THE PLANETARY NEBULA IN THE GLOBULAR CLUSTER M15

C. R. O'Dell and M. Peimbert
Berkeley Astronomical Department, Berkeley, California

T. D. Kinman
Lick Observatory, Mount Hamilton, California

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ABSTRACT

The results of a photographic spectrophotometric investigation of the nebulous object K648 in the globular cluster M15 are presented. On the basis of a discussion of the size, density, and mass it is shown that K648 represents a typical example of the planetary nebula phenomena. The relative abundances of hydrogen, helium, oxygen, and neon were determined. The oxygen abundance, relative to hydrogen, is deficient by a factor of 61 relative to the Sun. The helium abundance, $N(\mathrm{He})/N(\mathrm{H}) = 0.18 \pm 0.03$, is compared with that found in field planetary nebulae, a very high-velocity planetary nebula, and the Orion Nebula. It is shown that strong arguments can be presented, supporting the hypothesis that the original helium content of the globular clusters was much higher than the very low values usually assumed.

I. INTRODUCTION

The presence of a seemingly typical planetary nebula in a globular cluster presents an almost unique opportunity for testing theories of the evolution of the planetary nebulae and the determination of the relative atomic abundances for the globular clusters. Although the nebula is faint and located in a very crowded field, the possible significance of a thorough study made it seem worthwhile to undertake an observational program in M15.

Pease (1928) first noted that the object K648 (Küstner 1921) in the globular cluster M15 (NGC 7078) has an emission-line spectrum corresponding to that of a planetary nebula. The measurements by Joy (1949) of two plates of this object indicated a radial velocity of −122 km/sec, a value very similar to that derived from cluster stars ($V_r = -107$ km/sec; Kinman 1959*a*). Although agreement of radial velocity is not a definitive proof of association of two objects, there are no field planetary nebulae in this region ($l^{\mathrm{II}} = 65\overset{\circ}{.}03$, $b^{\mathrm{II}} = -27\overset{\circ}{.}32$) with similar high values, thus strengthening the argument for membership of the nebula-central star in this cluster. Osterbrock (1960) has obtained a single spectral plate of the nebula in the ultraviolet and measured the [O II] doublet λ 3729/λ 3726. None of these studies indicated peculiarities in the spectrum of the nebula.

There exists substantial proof that certain globular clusters are highly deficient in metal content (Kinman 1959; Deutsch 1963). Of these metal-weak clusters M15 must be included among the metal-weakest group, with an approximate metal deficiency of about 100 relative to the Sun. It seems, therefore, very important to derive the relative abundances of the atoms in this nebula, which, if this is a typical planetary nebula system, represents mass ejected from a highly evolved parent star (O'Dell 1963*a*). It is also important to compare this nebula with field planetaries in order to test its membership in this roughly homogeneous group of objects.

II. OBSERVATIONS

Photographic spectra of the nebula were obtained with the prime-focus spectrograph of the 120-inch telescope at Lick Observatory during July and August, 1963. Using a grating with 21000 lines/inch in the second-order blue yielded a dispersion of 50 Å/mm.

