ABUNDANCES OF HELIUM IN GASEOUS NEBULAE

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During the past two or three years much work has been done on the determination of helium abundances in gaseous nebulae, using observations at both optical wavelengths and radio wavelengths. I imagine that the organisers of this Discussion must have asked whether the subject should be reviewed by an optical observer or a radio observer, and have finally resolved their dilemma by choosing a speaker who has not made observations at any wavelength whatsoever.

1. Summary of Results

I will summarise the results obtained before discussing in more detail the various techniques and special problems involved. Let y be the percentage abundance of helium atoms, relative to the number of hydrogen atoms:

$$y = 100 \times \frac{N(\text{He})}{N(\text{H})}. \tag{1}$$

The helium abundance as a fraction of the total mass, for a mixture of hydrogen and helium, is

$$Y = 0.04y/(1 + 0.04y). \tag{2}$$

A concise summary of results is given in Table I. For H^+ regions* I adopt $y = 9 \pm 2$.

TABLE I
Summary of results

Objects	y
H+ regions, galactic and extra-galactic	9 ± 2
Planetary Nebulae	12 ± 3

Values of y from optical observations tend to be slightly larger than those obtained from radio observations, but the discrepancy is not serious. Observations have been made for galactic H^+ regions, for a number of galaxies in the local group, and for two galaxies not in the local group. To within probable observational errors, it would appear that y is essentially the same for all these objects. The galaxy NGC 6822 is of interest as a member of the local group with a small mass, a large fraction by mass of interstellar H, and low abundances of N and O; for this galaxy optical measurements give $y = 9.4$ (Peimbert and Spinrad, 1970a). Some evidence has been presented for

* I refer to 'H+ regions' rather than 'HII regions', since the Roman numerals should be used only for the designation of spectra.

variations in y at different points in the galaxy M31 (Schmidt, 1962; Rubin and Ford, 1968): I will leave it to the observers to discuss whether these effects are real.

All determinations of y in planetary nebulae have been made at optical wavelengths. I adopt $y = 12 \pm 3$. Is there any significant difference between the values of y for planetary nebulae and for galactic H^+ regions? The comparisons should be made using the same observing techniques. The most recent photo-electric observations show that the results for planetaries and H^+ regions are in quite close agreement.

The planetary observed in the globular cluster M15 (O'Dell *et al.*, 1964) is of interest in providing information about the He abundance in Population II. This planetary has low abundances of O and N, but a normal value of y ($y = 13$). The planetaries are formed by ejection of material from the outer envelopes of highly evolved stars and this material could be He-rich. However, the close agreement between He abundances in galactic planetaries and galactic H^+ regions indicates that any such effect must be small, and it is therefore reasonable to assume that the He abundance observed in the globular cluster planetary does not differ significantly from the abundance in the material out of which the cluster was formed. The evidence is that the He abundance is the same in Populations I and II. Further support comes from the work of Miller (1969), who obtains $y = 13$ for a distant planetary in a direction close to that of the galactic pole, and which also presumably belongs to Population II.

2. Theory

Helium abundances in gaseous nebulae are obtained from the interpretation of recombination spectra of hydrogen and helium. An ion X^+ ($X^+ = H^+$, He^+ or He^{++}) undergoes radiative recombination,

$$X^+ + e \rightarrow X_n + h\nu \tag{3}$$

to give an atom X in some excited state n, which may then emit further radiation in spectrum lines,

$$X_n \rightarrow X_{n'} + h\nu_{nn'}. \tag{4}$$

In order to calculate the emissivity in a particular spectrum line one must take account of all relevant radiative and collisional processes; the theory of such calculations is reviewed by Seaton (1968). From the observed intensities of HeI and HeII lines, relative to HI lines, one deduces a quantity

$$y' = 100 \frac{\int N_e \{N(He^+) + N(He^{++})\} \, dV}{\int N_e N(H^+) \, dV} \tag{5}$$

where the integrals are over the observed volume. In high excitation planetaries a significant fraction of the He may be He^{++}. In most other nebulae HeII lines are weak or absent and He^{++} may be neglected. It is more difficult to allow for the fact

