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The Ionization Structure of Planetary Nebulae

III. NGC 7009

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ABSTRACT

Spectrophotometric observations of emission line intensities have been made in 8 positions in the planetary nebula NGC 7009. For the 6 brightest positions, the coverage is from 1400 Å to 10,000 Å. Standard equations used to correct for the existence of elements in other than the optically-observable ionization stages give results over a wide range of ionization that are consistent and agree with abundances calculated using ultraviolet lines. This result is particularly gratifying for N because previous investigations found that the standard formula gave inconsistent abundances in NGC 7009. The major outstanding problem is that the λ4267 CII line implies a C^{2+} abundance as much as 12 times greater than that determined from the UV lines. This discrepancy is greatest nearest the central star, as is the case in the planetary nebula NGC 6720, which was studied in Paper II in this series. The logarithmic abundances (relative to H=12.00) are: He=11.07, O=8.68, N=8.10, Ne=8.16, C=8.18, Ar=6.36, and S=7.12. The average of the Ne, Ar, and S abundances agrees to within 5% of that for NGC 6720, but the O, N, and C abundances average 1.9 times lower in NGC 7009, suggesting that there may have been mixing of processed material in the planetary precursor in NGC 6720.

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INTRODUCTION

It has been found that combined optical (Barker 1980b, hereafter Paper I) and ultraviolet (Barker 1982, hereafter Paper II) observations in several different regions of one planetary nebula, NGC 6720, can be used both to estimate particularly reliable total elemental abundances and to learn more about the physical conditions in the nebula. It is important, however, that all the observations be made in the same regions of a nebula; because the ionization frequently changes dramatically from place to place, it is otherwise usually nearly impossible to make meaningful comparisons between optical and UV spectra. Unfortunately, most optical observations of planetaries have been made in only a single position with an entrance aperture that does not correspond to those available with the International Ultraviolet Explorer (IUE) Satellite. For these reasons, I have decided to make optical and ultraviolet observations with similar entrance apertures in a number of positions in several extended planetary nebulae.

I chose NGC 7009 as the next planetary in this series partly because of its rather large angular size, high surface brightness, and wide range of ionization. The main reason for examining NGC 7009, however, is that two previous studies (Aller and Epps 1975, Czyzak and Aller, 1979) found that the usual procedure for correcting for the presence of N in higher stages than the optically-observable N^+ ionization state does not give consistent results for this object; the calculated N abundance is substantially lower in the higher ionization region near the central star. The authors suspected a failure of the ionization correction procedure but also noted that an actual N abundance gradient could not be ruled out. It is clearly important to investigate both possibilities - the first because it casts doubt on the analysis of N abundances

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in all gaseous nebulae, the second because it could provide an interesting check on theories of CNO processing and mixing in the planetary progenitor. The only way to decide between these possibilities is to make UV measurements of emission lines due to N^{2+} and N^{3+} in the same nebular positions as the optical observations of the N^{+} lines.

II. OBSERVATIONS

a) Ultraviolet Observations

The UV observations were made at low dispersion with the IUE satellite using the small (~3.2" diameter) entrance aperture in 1981 July. The positions listed in Table 1 were chosen to include as wide a range of ionization as possible. (Positions 7 and 8 are the "ansae" and are too faint to observe in reasonable exposure times with the IUE.) The offsets were made under the assumption that the center of light position measured by the IUE fine error sensor coincided with the central star. As a check, exposures were taken with the small aperture centered on the assumed position of the central star. The observed stellar continuum was measured to be approximately as strong as in exposures obtained by other observers through the large entrance aperture, and it therefore seems probable that the IUE observations were made within 1"-2" of the indicated positions.

The line fluxes were extracted from the IUE data tapes by a procedure similar to that described in Paper II. The fluxes on the tapes had already been put on an absolute scale using the IUE May 1980 calibration, the same calibration used in Paper II. In addition, background subtraction had also been performed, so it was necessary to subtract only continuum emission, measured for about 25 Å either side of the lines, from the total line strength.