This dispersion was quite satisfactory for this photometric study. Although the spectrograph camera focus was always adjusted to be sharp, in short exposures a wide entrance slit was used to produce flattopped lines. Not only were these wide-slit measures easier to photometer; but they also minimized the effects of differential atmospheric refraction. Since a large range in intensities and wavelengths of emission lines was to be studied, both IIa-O and 103a-F film was used with a range of exposure times from 10 to 100 minutes (cf. Table 1). In all cases an entrance slit length of 30″ was used, the object being trailed over 20″ of the slit. This produced an emission-line length of 0.34 mm on the film. Due to the crowded nature of the field, a slit position angle of 345° was used with trailing in both right ascension and declination. In order to convert the measured plate densities into relative line intensities, the results of step-wedge spectra were used. Since the small films employed ($\frac{1}{2} \times 1$ inch) did not have space for the imprint of the step-wedge spectra, separate exposures were made of either the twilight sky or the inside of the telescope dome illuminated by a tungsten lamp. In each case the film was taken from the same roll and exposed for times comparable with the exposure on the nebula. The calibration into relative absolute energy units was achieved by obtaining photometric spectra of HD 195592, a highly reddened O9.5Ia star for which the relative absolute energy distribution in the continuum has been determined by Code (unpublished; cf. Code 1960) with a photoelectric spectrograph. Since the largest color variations in the sensitivity of the system are due to the grating glaze and lens transmission which should not vary with exposure time, it was assumed to be safe to use shorter exposure times for HD 195592. The 120-inch coudé plate EC817 was loaned by Dr. George Herbig to the authors for this program. Although the sensitivity function of this system could not be determined from this single plate, it was satisfactory for the measurement of the [O II] doublet at λ 3727. The higher dispersion (16 Å/mm) and accurate strip calibration made a very accurate ratio determination possible, this weighted ratio being used in the derivation given in Table 2. The coudé plate ratio was in excellent agreement with the average ratio from the prime-focus spectra. The agreement with Osterbrock's (1960) value was not as good. The radial velocity of K648 was determined from the single coudé plate and from three of the prime-focus plates, giving −121 and −120 km/sec, respectively, confirming Joy's measures and thereby strengthening the assumption of a common motion.

TABLE 1

PLATES USED IN DERIVING RELATIVE LINE INTENSITIES

Designation	Emulsion	λ_{central}	Exposure (min.)
ES 507....	IIa-O	4200	100
522....	IIa-O	4200	70
524....	IIa-O	4200	60
564....	103a-F	4600	10
565....	IIa-O	4200	30
566....	IIa-O	4200	15
567....	103a-F	4600	27

The accuracy of the resulting line intensities was largely determined by the strength of the background continuum. On the longest exposures, the spectra of faint cluster stars became strong enough to limit the exposure-time values. The degree of contamination by these stars for a given exposure time varied quite strongly with the seeing. Fortunately, the seeing disk was usually less than 1″ during most of these exposures. The emission line Hδ was used as the reference in the reduction to relative absolute line ratios since it was of photometric density on each plate. Table 2 lists the adopted line ratios. The probable errors given are approximated from the scatter demonstrated from plate to plate. The correction for interstellar reddening was made by adopting a logarithmic absorption of 0.1 at Hβ and using the reddening function given by Seaton (1960). The relative intensities, corrected for reddening, are given in the fourth column of Table 2. The average relative line intensities, corrected for reddening, of unblended Balmer lines derived from field planetary nebulae are given in the sixth column and provide a measure of the accuracy of this study.

TABLE 2

RELATIVE ABSOLUTE-EMISSION-LINE INTENSITIES IN K648

λ	Ion	$\log F/F_{\mathrm{H}\delta}$	$\log I/I_{\mathrm{H}\delta}$	Probable Error	$\log F/F_{\mathrm{H}\delta}$ Field Planetary Nebulae
3726...........	[O II]	+0.15	+0.16	±0.07	....
3729...........	[O II]	− .02	− .01	.08	....
3771...........	H_{11}	− .81	− .80	.08	....
3798...........	H_{10}	− .73	− .72	.08	−0.77
3835...........	H_{9}	− .54	− .53	.08	− .56
3869...........	[Ne III]	− .33	− .32	.08	....
3889...........	H+He I	− .07	− .06	.12	....
3967...........	[Ne III]	− .48	− .47	.20	....
3970...........	H_{8}	− .24	− .23	.12	....
4026...........	He I	− .84	− .84	.08	....
4102...........	Hδ	.00	.00	....	.00
4340...........	H	+ .27	+ .26	.05	+ .25
4363...........	[O III]	− .85	− .86	.05	....
4471...........	He I	− .67	− .68	.05	....
4861...........	Hβ	+ .55	+ .53	.08	+0.56
4957...........	[O III]	+ .14	+ .12	.16	....
5007...........	[G III]	+0.64	+0.62	±0.08	....