that an appreciable amount of neutral He, He^0, may exist in regions of ionized hydrogen. The ionization potential of He^0 (24.6 eV) is much larger than that of H^0 (13.6 eV). Consider a star radiating as a black body, at temperature T_s, completely surrounded by an optically thick nebulae. For small values of T_s the number of stellar quanta capable of ionizing He^0 is much smaller than the number capable of ionizing H^0. In this case one has two ionized regions, an inner region containing H^+ and He^+ and an outer region containing H^+ and He^0. Observations of such nebula will give $y' < y$. As T_s increases, the size of the (H^+, He^0) region decreases, relative to the size of the total H^+ region. The (H^+, He^0) region no longer exists for T_s larger than some critical value T_c; for $y = 10$, $T_c = 4 \times 10^4$ K. The theory, which was first discussed in detail by Hummer and Seaton (1964), is confirmed by observations of planetary nebulae (Harman and Seaton, 1966). Determining y from observations of high exci- tation planetaries, one obtains $y' < y$ for a number of low excitation planetaries, having $T_s < T_c$.

The stars exciting diffuse H^+ regions will generally have $T_s < T_c$. The interpretation of observations is complicated by the fact that the diffuse H^+ regions have very irreg- ular shapes and, in at least some directions, will not be optically thick. One may measure $He I/H I$ intensity ratios at various points in a nebula or, even better, obtain iso-photal contours in monochromatic $He I$ and $H I$ radiations. Observations of Orion give small values of y' at points near the edge of the nebula, which shows that there must be some outer regions containing H^+ and He^0 (Peimbert and Costero, 1969). One may attempt to allow for the presence of (H^+, He^0) regions on constructing three-dimensional models. Use may also be made of the intensities of various for- bidden lines. The [S II] lines give a particularly useful guide to the amount of He^0, since the ionization potential of S^+ (23.4 eV) is a bit smaller than that of He^0 (Peim- bert and Spinrad, 1970). In using [S II] line intensities to estimate the amount of He^0, the main uncertainty may arise from the fact that the [S II] line emissivities are sensitive to electron temperature.

3. The Interpretation of Optical Observations

Abundances are usually deduced from the intensities of helium triplet lines, since each triplet line is about three times as intense as the corresponding singlet line. Some complications in the interpretation of the triplet spectrum arise from the metasta- bility of $2\,^3S$. Self-absorption can occur in the lines $2\,^3S \to n\,^3P$, and $2\,^3P$ can be excited by collisions from $2\,^3S$. Fortunately, these processes do not influence signifi- cantly the intensities of the lines $n\,^3D \to 2\,^3P$. Helium abundances are usually deduced from measured intensities of $He I$ $3\,^3D \to 2\,^3P$, $\lambda 5876$ or $4\,^3D \to 2\,^3P$, $\lambda 4471$.

Calculations for $He I$ have been made in the following approximations:

(i) Using hydrogenic recombination rates and transition probabilities (Seaton, 1960). For values of the principal quantum number $n > 12$ it was assumed that colli- sions produced a complete redistribution among the levels of different angular mo- mentum quantum number l (Burgess, 1958).

(ii) As in (i), but neglecting all collisional redistribution in l (Pengelly, 1964).

(iii) Using helium recombination rates and transition probabilities, neglecting collisional redistribution in l (Pengelly, 1963). These results are quoted by Harman and Seaton (1966) and by Seaton (1968).

(iv) As in (iii), but making explicit allowance for collisional transitions between l-states (Robbins, 1968).

The results obtained in approximations (ii) and (iv) are in good agreement, and the calculated intensity ratios $I(5876)/I(4471)$ are in agreement with results of photo-electric observations (Peimbert and Costero, 1969).

A crucial test of the theory is that the calculated relative intensities in each spectrum should be in agreement with the observed relative intensities. A number of discrepancies have been reported between calculated intensities and intensities measured using photographic techniques. Such discrepancies could be due to errors in the theory or errors in the observations. Recent photo-electric work suggests that the discrepancies may be due to errors in photographic photometry such that the intensities of the weaker lines are too large. Further work is much to be desired, since one cannot have complete confidence in any results deduced from optical observations so long as there is doubt as to the measure of agreement between calculated and observed relative intensities in each spectrum.

Harman and Seaton (1966) consider 15 planetaries for which they would expect to have $y' = y$, and deduce a mean value of $y = 16$. The same date has been reconsidered by Osterbrock (1970), who selects the eight objects for which the most accurate photo-electric observations are available, and obtains $y = 13$. Further photo-electric observations have been made by Peimbert and Torres-Peimbert (1970) who obtain $y = 11.5 \pm 2$ for 10 planetaries. The discrepancy between photo-electric and photographic results is consistent with the overestimation of photographic intensities of weaker lines.