The measured fluxes were corrected for interstellar extinction using the

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standard method described in Papers I and II. The reddening parameter, c, (which equals the logarithmic extinction at H_β if R=3.0) was taken to be 0.12 for all positions; this is an average based on optical measurements of the whole nebula by Miller (1973) and Peimbert and Torres-Peimbert (1971). Only the reddening-corrected intensities, $I(\lambda)$ relative to $I(H_\beta)=100$ are listed in Table 2. The observed fluxes relative to H_β can be calculated by multiplying the intensities by $10^{-cf(\lambda)}$; the values of $f(\lambda)$ are listed in column 3 of Table II. The UV intensities can in principle be tied in to the optical intensities (i.e., normalized to $I(H_\beta)=100$) by comparing absolute intensities measured optically and in the UV. In practice, however, uncertainties in the photometric areas of the entrance apertures and the lack of perfectly photometric conditions when the optical observations were made ruled out this method. Instead, the normalization was done by requiring that I(1640)=6.25 I(4686) (Seaton 1978). (This method has the advantage that it is relatively insensitive to errors in c.) For Position 6 (which has no measured HeII λ1640 emission), I(1661,66) was normalized to the value that gave the same O^{++} abundance as I(5007). Because I(1661,66) is rather faint, the relative intensities of the optical and UV lines are much more uncertain for Position 6. Finally, the intensities measured with the LWR camera (for 1950Å< <3200Å) were multiplied by an additional factor of 1.20 (Harrington, Seaton, Adams, and Lutz, 1982) to correct for the differences in the LWR and SWP camera aperture areas and transmission factors for an extended source.

Although NGC 7009 has a high surface brightness, its rather low electron temperature (see §III) and the small aperture size used result in the ultraviolet lines being rather weak and difficult to measure. Intensities of UV lines stronger than H_β are judged to be accurate to ~10%, those weaker than half of H_β

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are accurate to ~30%, and the faintest measured lines are thought to be good to only a factor of two. Even so, as discussed in §III, errors in electron temperatures generally have a greater effect on the accuracy of abundances than do errors in measuring line intensities.

b) Optical Observations

The observations over the wavelength range 3700-7200Å were made with the Intensified Reticon Scanner (IRS) on the Number 1 0.9m telescope at Kitt Peak National Observatory in 1980 and 1981 July. Spectra were obtained at two grating settings which covered the approximate ranges of 3700-5200Å and 5800-7200Å at a resolution of about 5Å full width at half-maximum. At this resolution, most of the important closely-spaced lines such as [OI] λ6300 and [SIII] λ6312, [NII] λ6548 and H_α λ6563, and [S II] λ6717 and λ6731, could be clearly separated. Standard calibration techniques were used, and the planetary nebula NGC 6210 was also observed as a check on the accuracy of the measurements. It is judged that the intensities of the strongest lines are accurate to ~15%, those weaker than half of H_β are accurate to ~20%, and even the faintest lines listed are accurate to ~30%. Even through the 3.6" diameter entrance aperture, the several hundred counts a second were obtained on the strongest lines in Positions 1-5. Positions 6, and, especially, 7 and 8 were much fainter, and the uncertainties are about a factor of two greater for these positions. The accuracy of the intensities of the stronger lines in the brighter positions is limited primarily by the large air mass (1.4 to 1.7) of NGC 7009 as observed at the latitude of Kitt Peak and by offsetting errors (which are judged to be less than 2").

The intensities of the λ9069 and λ9532 [S III] lines relative to H_α were measured in 1980 and 1982 July at KPNO using the "Harvard" sequential scanner

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with a single-channel photomultiplier, the same instrument described in Paper I. The smallest available entrance aperture, 4.4" in diameter, was used. Although this is somewhat larger than the apertures used for the other observations, it is not felt that this had an appreciable (>10%) effect on the measured intensities relative to H_α. The resolution with this aperture is approximately 8Å, so the lines were clearly resolved from nearby lines such as HI λ9546 and [N II] λ6548.

An attempt was made to measure the H_α/H_β ratio with the sequential scanner, but the counting statistics were too poor to give reliable results. In the end, it was assumed that this ratio is 3.12 (Peimbert and Torres-Peimbert, 1971, Miller, 1973) for all positions, implying a reddening parameter, c, of 0.12 as described above. A check on this assumption is the degree to which the reddening-corrected intensities listed in Table 2 of the H I lines at λ4340, λ4102, λ3835, and λ3798 agree with the theoretical values (Brocklehurst, 1971) of 46.9, 25.9, 7.34, and 5.30, respectively. The agreement is generally within the estimated errors in the brighter positions.