III. DETERMINATION OF THE ABUNDANCES

The values of the electron temperature (T_e) and the electron density (N_e) were obtained from the relative intensities of the lines of [O III] $\lambda\lambda$ 5007, 4959, and 4363 and [O II] $\lambda\lambda$ 3729/3726 using equations (1) and (2) which relate the line intensities (Seaton 1960; Seaton and Osterbrock 1957).

$$\frac{I(4959)+I(5007)}{I(4363)}=\frac{7.1\exp(3.30/t)}{1+0.038x}, \tag{1}$$

$$\frac{I(3729)}{I(3726)}=1.5\left[\frac{1+0.33\epsilon+2.30x(1+0.75\epsilon)}{1+0.40\epsilon+9.9x(1+0.84\epsilon)}\right]; \tag{2}$$

t, x, and ϵ are given by

$$t=10^{-4}T_e\,,\qquad x=\frac{10^{-4}N_e}{t^{1/2}}\,,\qquad \epsilon=e^{-1.96/t}\,.$$

Equation (1) was first solved neglecting the term in x, giving as a first approximation the value T_e = 19200° K; this value was then used in equation (2), where an electron density of N_e = 2880 electrons/cm^3 was obtained. Equation (1) was then solved with the value x = 0.208 from equation (2) to obtain T_e = 19100° K. Unless otherwise noted, this value is used throughout the present work. It can be seen that equation (1) is almost independent of the electron density; therefore, the error in T_e is roughly proportional to the uncertainty in the logarithm of the relative line intensities. In equation (2) it can be seen that the error in N_e is proportional to the uncertainty in the relative line intensities.

The relative abundance of He$^+$ was obtained using the expression

$$\frac{N(\mathrm{He}^+)}{N(\mathrm{H}^+)}=\frac{4471}{4102}\frac{I(4471)}{I(4102)}\frac{\alpha(6,2;\mathrm{H}^0)}{\alpha(4^2D_2{}^3P;\mathrm{He}^0)} \tag{3}$$

and a similar one for λ 4026. The recombination coefficients of equation (3) were obtained from the values for $\alpha(6, 2; \mathrm{H}^0)$ and $\alpha(3^2D_2{}^3P; \mathrm{He}^0)$ given by Seaton (1960) and using the Balmer decrements of hydrogen and helium given by Burgess (1958), for Case B, and Seaton (1960). The published values for various electron temperatures were interpolated to obtain the correct values of the recombination coefficients for $T_e = 19100$. Weights were assigned, taking into account the number of plates on which the lines appeared and their position on the characteristic curve of each plate. The final result was $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.18 \pm 0.03$. Due to the fact that λ 4363 was observed but not λ 4686, it was possible to calculate an upper limit for $N(\mathrm{He}^{++})/N(\mathrm{H}^+)$ by assuming that the intensity of λ 4686 was equal to λ 4363; the value

$$\frac{N(\mathrm{He}^{++})}{N(\mathrm{H}^+)}=\frac{4686}{4102}\frac{I(4686)}{I(4102)}\frac{\alpha(6,2;\mathrm{H}^0)}{\alpha(4,3;\mathrm{He}^+)}<0.01$$

was obtained, where $\alpha(4, 3; \mathrm{He}^+)$ was taken from Seaton (1960). From the lower limit of λ 4471/λ 4686 it was ascertained that the nebula presents complete absorption in He^0; therefore, the abundance of He^0 is negligible. Due to the absence of He^0 and to the low upper limit of He^{++} the adopted abundance of helium with respect to hydrogen is

$$\log N(\mathrm{He})/N(\mathrm{H}) = -0.74 \pm 0.07\ .$$

The probable error is due to the uncertainties in the intensity of the lines and the upper limit of $N(\mathrm{He}^{++})/N(\mathrm{H}^+)$. The variation with temperature of the ratio of the recombination coefficients is almost negligible.