References to work on He abundances in H^+ regions are given in a review by Osterbrock (1970) and I will therefore cite only the most recent papers. From photo-electric observations of three galactic H^+ regions (Orion, M8 and M17), Peimbert and Costero (1969) obtain $y = 11$. The most recent work on H^+ regions in other galaxies is that of Peimbert and Spinrad (1970a, b).

4. The Interpretation of Radio Observations

The lines observed at radio wavelengths are due to transitions, $n \rightarrow n'$, between highly excited states. For a given transition the frequency of the He I line differs from that of the H I line due to the differences in the nuclear masses.

The number of atoms N_n in an excited state is expressed in terms of the number for conditions of Saha equilibrium,

$$N_n = b_n N_n \, (\text{Saha}). \tag{6}$$

The factors b_n must be calculated allowing for radiative and collisional processes.

The most accurate calculations are those of Brocklehurst (1970). For given values of electron temperature T_e and electron density N_e the factors b_n will be the same for highly excited states of hydrogen and helium. Calculations show that $b_n > b_{n'}$ for $n > n'$, that is to say the upper levels are overpopulated with respect to the lower levels. It follows that partial maser action can occur (Goldberg, 1966). The intensity in the free–free continuum is large compared with the intensities in the lines, and the maser process therefore involves stimulated emission of line photons by continuum photons; the line intensities depend on T_e, N_e and continuum optical depth, τ_c. As in the optical case, one must consider whether the observed relative intensities in each spectrum are in agreement with theory. It is found that maser action does occur in many nebulae. One can determine values of T_e, N_e and τ_c such that all of the observed line intensities agree with theory, to within the probable accuracy of the observations, but it is found that the values of τ_c required are larger than the values deduced from observed continuum surface brightnesses (Hjellming and Davies, 1970; Gordon, 1970). A plausible explanation of the discrepancies in τ_c is that much of the emission comes from localised regions of high surface brightness, with angular diameters too small to be resolved at radio wavelengths.

We may now discuss the determination of He/H abundance ratios. Three cases may be considered:

(i) If no maser action occurs, the integrated H I and He I line intensities are proportional to H^+ and He^+ abundances, and we therefore obtain

$$\frac{I(n \to n', \text{He I})}{I(n \to n', \text{H I})} 100 = y' \tag{7}$$

(it is here assumed that He^{++} can be neglected).

(ii) If we have a (H^+, He^+) region but no (H^+, He^0) region,

$$\frac{I(n \to n', \text{He I})}{I(n \to n', \text{H I})} 100 = y. \tag{8}$$

In this case, maser action will enhance the He I and H I lines by the same fractional amount and Equation (8) remains valid even if maser action does occur.

(iii) If we have both (H^+, He^+) and (H^+, He^0) regions in the line of sight, and maser action occurs, then the situation is more complicated. This case does not appear to have been discussed previously. Consider the case that we have a (H^+, He^0) region in front of a (H^+, He^+) region. Maser action in the He I lines then depends on the value of τ_c for the (H^+, He^+) region alone, while maser action in the H I lines depends on the value of τ_c for both regions combined. In this case we obtain

$$\frac{I(n \to n', \text{He I})}{I(n \to n', \text{H I})} 100 < y'. \tag{9}$$

The observational evidence is that the intensity ratios $I(n \to n', \text{He I})/I(n \to n', \text{H I})$ are the same for lines which show maser action and for lines which do not show maser action (Mezger et al., 1970a and b; Gordon, 1970). This has been taken to provide

a good check on the theory. It also indicates that there is no very extensive (H^+, He^0) region contributing to the observed emission. It would be of interest to obtain, from the observational material, an upper limit on the possible contributions from (H^+, He^0) regions.