The intensities of the [O II] lines at λ3727 listed in Table 2 have been corrected for blending with H I lines at λ3722 and λ3734, a He II line at λ3733, and a [S III] at λ3732. The intensities of these lines can be predicted based on their theoretical intensities relative to other observed lines of the same ions. In Positions 1 and 2 (where the [O II] emission is weak), this correction amounted to approximately half the observed intensity at λ3727; at the other positions, the correction was less than 15%.

The intensity of the λ9532 [S III] line is theoretically 2.4 times that of the λ9069 line, but the observed intensity is much less than this. In addition, the dispersion in measured values of I(λ9532) was much higher than for I(λ9069).

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The explanation is almost certainly terrestrial H_2O absorption. There is a strong absorption line at 9529.4Å, which is the wavelength that the nebular 9532Å line would be shifted to because of the nebula's radial velocity and the earth's orbital velocity relative to the nebula in July. Fortunately, this velocity shift also carries the 9069Å line to a wavelength that is completely free of H_2O absorption; only this line is therefore used in the following analysis.

III. Temperature, Densities, and Ionic Abundances

Calculations of the electron temperature (T_e), electron density (N_e), and ionic abundances were made using the same methods and atomic constants as in Paper I, except that the more recent collision strength calculations by Pradhan (1978) for S^+ were used. The indicators and calculated values of N_e and T_e are summarized in Table 3. Note that there is generally quite good agreement between different values of T_e for a given position. The one exception is Position 2, where the [S III] Te is anomalously low. The λ6312 [S III] line is quite faint and possibly contaminated by bad subtraction of the λ6300 [O I] night sky line. A further complication is that I(9069) was not measured on the same nights as I(6312). For these reasons, the values of Te measured from the [O III] and [N II] indicators are to be preferred. Even so, the discrepancy for Position 2 is cause for concern. Because the different indicators generally agreed quite well, however, average values of T_e were adopted for each position and are listed in Table 3. The values of of N_e for Positions 1, 2, 3, 6, and 8 are estimated from the measurements by Czyzak and Aller (1979) in similar positions. These estimates are uncertain (as reflected by the large errors assigned to them in Table 3), but fortunately highly accurate electron densities are needed only for the estimates of the O^+

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abundances.

The ionic abundances calculated using the temperature and densities from Table 3 are listed in Table 4. It should be emphasized that these temperatures may not be suitable for elements in the highest ionization stages, such as O^{3+}, N^{3+}, Ne^{3+}, C^{3+}, and Ar^{3+}. Indeed, Perinotto and Benvenuti (1982) estimate $T_e \sim 13,000$ or higher for the Ne^{3+} zone. (Unfortunately, the temperature in this region cannot be estimated from the observations given here because the optical λ4724,26 [Ne IV] lines were too faint to detect.) The temperatures relavent to these highly-ionized species are probably higher than those adapted here, and so the calculated abundances for them should be regarded as upper limits.

IV. Total Abundances

Total abundances may be estimated by adding together the ionic abundances or by using only optically-determined abundances and correcting theoretically for the presence of elements in optically unobservable stages of ionization. The former procedure would appear to be the more reliable, but it is subject to the uncertainties in electron temperatures described above. In addition, even if the temperatures can be measured in high-ionization regions, relatively small errors in T_e will result in very large errors in abundances determined from UV lines. At the very least, however, this method serves as a valuable check on abundances estimated using the ionization correction procedure.

The ionization correction procedures that will be discussed here are summarized below:

$$He/H = (He^+/H^+ + He^{2+}/H^+) \times i_{cf}(He), \quad (1a)$$

$$i_{cf}(He) = 0.87 \times S/(S-S^+) + 0.13 \times O/(O-O^+), \quad (1b)$$

$$O/H = (O^+/H^+ + O^{2+}/H^+) \times i_{cf}(O), \quad (2a)$$

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$$i_{cf}(O) = (1 - He^{2+}/He)^{-1}, \quad (2b)$$

