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REDUCED HELIUM ABUNDANCES IN NEBULAE

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ABSTRACT

Recent capture-cascade calculations by Robbins and Robinson for the helium singlets, and also calculations by Cox and Daltabuit concerning collisional excitation in the helium triplets, imply a reduction in nebular helium abundances. For planetary nebulae, $\langle \mathrm{He/H} \rangle \sim 0.081 \pm 0.03$ from singlet lines and 0.093 ± 0.02 from triplet lines, if all published data are used. Selecting the three best observed nebulae only, one finds $\langle \mathrm{He/H} \rangle \sim 0.092 \pm 0.015$. For the Orion nebula, He/H ranges from 0.064 to 0.081 for various regions of the nebula. Some consequences of these reductions are discussed.

I. CALCULATIONS

Robbins and Robinson (1971) have calculated effective recombination coefficients and spectra for the helium singlets under case A nebular conditions. Preliminary transfer solutions for optical-depth effects in the singlets show that the $n\ {}^1D$–$2\ {}^1P$ emission series is the least contaminated by optical-depth and collisional effects and hence the most appropriate for determining a helium abundance from singlet lines. Since most observers have not measured λ6678 ($3\ {}^1D$–$2\ {}^1P$), we here utilize primarily the next two lines in the series (λλ4922, 4388). Using the fact that the energy emitted $\mathrm{cm}^{+3}\ \mathrm{s}^{-1}$ is proportional to β(upper level)P(line)$h\nu$, where β is the effective recombination coefficient and P(line) is the Einstein A-coefficient for that transition divided by the total A for the upper level, we may write

$$\frac{I(4922)}{I(\mathrm{H}\beta)} = \frac{\beta(\mathrm{He}\ 4\ {}^1D)P(4922)}{\alpha_{\mathrm{eff}}(\mathrm{H}\beta)}\ \frac{4861}{4922}\ \frac{N(\mathrm{He}^+)}{N(\mathrm{H}^+)}\ ,$$

$$\frac{I(4388)}{I(\mathrm{H}\gamma)} = \frac{\beta(\mathrm{He}\ 5\ {}^1D)P(4388)}{\alpha_{\mathrm{eff}}(\mathrm{H}\gamma)}\ \frac{4340}{4388}\ \frac{N(\mathrm{He}^+)}{N(\mathrm{H}^+)}\ ,$$

where $\alpha_{\mathrm{eff}}(\mathrm{H}\beta)$ and $\alpha_{\mathrm{eff}}(\mathrm{H}\gamma)$ are the effective recombination coefficients for the lines Hβ and Hγ. An advantage of this particular comparison is that the reddening correction for line ratios so near in wavelength is negligible, as may be seen by consulting the photometry of O'Dell (1963). Using values for $\alpha_{\mathrm{eff}}(\mathrm{H}\beta)$ and $\alpha_{\mathrm{eff}}(\mathrm{H}\gamma)$ taken from Clark (1965, as given in Aller and Liller 1968, Table 2) and using helium β's and P's from Robbins and Robinson (1971), we obtain

$$\begin{aligned}\frac{N(\mathrm{He}^+)}{N(\mathrm{H}^+)} &= [6.9 + 0.8(T_4 - 1)]\,\frac{I(6678)}{I(\mathrm{H}\alpha)}\\ &= [2.42 + 0.19(T_4 - 1)]\,\frac{I(4922)}{I(\mathrm{H}\beta)}\\ &= [3.31 + 0.19(T_4 - 1)]\,\frac{I(4388)}{I(\mathrm{H}\gamma)} \qquad (1)\end{aligned}$$

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where $T_4 = T_e/10^4$ ° K. The ratio $\mathrm{He}^+/\mathrm{H}^+$ by number derived from these equations for a number of nebulae is shown in Table 1. The temperatures given in the table are either those derived by the observer or the value listed in Aller and Liller (1968), Table 14. The results, however, are rather insensitive to T_e.