Results of radio determinations of y' are summarised in Table II. Careful com-

TABLE II

Values of y' obtained from radio observations

Object	y'	Reference
Five galactic H$^+$ regions	8.4 ± 0.3	Palmer *et al.*, 1969
Northern galactic H$^+$ regions	8	Reifenstein *et al.*, 1970
Southern galactic H$^+$ regions	8.8	Mezger *et al.*, 1970a
Orion Nebula (M42)	7.3 ± 0.8	Gordon, 1970
Orion Nebula (M42)	8.1 ± 0.2 ⎫	
Lagoon Nebula (M8)	9.3 ± 2.9 ⎬	Churchwell and Mezger, 1970
Omega Nebula (M17)	9.4 ± 0.6 ⎭	
30 Doradus nebula (LMC)	17 ± 9	Mezger *et al.*, 1970b

parisons of optical and radio determinations of y' have been made (Churchwell and Mezger, 1970), particularly for the Orion nebula. Agreement is generally good, but there may be some tendency for the optical values of y' to be slightly larger than the radio values. It should also be noted that estimated corrections for He^0 in the ionized regions have been made in several recent papers by optical observers, but not in the work of the radio observers.

5. Conclusions

The accuracy of the best optical determinations of He/H abundance ratios is probably comparable to that of the best radio determinations. One advantage of optical work is that observations can be made on sources with small total flux (planetary nebulae and extra-galactic objects).

Further careful comparisons of radio and optical results should be made for selected objects. In order to gain complete confidence in the interpretation of the observations it is also highly desirable to make further careful studies of the relative intensities in each spectrum, at both radio and optical wavelengths.

So far there is no very convincing evidence for variations in y between different objects. Once again, further observational work is required.

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DISCUSSION

D. E. Osterbrock: Dr Vera Rubin is unable to attend our session, but would like me to read the following note:

"Spectra of 50 HII regions in M31 have been observed, with distances from the nucleus ranging from 3 to 24 kpc. The line He $\lambda 5876$ is in the spectral region observed.

(1) For 15 regions, the observed line ratio $\lambda 5876/H\alpha$ ranges from 0.01 to 0.08 (with an uncertainty of about 30% for each value). This implies $N(\text{He})/N(\text{H})$ ranges from 2% to 15% by number. The mean value for 15 regions is 12%. There is a large scatter at each R, but no systematic variation with distance from the nucleus.

(2) For 21 regions $N(\text{He})/N(\text{H})$ is less than 3% (i.e. no line observed on well exposed plate). These 21 regions are at all distances from nucleus.

(3) For these $15 + 21$ regions, mean $N(\text{He})/N(\text{H}) < 0.08$. Note that for [NII]/H and [SII]/H line ratios, there is a strong dependence on R, i.e. both line ratios are largest for regions near the nucleus, and decrease with increasing R."

M. Schwarzschild: Dr Seaton's reference to the planetary nebula in M15 seems to me to be of special interest. In the commission for stellar structure, Dr Paczinski has given us a most fascinating report on his computations regarding the ejection of a planetary nebula from a red giant, caused by releasing the ionization energy of H and He within the extended envelope. His results make it appear plausible that purely unmixed and unburned matter is ejected by this mechanism. If this is true, then the observed 'normal' He abundance of the planetary nebula in M15 should give us directly the initial He abundance of this cluster. On this basis I think I am now ready to bet that our Galaxy started with a substantial, i.e. near 'normal', abundance of He.

L. H. Aller: There is an acute need for additional improved observational data. Czyzak and I have tried to calibrate all our photographic line intensity measurements by photoelectric photometry; in particular the $I(4471)/I(H\beta)$ ratio is measured photoelectrically. Of course, the photoelectric calibration should be extended to the fainter lines.

Effects of filamentary structure are particularly troublesome. One needs for high resolution direct photographs secured with narrow bandpass filters in the radiation of [SII], [OII], $\lambda 4471$ and $H\beta$. Huge fluctuations in N_e and T_e can occur and will affect the H and HeI emissions differently. Note that photoelectric observations integrate over large surface areas and thus possibly tend to smooth over fluctuations.

If collisional excitation can occur, note that the effects will be markedly different for H and He because of the differences in term structure.

Finally, mention may be made of the work of Kaler who employed all available observations of line intensities and found He/H ratios in the range $0.09 < \text{He/H} < 0.20$. This ratio appeared to be inversely correlated with the O/H ratio.

Roger Cayrel: I want to support the view expressed by Dr. Schwarzschild that it seems somewhat unlikely that the high helium of the planetary nebule in M15 found by O'Dell, Peimbert, and Kinman is produced within the nebula.

It would be a strange coincidence that the central star had managed to put into its expelled shell exactly the proper amount of He found in all other planetaries from an initially helium-poor matter. One would expect more likely to have much more or much less.