$$N/H = (N^{+}/H^{+}) \times i_{cf}(N), \quad (3a)$$

$$i_{cf}(N) = O/O^{+}, \quad (3b)$$

$$Ne/H = (Ne^{2+}/H^{+}) \times i_{cf}(Ne), \quad (4a)$$

$$i_{cf}(Ne) = O/O^{2+}, \quad (4b)$$

$$Ar/H = (Ar^{2+} + Ar^{3+} + Ar^{4+})/H^{+} \times i_{cf}(Ar), \quad (5a)$$

$$i_{cf}(Ar) = (S^{+} + S^{2+})/S^{2+}, \quad (5b)$$

$$S/H = (S^{+} + S^{2+})/H^{+} \times i_{cf}(S), \text{ and} \quad (6a)$$

$$i_{cf}(S) = \{1 - [1 - O^{+}/O]^{3}\}^{-1/3}. \quad (6b)$$

The errors assigned to all the elemental abundances except He are based on the errors in T_e, Ne, and the line intensities. In most cases, the errors in T_e dominate over other sources.

a) Helium

The He^{+}/H^{+} abundances was calculated using three different He I lines; the average value and its mean error listed in Table 4 are based on a 1:3:1 weighting of I(4471), I(5876), and I(6678) respectively. The total He abundance is just the sum of the He^{+} and He^{++} abundances. Note that this abundance is essentially constant across the nebula; although it is slightly lower in Position 7, it should be remembered that this is an extremely faint position, and I(5876) is therefore rather uncertain. If equation (1b) were to be employed, $i_{cf}(He)$ would be less than 1.05 for the positions where it can be determined. The range of ionization in NGC 7009 is clearly not great enough to test the applicability of this equation. Applying equation (1b) to the 4 positions in NGC 6720 (Paper I), however, would have given a monotonically increasing He abundance that was over twice as great in the lowest ionization region as in the highest. Although French (1981) found equation (1b) to be

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reliable, it is a purely empirical expression, and its applicability is suspect.

b) Oxygen

Although the UV and optical measurements of the O^{2+}/H^{+} ratio differ by as much as a factor of 2, this is not surprising in view of the faintness of the UV lines. (As explained in §IIa, the optical and UV O^{2+} abundances agree for Position 6 because the UV intensities for this position were normalized by requiring that the UV and optical O^{2+} abundances be the same.) Similarly, the different measurements of the total O abundances generally agree to within the estimated errors. The O^{3+}/H^{+} measurement for Position 1 is undoubtedly an overestimate, since the T_e relevant to this ion is probably higher than the value used in the abundance calculation; this effect was discussed more fully in Paper II. The calculated O abundance is marginally lower in the two faint outer positions, but there is no convincing evidence of a systematic variation with position; there is some evidence (see Paper I) that the O/H ratio is underestimated in high-ionization regions of NGC 6720, but this does not seem to be the case in NGC 7009.

c) Nitrogen

Czyzak and Aller (1979) found that the N abundance calculated using equation (3) increased by over a factor of 6 from the innermost (high-ionization) region to the east ansa (equivalent to Position 7). Aller and Epps (1975) found a similar, but even larger, trend. As discussed in §I, a major motivation for the current study was to see if this trend was real or if it was the result of a breakdown in the applicability of equation (3). As shown in Table 4, however, apparently neither explanation is correct; the calculated N abundance does not systematically vary over a range of over 40 in i_{cf}. In addition, the abundances inferred from the N^{+} abundances generally agree

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quite well with those found by summing the N^+, N^{2+}, and N^{3+} abundances. The largest discrepancy is for Position 6, which is faint and subject to greater uncertainty because of the less reliable method used for combining UV and optical measurements (see §IIa and §IVe). It seems probable, then, that there is no variation in N abundance within NGC 7009. In addition, the applicability of equation (3) has again been confirmed, this time over an even greater range in i_{cf} than for NGC 6720. It is possible that the earlier studies which found a discrepancy were in error because photographic coude spectra were used to estimate I(λ3727), which is critical to the calculation of i_{cf}. The I(λ3727) measurements may therefore not have exactly coincided in position with the photoelectric measurements. If the photoelectric measurements alone are used, there is a much smaller variation in calculated N abundance (Aller, 1982, private communication).