In the past, of course, helium abundances have generally been determined from the intrinsically stronger triplet lines. Again, the $n\,^3D$–$2\,^3P$ series has generally been employed, due to its relative insensitivity to optical-depth effects, but recently Cox and Daltabuit (1971) have pointed out that collisional excitation of the $3\,^3D$ and $4\,^3D$ levels from the metastable $2\,^3S$ level cannot be neglected. For an $n\,^3D$ level, the balance equation becomes

$$\beta(n\,^3D)N_eN(\mathrm{He}^+) + q(2\,^3S \rightarrow n\,^3D)N_eN(2\,^3S) = N(n\,^3D)A\ ,$$

where q is the collisional-excitation rate. If we let $R = I(5876)/I(4471)$ and use the fact that $\beta(2\,^3S)N_eN(\mathrm{He}^+) = N(2\,^3S) \times$ (depopulating terms), elementary manipulations demonstrate that

$$\frac{R(\text{observed})}{R(\text{radiative theory, no collisions})} = \frac{1 + \gamma(5876)}{1 + \gamma(4471)}\ , \tag{2}$$

where

$$\gamma(5876) = \frac{q(3\,^3D)N(2\,^3S)}{\beta(3\,^3D)N(\mathrm{He}^+)} \quad \text{and} \quad \gamma(4471) = \frac{q(4\,^3D)N(2\,^3S)}{\beta(4\,^3D)N(\mathrm{He}^+)}$$

are the fractional contributions to these lines due to collisional excitation. Since

$$\frac{\gamma(5876)}{\gamma(4471)} = \frac{q(3\,^3D)\beta(4\,^3D)}{q(4\,^3D)\beta(3\,^3D)} = f(T_e)\ , \tag{3}$$

we may solve equations (2) and (3) for the γ's, using the q rates computed by Cox and Daltabuit and helium parameters from Robbins (1968*a*). Comparison with Hβ then yields

$$\frac{I(5876)}{I(\mathrm{H}\beta)} = \frac{4861}{5876}\,\frac{\beta(3\,^3D)N(\mathrm{He}^+) + q(3\,^3D)N(2\,^3S)}{\alpha_{\mathrm{eff}}(\mathrm{H}\beta)N(\mathrm{H}^+)}\ ,$$

from which follows

$$\frac{5876}{4861}\,\frac{\alpha_{\mathrm{eff}}(\mathrm{H}\beta)}{\beta(3\,^3D)}\,\frac{I(5876)}{I(\mathrm{H}\beta)} = \frac{N(\mathrm{He}^+)}{N(\mathrm{H}^+)}\,[1 + \gamma(5876)]\ . \tag{4}$$

TABLE 1

$\mathrm{He}^+/\mathrm{H}^+$ FROM SINGLETS

Nebula	T_4	$[N(\mathrm{He}^+)/N(\mathrm{H}^+)]_{4922}$	$[N(\mathrm{He}^+)/N(\mathrm{H}^+)]_{4388}$	$[N(\mathrm{He}^+)/N(\mathrm{H}^+)]_{\mathrm{av}}$	Observer
NGC 7027...	1.6	0.081	0.133	0.107	Aller, Bowen, and Wilson (1963)
NGC 7009...	1.2	0.004:	0.041	0.041*	Aller and Kaler (1964*a*)
IC 418.......	1.25	0.015	0.052	0.034	Aller and Kaler (1964*c*)
NGC 7662...	1.4	0.062	0.032	0.047	Aller, Kaler, and Bowen (1966)
NGC 2440...	1.34	0.009	0.034	0.022	Aller, Czyzak, and Kaler (1968)
IC 2165......	1.22	0.016	...	0.016*	Kaler, Czyzak, and Aller (1968)
NGC 6543...	0.82	0.032	0.075	0.054	Czyzak, Aller, and Kaler (1968)
IC 3568......	1.24	0.036	0.060	0.048	Lee *et al.* (1969)
NGC 6302...	1.8	...	0.090	0.090*	Aller and Oliver (1969)
IC 4997......	1.8	0.0015:	...	...	Aller and Kaler (1964*b*)
IC 5217......	~1.2	0.064	0.080	0.072	Czyzak, Aller, and Leckrone (1969)
NGC 6741...	~1.2	...	0.094	0.094*	Aller, Krupp, and Czyzak (1969)

* Only one line available.

