underestimate of the strength of the emission line.) The size of the discrepancy in positions 2, 3, and 5 is in good agreement with the results of Paper II. Only an upper limit was measured in Paper II for the λ4267 line in position 8; the fact that the UV and optical measurements give consistent results here and in the outer positions in general strengthens the argument made in Paper I that the excitation mechanism for the λ4267 line is not well understood. As for the other planetaries observed in this series, I believe that the discrepancy in the inner positions is too great to be explained by observational error. Note also that, even if absolute fluxes had been used instead of He II lines to combine UV and optical data in the inner positions, the discrepancy would have still been significant for these positions.

Kaler (1986) recently examined this problem by comparing abundances measured from the C III] λ1909 and C II λ4267 lines in 30 planetary nebulae. He concluded that the λ4267 line does indeed give systematically higher abundances and that the difficulty is most likely due to an underestimate of the C^+ (λ4267) effective recombination coefficient by a factor of about 4. Although this is a possible explanation for Kaler's results, however, it would not explain the positional effect found in the Ring Nebula and in other planetary nebulae in this series. Note that, if positional information were not available for the Ring Nebula (as it was not for the objects in Kaler's study), an integrated spectrum of the nebula as a whole would give roughly a factor of 3 discrepancy between the two measurements, consistent with the factor of 4 that Kaler finds in his sample. Other possible explanations for the discrepancy were discussed in Paper II, but none appears fully satisfactory. I believe that a detailed theroretical examination of the line transfer problem for the λ4267 line is warranted.

The total C abundance for each position is the sum of the ionic abundances, using the UV rather than the optical measurement of C^{++}. The fact that the calculated C abundance is systematically lower in the inner positions is probably due to absorption of the C IV resonance lines by dust (see Paper II); only the outer six positions were therefore used to calculate the average C abundance given in Table 5. The C abundance is much higer than that found in Paper II primarily because of the somewhat lower electron temperatures, which affect abundances measured from UV lines much more than those measured from optical lines. The somewhat larger UV intensities measured here, especially in the outer positions, also contribute to making the C abundances larger.

Flower (1982) measured a C/O abundance ratio in the Ring Nebula based on the intensities of UV lines alone, a method which, as Flower notes, is insensitive to errors in c, and T_e and also to uncertainties in combining the UV and optical measurements. His result of 1.2 is significantly higher than the value of 0.6 found in Paper II but in good agreement with the value of 1.1 found here.

f) Argon

Since the near-infrared [S III] lines were not observed in the current study, it was not possible to use the ionization correction equation for Ar that was proposed in Paper I. The ionization correction factors for the Ring Nebula found in Paper I were small (less than 1.6), however, and the consistency of the sums of the ionic abundances in Table 4 also suggests that almost all the Ar is in observed ionization stages. The Ar abundance listed in Table 5 is therefore the straight average of these 8 sums. The equation $Ar/H = 1.5\ Ar^{++}$ (see Paper I), which is a useful approximation for faint planetaries where only the λ7135 [Ar III] line is observable, gives an average Ar/H ratio of 3.2×10^{-6}, close to the ratio listed in Table 5.

g) Sulfur

Since no measurements of the S^{++} abundance were made in the current study, the S abundance found in Paper I is preferable.

h) Comparison of Abundances in Different Objects

In general, the abundances in the objects in Table 5 are similar, but there are some interesting differences. The O, C, and N abundances in the Ring Nebula are significantly higher than the values for the sun and H II regions, suggesting that there may have been some mixing of CNO-processed material into the envelope before it was ejected. The C/O ratio, which is greater than for any object except NGC 7662, supports this conclusion. The high N abundance is perhaps the most convincing evidence for mixing, because the three different studies give values which are so consistent.

V. CONCLUSIONS

In summary, this more detailed study essentially confirms the results of Papers I and II. The Ring Nebula is another planetary nebula for which total abundances of all elements except C can apparently be accurately determined from optical measurements alone. This result is particularly gratifying for N in view of the large ionization correction factor for it in the Ring Nebula. As found in Paper II and for the other nebulae in this series, however, the UV and optical measurements of the C^{++}

abundance do not agree; the dependence on distance from the central star again indicates that the λ4267 line intensity is not being interpreted correctly. Finally, the high abundances of O, N, and C imply that some mixing of processed material occurred in the inner part of Ring Nebula; I hope to be able to test this hypothesis by measuring abundances in the faint outer shell to see if they are significantly lower.

I am grateful to the IUE and Kitt Peak staffs for their assistance in obtaining the measurements. The use of the Regional Data Analysis Facility at Goddard is also gratefully acknowledged.