d) Neon

NGC 7009 is more highly ionized than NGC 6720, so i_{cf} for Ne is small at all positions. There is no evidence that the Ne abundance is overestimated in low ionization regions as in NGC 6720 (see Paper I). The Ne abundance for NGC 7009 is therefore probably reliable. Note that most of the Ne is apparently in the Ne^{2+} state (and therefore the lack of measurements of [Ne V] λ3425 is not a problem) and that i_{cf} seems to approximately allow for the fraction of Ne in the Ne^{3+} state.

e) Carbon

In NGC 7009, as in NGC 6720, the optically-measured C^{2+} abundance is much higher than that found from the UV lines. In addition, this discrepancy increases systematically with increasing ionization in both planetaries. Perinotto and Benvenuti (1982) also noted that the λ4267 line implies a much

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higher C^{2+} abundance in NGC 7009 than the UV λ1906,09 lines. At the present time, there appears to be no satisfactory explanation, although several possible ones are discussed in detail in Paper 2.

Marionni and Harrington (1981) have suggested that the C/N abundance ratio may be estimated from UV observations alone using the formula C/N ~ 0.15 I(λ1909)/I(λ1747). This expression gives C/N ratios of 2.40, 1.18, 1.11, 1.21, 1.08, and 1.22 for Positions 1-6, close to the average C/N ratio of 1.20 found for NGC 7009 (see Table 5).

The total C abundance is the sum of the C^{+}, C^{2+} (from λ1906,09), C^{3+} abundances; the optical C^{2+} abundance is not considered reliable and is not included. The C abundances are in good agreement, except for Position 6, which is subject to considerable uncertainty because of the method used to combine the optical and UV data.

f) Argon

The applicability of equation (5), which was developed in Paper I, has been questioned by French (1981), who argues that i_{cf}(He) should be used instead of i_{cf}(Ar). Either would lead to essentially the same result for NGC 7009 because the ionization is so high that presumably very little Ar is in the Ar^{+} state. Using French's method would have given an Ar abundance in the lowest ionization position of NGC 6720 that is a little closer to the average for the other positions. In addition, as French points out, his method has a firmer theoretical justification. Still, the fact that i_{cf}(He) seems inappropriate even for He (see §IVa) makes one hesitate to use it for Ar. One way to settle this question will be to study planetaries that have regions of lower ionization than those in NGC 7009.

It was suggested in Paper I that the equation

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$$Ar/H = 1.5\ Ar^{2+}/H^{+} \qquad (7)$$

gives fairly accurate Ar abundances for planetaries where only the [Ar III] λ7135 line is observed (as is the case for three halo planetaries; Barker, 1980a). Equation (7) gives Ar/H ratios of (0.75, 1.58, 1.17, 2.5, 2.16, 2.72, 5.73) X 10^{-4} for Positions 1-7, respectively, in reasonable agreement with the average value of 2.3 X 10^{-4} for the nebula.

g) Sulfur

Note that only a very small fraction of S is in the form of S^{+}, which gives rise to the most commonly-observed lines at λ6717,31. It is obviously important to measure the S^{2+} abundance whenever possible. The consistency of calculated S abundances over a wide range of ionization implies that equation (6) corrects adequately for the higher ionization stages; this result was also found for NGC 6720. The ionization correction formula proposed by Natta, Panagia, and Preite-Martinez (1980) gives total S abundances of (37, 69, 29, 20, 16) X 10^{-6} for Positions 1-5, respectively. The systematic decrease in calculated S abundance with decreasing ionization casts doubt on the applicability of their formula, which was not used in this paper or Paper I. It would be useful, however, to have infrared observations of the 10.5μ [S IV] line as a direct check on the total S abundance in NGC 7009.

V. CONCLUSIONS

In summary, it is apparent that optical estimates of the abundances of a number of elements in NGC 7009 have been confirmed by UV measurements of their higher ionization stages. This is particularly gratifying for N, which previous studies suggested could not be adequately measured from optical observations alone. A major problem remains for C; the λ4267 line is apparently not a pure recombination feature, and C abundances based on it are likely to be overestimates.

The total abundances listed in Table 5 are weighted averages of measurements made in the different positions. As discussed previously, abundances measured from UV lines are judged to be less reliable both because they are much more sensitive to errors in T_e than are optical lines and because the T_e appropriate to these ions was not measured directly. For this reason, the listed abundances are based on optical lines for all elements except C.