Thus we may solve for $N(\mathrm{He}^+)/N(\mathrm{H}^+)$. The left-hand side of equation (4) is the value of $N(\mathrm{He}^+)/N(\mathrm{H}^+)$ that would be derived if no collisional excitation were taken into account. If the recent photoelectric observations of Peimbert (1971) are used, the results including collisions for three well-observed nebulae are: $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.065$, 0.063, and 0.048 for NGC 7027, IC 418, and NGC 7662, respectively.

II. DISCUSSION OF RESULTS

Only three of the nebulae photoelectrically measured by O'Dell (1963) were suitable for determining helium abundances from triplet lines. For the others, R(observed) $<$ R(radiative theory, no collisions). Such a result not only leaves no room for collisional excitations, but cannot presently be accommodated theoretically. However, when collisional excitations are small and the intensities are close to their pure recombination values, it is to be expected that observational scatter would put approximately half the objects below the theoretical expectation value, especially for weaker lines. Further, R is considerably modified by reddening corrections. If the singlet ratio $I(4922)/I(4388)$ were similarly compared with radiative-theory predictions, about half of those would also scatter below predicted values. The triplet determinations could be reformulated in a manner analogous to the singlet determinations, i.e., in terms of the ratios $I(5876)/I(\mathrm{H}\beta)$ and $I(4471)/I(\mathrm{H}\beta)$ directly. However, this would necessitate substituting in a specific number for $N(2\,^3S)$, and earlier work has demonstrated that the balance equation for $2\,^3S$ probably does not correctly predict the level population in many nebulae. Thus, for accurate helium-abundance determinations from the triplet lines, both the observations and the reddening corrections must be known with considerable accuracy. Note also that the presence of collisional excitation introduces considerably more sensitivity to T_e than was previously present, and that the q's are probably known only to ± 50 percent.

The singlet lines, while less sensitive to T_e, are on the other hand even fainter (approximately one-third, on the average) and hence more subject to observational fluctuations, as is apparent from the dramatic (and most likely unreal) variations seen in abundance from object to object in Table 1. The singlet abundance for any particular object is probably rather unreliable, especially if only one line is available. It should be noted in connection with the singlet determinations that, due to the neglect of small optical-depth effects and small reddening corrections, the numbers in Table 1 are upper limits to $N(\mathrm{He}^+)/N(\mathrm{H}^+)$.

When averages are taken over several objects, however, the triplet and singlet determinations show good consistency. Considering only those objects in Table 1 where two singlet lines are well observed, we find $\langle \mathrm{He}^+/\mathrm{H}^+ \rangle = 0.060$. Above, for triplet lines in three well-observed objects, we have $\langle \mathrm{He}^+/\mathrm{H}^+ \rangle = 0.061$. Such close agreement is fortuitous; for a particular object, the triplet lines are probably more reliable, since they are stronger and have been observed photoelectrically.