TABLE 1

PARAMETERS OF OBSERVED POSITIONS

PARAMETER	POSITION 1	2	3	4	5	6	7	8
Offset (arcsec)	0.5W,4.9S	7.5E,4.9S	7.5E,13.3N	0.5W,17.3N	26.5W,4.9S	34.5W,0.9S	32.2E,17.2N	40.2E, 13.2N
ID in Paper II	1W	1E	3E	3W	4E	4W	6W	6E
c	0.25	0.25	0.38	0.35	0.32	0.25	0.22	0.20
SWP number	7230	7230	7219	7219	7232	7232	7231	7231
Exposure (min)	60	60	60	60	40	40	90	90
LWR number	6238	6238	6222	6222	6240	6240	6239	6239
Exposure (min)	90	90	30	30	40	40	90	90
$F(H_\beta)^a$, $10''.3$ ent.	0.61	0.72	1.06	1.93	1.42	0.92	0.86	0.39
F $(\lambda 1640)^a$ predicted	1.93	2.31	1.82	1.55	0.58	0.24	0.28	0.04
F $(\lambda 1640)^a$ observed	2.63	3.46	3.10	2.29	0.96	0.07	0.25	0.05

[a] Units: 10^{-12} ergs cm^{-2} s^{-1}, uncorrected for intersteller extinction.

TABLE 2

LINE INTENSITIES

λ(Å)	ID	f(λ)	I (λ)							
			Pos.1	Pos.2	Pos.3	Pos.4	Pos.5	Pos.6	Pos.7	Pos.8
1403,1409	O IV]	1.31	47.8	15.3	.....	.....	.....	.....	.....	.....
1487	N IV]	1.23	121.	26.9	36.0	.....	.....	.....	.....	.....
1548,1550	C IV	1.18	248.	181.	.....	.....	.....	.....	.....	.....
1640	He II	1.14	440.	446.	333.	142.	65.9	9.5	35.6	14.4
1661,1666	O III]	1.13	....[a]	20.7	33.7	....[a]	6.4	....[a]	....[a]	24.4
1747	N III]	1.12	....[b]	17.7	32.5	....[b]	10.6	....[b]	....[b]	9.3
1906,1909	C III]	1.23	271.	225.	357.	236.	254.	166.	193.	380.
2326,2328	C II]	1.35	28.9	27.9	66.7	85.1	119.	205.	160.	275.
2422,2424	[Ne IV]	1.12	96.1	74.8	25.7	11.6	.....	.....	.....	.....
2470	[O II]	1.10	.....	.....	.....	.....	8.2	25.3	24.0	37.9
2734	He II	0.74	.....	15.6	11.1	6.0	2.9	.....	.....	.....
3133	O III	0.45	23.3	40.6	40.8	17.4	5.9	.....	.....	.....
3426	[Ne V],O III	0.38	38.0	12.8	6.3	.....	.....	.....	.....	.....
3444	O III	0.37	12.5	14.3	12.7	6.2	2.5	.....	.....	.....
3727	[O II]	0.29	94.8[c]	58.0[c]	136.[c]	364.[c]	665.[c]	908.[c]	758.[c]	1313.[c]
3798	H 10	0.27	7.8	5.5	5.1	5.5	4.5	5.1	5.4	5.3
3835	H 9	0.26	9.3	7.3	7.9	7.4	6.6	8.5	7.1	7.2
3869	[Ne III]	0.25	107.	98.2	130.	149.	151.	148.	144.	177.

TABLE 2 continued

			I (λ)							
λ(Å)	ID	f(λ)	Pos. 1	Pos. 2	Pos. 3	Pos. 4	Pos. 5	Pos. 6	Pos. 7	Pos. 8
4069-4076	(blend)	0.21	1.9	3.6	3.1	3.5	5.0	6.7	6.6	8.0
4102	Hδ	0.20	27.7	29.1	29.6	26.6	26.8	25.0	26.1	27.0
4267	C II	0.17	0.51	1.6	1.0	0.80	0.66	0.51	0.77	0.91
4340	Hγ	0.15	48.5	48.2	51.2	48.0	48.8	46.7	47.4	50.1
4363	[O III]	0.15	11.5	11.0	11.4	9.1	7.2	4.7	5.6	5.4
4471	He I	0.11	2.7	2.9	3.3	4.1	4.8	5.2	5.2	6.3
4686	He II	0.05	70.5	71.3	53.3	22.8	10.5	5.6	6.4	2.2
4711	[Ar IV], He I	0.04	6.3	6.6	3.9	1.8	1.1	1.0	1.6	0.9
4740	[Ar IV]	0.03	4.0	4.6	2.8	1.0	0.5	0.5	...	...
4861	Hβ	0.00	100.	100.	100.	100.	100.	100.	100.	100.
4959	[O III]	-0.03	378.	378.	411.	465.	392.	312.	330.	250.
5007	[O III]	-0.04	1190.	1211.	1327.	1492.	1247.	970.	1054.	800.
5200	[N I]	-0.08	...	...	0.8	1.7	6.6	10.8	9.2	16.2
5412	He II	-0.13	4.9	5.9	3.8	3.1	1.1	...	...	...
5755	[N II]	-0.20	0.69	0.85	1.2	2.3	5.3	9.6	5.8	13.2
5876	He I	-0.22	7.6	6.4	7.5	9.4	13.3	14.3	13.9	16.7
6300	[O I]	-0.29	...	1.3	5.1	7.0	25.9	51.4	38.8	71.8
6312	[S III]	-0.29	5.0	0.8	...	...	...	...	...	...
6364	[O I]	-0.30	...	...	1.0	1.8	8.0	17.0	12.6	25.8
6563	Hα	-0.33	308.	288.	291.	296.	276.	282.	292.	299.