The abundances agree reasonably well with previous determinations, considering the differences in the methods used. The higher N abundance found by Perinotto and Benvenuti is apparently a result of their measured N III] line intensity being somewhat greater. The S abundance is lower than that estimated by Czyzak and Aller, but it is probably more accurate because the S^{2+} abundance was measured from the [S III] λ9069 line in this study but not in theirs.

It is interesting to compare the abundances in NGC 7009 with those found in NGC 6720 using nearly identical techniques. The average of the abundances of the heavier elements Ne, Ar, and S, which are unlikely to be affected by nucleosynthesis in the presumably relatively low mass planetary progenitor, are the same to within 5% for the two nebulae. The abundances of O, N, and C, which might be affected by nucleosynthesis, average 1.9 times higher in NGC 6720. A related piece of evidence is that Flower (1982) finds a C/O ratio for NGC 6720 of about 1.2 (about twice that found in Paper II), which is about twice the solar value and therefore also suggests the possibility of mixing of processed material into the outer layers of the progenitor. The evidence for such mixing is marginal at the present time, but it will be interesting to make similar

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~~marginal at the present time, but it will be interesting to make similar~~ comparisons when more planetaries are studied using the same techniques.

I am grateful to L.H. Aller and H.L. Dinnerstein for providing me with valuable information and to the staffs of the IUE and Kitt Peak National Observatory for their assistance in obtaining the observations.

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TABLE 1

Parameters of Observed Positions

Position	1	2	3	4	5	6	7	8
Offset (arc sec)	4N	4W,2S	4W,2N	8W,4S	10E,2N	2W,10N	23E,4N	25W,4S
SWP number	14395,6	14404	14406	14405	14407	14409	--	--
Exposure (min)	15,40	80	30	60	55	100	--	--
LWR number	11006	11006	11014	11008	11015	11017	--	--
Exposure (min)	40	60	80	50	60	120	--	--
F(1640)[a]	34.5	21.3	36.3	5.9	6.1	--	--	--

[a]Using 3.2" diameter aperture; units of 10^{-13} erg/cm^2/sec.

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TABLE 2

Line Intensities

Position			1	2	3	4	5	6	7	8
λ(Å)	I.D.	f(λ)	I(λ)	I(λ)	I(λ)	I(λ)	I(λ)	I(λ)	I(λ)	I(λ)
1403,09	O IV]	1.34	4.7	--	--	--	--	--	--	--
1487	N IV]	1.26	7.8	--	--	--	--	--	--	--
1548,50	C IV	1.21	8.9	9.9	--	--	9.3	--	--	--
1640	He II	1.16	135.	97.9	111.	42.8	49.1	--	--	--
1661,66	O III]	1.15	6.4	3.6	--	--	9.9	8.5	--	--
1747	N III]	1.14	3.8	5.8	6.7	5.7	6.9	17.3	--	--
1906,09	C III]	1.25	60.9	45.7	49.4	46.1	49.8	14.1	--	--
2326,28	C II]	1.39	1.0	--	--	7.1	--	--		
2422	[Ne IV]	1.11	4.3	--	2.3	4.9	--	--	--	--
2734	He II	0.72	2.1	--	--	--	--	--	--	--
2830	He I	0.64	5.2	4.1	2.9	--	--	--	--	--
3133	O III	0.46	35.9	14.9	18.8	8.8	--	--	--	--
3727	[O II]	0.29	5.6[a]	5.5[a]	7.7[a]	31.0[a]	44.4[a]	23.7[a]	254.[a]	306.[a]
3798	H 10	0.27	6.4	5.5	5.6	5.0	--	--	--	--
3835	H 9	0.26	8.0	6.1	8.1	6.1	--	--	--	--
3869	[Ne III]	0.25	116.	89.9	103.	93.9	132.	212.	150.	140.
4102	Hδ	0.20	28.5	23.3	28.3	22.5	27.5	49.0	--	27.9
4267	C II	0.17	1.0	0.6	0.91	0.54	<0.6	--	--	--
4340	Hδ	0.15	48.9	42.0	40.7	39.4	44.7	86.7	28.4	41.1
4363	[O III]	0.15	9.1	6.6	7.0	6.2	7.3	8.7	11.8	--
4471	He I	0.11	5.3	4.5	5.6	4.1	5.7	7.3	--	--
4686	He II	0.05	21.5	15.5	17.6	6.8	7.8	--	--	--
4711	[Ar IV]	0.04	5.3	3.6	4.4	2.4	--	--	--	--
4740	[Ar IV]	0.03	5.8	4.1	4.7	1.6	--	--	--	--
4861	Hβ	0.00	100.	100.	100.	100.	100.	100.	100.	100.
4959	[O III]	-0.03	393.	392.	394.	417.	427.	355.	330.	427.
5007	[O III]	-0.04	1266.	1264.	1122.	1266.	1216.	1479.	1103.	1225.