Total helium abundances must also allow for the presence of He^{++}, which is easily done since

$$\frac{I(\mathrm{He\,II}\ \lambda 4686)}{I(\mathrm{H}\beta)} = \frac{\alpha_{\mathrm{eff}}(4686)}{\alpha_{\mathrm{eff}}(\mathrm{H}\beta)} \frac{4861}{4686} \frac{N(\mathrm{He}^{++})}{N(\mathrm{H}^+)} .$$

For $\alpha(\mathrm{He\,II}\ \lambda 4686)$, which is rather sensitive to N_e, we may use the numbers given by Seaton (1968) for $N_e = 10^4\ \mathrm{cm}^{-3}$. Using $I(4686)/I(4861)$ from the observers in Table 1 (or the values of O'Dell 1963 when available), we may summarize total helium-to-hydrogen ratios as in Table 2, where only objects with two singlet lines observed have been included. We then find

$$\langle \mathrm{He/H} \rangle_{\mathrm{singlets}} \simeq 0.081\ , \quad \langle \mathrm{He/H} \rangle_{\mathrm{triplets}} \simeq 0.093\ .$$

Averaging the singlet and triplet determinations for the three best-observed nebulae NGC 7027, NGC 7662, and IC 418, we find $\langle \mathrm{He/H} \rangle \sim 0.092 \pm 0.015$. Existing values

TABLE 2

TOTAL He/H

Nebula	He^{++}/H^{+}	$(He/H)_{singlet}$	$(He/H)_{triplet}$	$(He/H)_{equal\ av}$
NGC 7027..	0.042	0.149	0.107	0.128±0.021
IC 418......	0	0.034	0.063	0.048±0.015
NGC 7662..	0.060	0.107	0.108	0.100±0.005
NGC 2440..	0.059	0.080	...	...
NGC 6543..	0.008	0.062	...	...
IC 3568.....	0.001	0.049	...	...
IC 5217.....	0.015	0.087	...	...
Average...	...	0.081±0.03	0.093±0.02	0.092±0.015

in the literature, using only triplet lines and not allowing for collisional excitation, are ~0.13 according to Osterbrock (1970), with an error bar probably at least as large as in the present work. The values obtained in this paper strongly reinforce the concept that the ejected envelopes of planetary nebulae are not significantly enriched in helium.

The best observed diffuse nebula is Orion, and we may carry out the procedures above, using parameters appropriate to a temperature of 7500° K interpolated from Robbins (1970). Peimbert and Costero (1969) and Peimbert (1971) have observed the triplet lines λλ5876 and 4471 and the singlet line λ6678 photoelectrically for three separate regions in Orion. Assuming that the photographic values of Kaler, Aller, and Bowen (1965) for the singlet lines λλ4922 and 4388 apply to all regions of the nebula and averaging the singlets weighted by their intensity so that the photoelectric λ6678 value dominates, we find $N(He^{+})/N(H^{+}) = 0.050$, 0.067, and 0.067 for the three regions. The observed value of $I(5876)/I(4471)$ in the triplets is identical with the theoretical value for $T_e = 7500°$ K, so for the triplet determination, there is no change from the values previously derived by Peimbert and Costero, which range from 0.077 to 0.095. Giving the singlet and triplet determinations equal weight, and noting that $N(He^{++})$ is negligibly small, we then find He/H for Orion ranging from 0.064 to 0.081 for various regions, with error bars at least comparable to the differences in the values. Such values are ~25 percent down from previous determinations and are slightly lower than typical O and B star determinations, which are ~0.10 according to Peterson and Scholz (1971). It should be noted that no correction has been applied for the possible presence of He^0 in the Orion Nebula. Since the transfer calculations of Robbins (1968*b*) show that optical-depth effects in Orion are roughly comparable to those seen in planetaries, it is felt that such a correction is probably *on the average* small.

For the solar helium-to-hydrogen ratio, Lambert (1967) finds 0.063, which, like the Orion number, is slightly and perhaps significantly below the predictions for helium synthesis in a primordial fireball. Further, comparison of the Orion and solar results suggests the possibility that the contribution to interstellar helium from stellar nucleosynthesis over the last 5×10^9 years has been small, less than 20 percent of the total abundance. Photoelectric observations of the singlet lines in diffuse nebulae would be desirable, however, before extensive conjectures along such lines are developed.

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