TABLE 2 continued

λ(Å)	ID	f(λ)	I (λ)							
			Pos.1	Pos.2	Pos3.	Pos4.	Pos5.	Pos.6	Pos.7	Pos.8
6583	[N II]	-0.34	64.4	37.3	72.9	165.	409.	748.	593.	971.
6678	He I	-0.35	2.8	2.4	2.6	2.9	3.8	3.3	4.1	7.7
6717	[S II]	-0.36	4.4	3.4	5.7	10.5	21.7	33.9	35.0	48.9
6731	[S II]	-0.36	4.4	2.3	6.9	11.4	19.3	33.2	35.0	49.5
7005	[Ar V]	-0.39	...	0.7	...	...	...	...	...	...
7065	He I	-0.40	1.7	1.8	1.3	1.7	2.7	2.8	3.5	3.5
7135	[Ar III]	-0.41	17.7	17.2	18.7	24.6	26.1	28.6	28.7	29.4

[a] Reseau Point.

[b] Hot pixel.

[c] Corrected for blending; see text.

TABLE 3

ELECTRON TEMPERATURES AND DENSITIES

QUANTITY	ION	RATIO	POSITION 1	2	3	4	5	6	7	8
N_e (cm^{-3})	S^+	I(6731)/I(6717)	1200	0	2300	1600	750	1100	1200	1200
N_e (cm^{-3})	S^+	I(4072)/I(6724)	...	...	...	...	2000	1300	1200	500
T_e (K)	N^+	I(6583)/I(5755)	8500:	11500:	9900	9300	9200	9000	8300	9300
T_e (K)	O^{++}	I(5007)/I(4363)	11200	10900	10700	9700	9600	9100	9300	10000
T_e (K)	H^+	I(Bac)/I(Hβ)	...	9400	8100	9800	10900	10300	10200	9200
N_e (adopted)			1200±500	1500±500	2300±1000	1600±1000	1000±500	1200±500	1200±500	1000±500
T_e (singly-ionized species)			11000±500	11000±500	9900±500	9300±500	9200±500	9000±500	8300±500	9300±500
T_e (doubly-ionized species)			11000±500	11000±500	10700±500	9700±500	9600±500	9100±500	9300±500	10000±500
T_e (highly-ionized species)			13800±1000	13800±1000	13800±1000	13800±1000	13800±1000	13800±1000	...	...