[a]Corrected for blending; see text.

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Table 2, continued

5755	[N II]	-0.20	--	--	--	0.65	0.71	--	6.8	--
5876	He I	-0.22	13.9	15.2	14.4	14.3	14.4	14.2	11.8	--
6300	[O I]	-0.29	--	--	--	1.5	1.6	--	16.0	--
6312	[S III]	-0.30	1.02	0.97	1.0	1.81	2.1	3.9	11.0	--
6563	H_α	-0.33	285.	285.	285.	285.	285.	285.	285.	285.
6583	[N II]	-0.34	4.3	6.5	4.6	40.1	40.7	8.4	262.	329.
6678	He I	-0.35	3.3	3.6	4.4	4.0	3.4	4.8	--	--
6717	[S II]	-0.36	1.0	0.37	2.5	3.5	3.7	13.	42.	--
6731	[S II]	-0.36		1.62		5.6	5.4		72.	
7136	[Ar III]	-0.41	6.8	11.3	9.2	17.9	17.1	19.4	70.4	--
9069	[S III]	-0.50	16.2	27.7	18.3	32.0	31.3	--	--	--
9532	[S III]	-0.63	12.2[b]	16.7[b]	16.1[b]	31.9[b]	23.6[b]	--	--	--

[b]Affected by H_2O absorption; see text.

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TABLE 3

Electron Temperatures and Densities

Quantity	Ion	Ratio	1	2	3	4	5	6	7	8
N_e (cm^{-3})	S^+	$\frac{I(6731)}{I(6717)}$	--	--	--	3600	2600	--	4300	-
T_e (K)	N^+	$\frac{I(6583)}{I(5755)}$	--	--	--	9880	10,200	--	12,200	--
T_e (K)	S^{++}	$\frac{I(9069)}{I(6312)}$	9700	7700	9200	9500	10,000	--	--	-
T_e (K)	O^{++}	$\frac{I(5007)}{I(4363)}$	10,600	9600	10,000	9400	9900	9600	12,100	--
Ne (adopted) error			4000 ±1000	4000 ±1000	3600 ±1000	3600 ±500	2600 ±500	4000 ±1000	4300 ±1000	4000 ±1000
T_e (adopted) error			10,600 ±500	9600 ±500	10,000 ±500	9600 ±500	10,000 ±500	9600 ±500	12,200 ±1000	12,000 ±1000

TABLE 4

Ionic and Total Abundances

Position λ (A)	Ratio	1	2	3	4	5	6	7	8
4471	He^+/H^+	0.109	0.091	0.114	0.083	0.116	0.148	--	--
5876	He^+/H^+	0.104	0.111	0.106	0.105	0.106	0.104	0.092	--
6678	He^+/H^+	0.079	0.085	0.105	0.094	0.081	0.113	--	--
average	He^+/H^+	0.100±0.008	0.102±0.008	0.107±0.002	0.098±0.006	0.103±0.008	0.115±0.012	0.092±0.015	--
4686	He^{2+}/H^+	0.018	0.013	0.015	0.006	0.007	--	--	--
	He/H	0.118±0.009	0.115±0.009	0.122±0.004	0.104±0.007	0.111±0.009	0.115±0.012	0.092±0.015	--
3728	$10^4 O^+/H^+$	0.028	0.043	0.049	0.24	0.24	0.18	0.76	0.94
5007	$10^4 O^{2+}/H^+$	3.5	4.8	3.7	4.8	4.0	5.6	2.0	2.3
1661,66	$10^4 O^{2+}/H^+$	1.7	2.4	--	--	4.5	5.6	--	--
1403,09	$10^4 O^{3+}/H^+$	5.8	--	--	--	--	--	--	--
	i_{cf}	1.18	1.13	1.14	1.06	1.08	1.00	1.00	1.00
optical	$10^4 O/H$	4.2±0.7	5.5±1.0	4.2±0.7	5.4±0.9	4.6±0.7	5.8±1.0	2.8±0.9	3.2±1.0
UV+opt.	$10^4 O/H$	7.5±3.7	2.5±1.0	--	--	4.8±1.8	5.8±2.3	--	--
6583	$10^5 N^+/H^+$	0.074	0.14	0.092	0.89	0.79	0.18	3.2	4.2
1747	$10^4 N^{2+}/H^+$	0.34	1.2	1.0	1.2	1.0	3.7	--	--
1487	$10^4 N^{3+}/H^+$	1.0	--	--	--	--	--	--	--
	i_{cf}	150.	128.	85.7	22.5	19.2	32.2	3.7	3.4
optical	$10^4 N/H$	1.1±0.1	1.8±0.3	0.79±0.10	2.0±0.3	1.5±0.2	0.58±0.10	1.2±0.2	1.4±0.3
UV-opt.	$10^4 N/H$	1.4±0.2	1.3±0.2	1.1±0.3	2.1±0.5	1.9±0.4	4.0±1.8	--	--

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TABLE 4 - cont.

3869	$10^4Ne^{2+}/H^+$	0.98	1.1	1.1	1.2	1.4	2.7	0.08	0.7
2422	$10^4Ne^{+3}/H^+$	0.10	--	0.05	0.15	--	--	--	--
	i_{cf}	1.20	1.15	1.16	1.13	1.15	1.04	1.45	1.43
	$10^4Ne/H$	1.2±0.2	1.3±0.2	1.4±0.2	1.3±0.2	1.6±0.3	2.8±0.06	1.2±0.3	1.0±0.3
2326,28	$10^4C^+/H^+$	0.01	--	--	0.14	--	--	--	--
1906,09	$10^4C^{2+}/H^+$	0.95	1.6	1.2	1.6	1.2	4.8	--	--
4267	$10^4C^{2+}/H^+$	11.1	6.6	10.0	5.9	<6.6	--	--	--
1548,50	$10^4C^{3+}/H^+$	0.14	0.4	--	--	0.25	--	--	--
	$10^4C/H$	1.1±0.4	2.0±0.8	1.2±0.5	1.8±0.7	1.5±0.6	4.8±1.8	--	--
7135	$10^6Ar^{2+}/H^+$	0.50	1.05	0.78	1.67	1.44	1.81	3.82	--
4740	$10^6Ar^{3+}/H^+$	1.79	1.78	1.77	0.70	--	--	--	--
	i_{cf}	1.01	1.01	1.02	1.04	1.04	--	--	--
	$10^6Ar/H$	2.31±0.50	2.84±0.60	2.61±0.50	2.47±0.50	1.50±0.30	--	--	--
6717,31	$10^6S^+/H^+$	0.03	0.03	0.08	0.29	0.25	0.45	2.12	--
9069	$10^6S^{2+}/H^+$	2.71	5.63	3.42	6.53	5.88	--	--	--
	i_{cf}	3.69	3.50	3.07	1.99	1.89	--	--	--
	$10^6S/H$	10.1±1.5	19.8±3.0	10.8±1.5	13.6±2.0	11.6±1.7	--	--	--

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TABLE 5

Comparison of Abundances

Object	He/H	10^4O/H	10^4N/H	10^4Ne/H	10^4C/H	10^6Ar/H	10^5S/H	Reference
NGC 7009	0.117	4.8	1.25	1.45	1.51	2.3	1.31	This paper
	±0.003	±0.3	±0.16	±0.17	±0.17	±0.3	±0.17	
NGC 7009	--	5.2	3.0	0.96	2.9	--	--	Perinotto and Benvenuti 1981
NGC 7009	0.10	6.8	1.3:	1.6	10:	3.2	3.2	Czyzak and Aller 19[illegible]
NGC 6720	0.110	6.2	2.2	1.6	3.9	3.7	0.97	Barker, 1980, 1982
H II regions	0.117	4.0	0.4	1.25	--	--	1.8	Hawley 1978

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