TABLE 4

IONIC AND TOTAL ABUNDANCES

		POSITION							
λ(Å)	ABUNDANCE	1	2	3	4	5	6	7	8
4471	He^{+}/H^{+}	0.056	0.060	0.068	0.083	0.097	0.105	0.104	0.128
5876	He^{+}/H^{+}	0.058	0.049	0.056	0.069	0.096	0.103	0.099	0.122
6678	He^{+}/H^{+}	0.075	0.064	0.069	0.075	0.098	0.085	0.104	0.200
Average	He^{+}/H^{+}	0.063±0.006	0.058±0.005	0.064±0.004	0.076±0.004	0.097±0.001	0.098±0.006	0.102±0.002	0.152±0.025
4686	He^{++}/H^{+}	0.060	0.061	0.045	0.019	0.009	0.005	0.005	0.002
	He/H	0.123±0.008	0.119±0.007	0.109±0.006	0.095±0.006	0.106±0.004	0.103±0.006	0.107±0.004	0.152±0.025
3726,3729	10^4 X O^{+}/H^{+}	0.29	0.18	0.75	2.47	4.20	6.58	8.23	7.90
5007	10^4 X O^{++}/H^{+}	2.92	2.97	3.54	5.48	4.75	4.45	4.48	2.66
1661,1666	10^4 X O^{++}/H^{+}	....	4.13	8.48	....	4.23	....	....	11.1
1403,1409	10^4 X O^{3+}/H^{+}	3.13	1.00	....	....	....	....	....	....
	i_{cf}	1.95	2.05	1.70	1.25	1.09	1.05	1.05	1.01
Optical	10^4 X O/H	6.3±2.5	6.5±2.5	7.3±3.0	9.9±4.0	9.8±4.0	11.6±4.7	13.3±5.3	10.7±5.0
6583	10^4 X N^{+}/H^{+}	0.095	0.055	0.14	0.38	0.96	1.88	1.89	2.21
1747	10^4 X N^{++}/H^{+}	.....	1.19	2.73	....	2.24	....	....	1.40
1487	10^4 X N^{3+}/H^{+}	1.68	0.37	0.50	....	....	....	....	....
	i_{cf}	21.7	36.1	1.73	4.11	2.33	1.76	1.62	1.35

TABLE 4 (continued)

		POSITION							
λ(Å)	ABUNDANCE	1	2	3	4	5	6	7	8
Optical	10^4 X N/H	2.1±0.04	2.0±0.4	1.4±0.3	1.6±0.3	2.2±0.5	3.3±0.4	3.1±0.7	3.0±0.6
UV +Optical	10^4 X N/H	....	1.6±0.9	3.4±1.8	....	3.2±1.7	....	....	3.6±1.9
3869	10^4 X Ne^{++}/H+	0.78	0.72	1.06	1.80	1.91	2.36	2.09	1.88
2422	10^4 X Ne^{3+}/H$^+$	0.39	0.30	0.11	0.05	....	....	....	....
3426	10^4 X Ne^{4+}/H$^+$	0.10	0.03	0.01	....	....	....	....	....
	i_{cf}	2.16	2.19	2.06	1.81	2.06	2.61	2.97	4.02
Optical	10^4 X Ne/H	1.7±0.5	1.6±0.5	2.2±0.7	3.3±1.1	3.9±1.3	6.2±1.9	6.2±2.0	7.6±2.3
UV +Optical	10^4 X Ne/H	1.3±0.5	1.1±0.3	1.2±0.3	1.9±0.7	....	....	....	....
2326,2328	10^4 X C$^+$/H$^+$	0.24	0.23	1.08	2.12	3.20	6.46	9.28	6.86
1906,1909	10^4 X C^{++}/H$^+$	3.22	2.67	5.19	7.37	5.23	8.87	8.56	9.29
4267	10^4 X C^{++}/H$^+$	5.70	17.9	11.1	8.76	7.21	5.52	8.37	10.0
1548,1550	10^4 X C^{3+}/H	0.46	0.33	....	....	....	....	....	....
UV	10^4 X C/H	3.9±2.2	3.2±1.7	6.3±3.1	9.5±6.2	8.4±6.1	15.3±10.8	17.8±9.1	16.1±11.8
7135	10^6 X Ar^{++}/H$^+$	1.20	1.16	1.35	2.23	2.43	3.06	2.90	2.48
4740	10^6 X Ar^{3+}/H$^+$	0.59	0.68	0.41	0.15	0.07	0.07	....	....
7005	10^6 X Ar^{4+}/H$^+$	....	0.20	....	....	....	....	....	....
	sum	1.79	2.04	1.76	2.38	2.50	3.13	2.90	2.48

TABLE 5

COMPARISON OF ABUNDANCES

Object	He/H	10^4 XO/H	10^4XN/H	10^4XNe/H	10^4XC/H	10^6XAr/H	10^6XS/H	Reference
NGC 6720	0.109±0.004	11.1±0.7	2.3±0.3	1.8±0.2	12.2±1.9	2.4±0.2	....	1
NGC 6720	0.110	6.2	2.2	1.6	3.9	3.7	9.7	2,3
NGC 6720	0.115	9.4	2.5	2.5	...	...	4.5	4
NGC 3242	0.091	4.4	0.9	1.1	2.6	1.4	3.2	5
NGC 6853	0.110	8.4	3.0	2.7	7.6	3.3	5.9	6
NGC 7009	0.117	4.8	1.3	1.5	1.5	2.3	13.0	7
NGC 7662	0.094	3.6	0.6	0.9	6.8	1.5	4.2	8
H II regions	0.117	4.0	0.4	1.3	...	...	18.0	9
Sun	0.100	7.4	0.9	1.1	4.5	3.7	17.0	10,11

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