The abundances of $N(\mathrm{O}^+)$, $N(\mathrm{O}^{++})$, and $N(\mathrm{Ne}^{++})$ can be derived utilizing the relative line strengths of Table 2 in the following equation:

$$\frac{I_\lambda}{I(4102)}=\frac{4102}{\lambda}\frac{N(x^{+p})}{N(\mathrm{H}^+)}\frac{A_{nm}}{N_e\alpha(6,2;\mathrm{H}^0)}\frac{N_n}{N}, \tag{4}$$

where $N(X^{+p})$ is the number of atoms of X in the state p of ionization, N_n/N gives the relative number of atoms in the energy level n with respect to all the atoms in that state of ionization, and A_{nm} is the probability per second of a radiative transition from level n to level m.

For O$^+$, using λ 3726, we found:

$$\frac{N(\mathrm{O}^+)}{N(\mathrm{H}^+)}=0.9\,\frac{I(3726)}{I(4102)}\frac{N_e\alpha(6,2;\mathrm{H}^0)}{A_{nm}}\frac{N}{N_n}=4.5\times10^{-6},$$

where

$$\alpha_{6,\,2}\sim\frac{1}{t}\quad\text{and}\quad\frac{N}{N_n}=\frac{P(^4S_{3/2})+P(^2D_{5/2})+P(^2D_{3/2})+P(^2P_{3/2})+P(^2P_{1/2})}{P(^2D_{3/2})}.$$

The expressions for the P's were taken from Seaton and Osterbrock (1957). An error in the logarithm of the O$^+$ abundance of 0.17 was obtained assuming an error in log T_e of 0.04, in log N_e of 0.08 and in the logarithms of the relative line intensities of 0.08.

For the O^{++} abundance using the λ 5007 line we found

$$\frac{N(O^{++})}{N(H^{+})}=K_1\frac{a(6,2;H^0)t^{1/2}}{e^{-2.89/t}}\frac{I(5007)}{I(4102)}=1.13\times10^{-5},$$

where K_1 is almost constant with respect to T_e and x. An error of 0.15 in the logarithm of the abundance was obtained assuming that the recombination coefficient is inversely proportional to T_e, an uncertainty in the log T_e of 0.04 and in the logarithm of the relative intensities of the lines of 0.08.

For Ne^{++} it was found

$$\frac{N(Ne^{++})}{N(H^{+})}=K_2\frac{a(6,2;H^0)t^{1/2}}{e^{-3.62/t}}\frac{I(3869)}{I(4102)}=3.1\times10^{-6},$$

where K_2 is almost constant with respect to T_e and x. From similar considerations, as those in the case of oxygen, an error of 0.15 in the logarithm was found.

In order to estimate the relative abundances of the ions of neon and oxygen that were not observed, the curve of ionization potential against relative abundances can be used (Aller 1957). This correction for other states can be done accurately for oxygen since $N(He^{+})/N(He^{++}) \geq 10$ and the ionization potential of He^{+} is 54.4 eV, while that of O^{++} is 54.89 eV. Since very little He^{++} can exist, then little O^{+++} is expected. Uncalibrated, red spectral plates indicate that [O I], λ 6300 is not strong and therefore the relative abundance of O^0 is negligible. It can be seen that the logarithm of the abundance of oxygen as given by O^{+} and O^{++} is equal to log $N(O)/N(H) = -4.81 \pm 0.15$; the error is given essentially by the error in O^{++}.

TABLE 3

RELATIVE ABUNDANCES IN K648

log H = 12.00
log He = 11.26 ± 0.07
log O = 7.19 ± 0.15
log Ne = 7.00 ± 0.3

In the case of neon, the abundances of Ne IV and Ne V are negligible, as in the case of O IV, because of the high ionization potentials; but this is not so for Ne^{+}. In order to estimate the abundance of Ne^{+}, different ionization distributions functions were used such that they fulfilled the requirements for O^{+}, O^{++}, He^{+}, and He^{++} and that they were not greatly different from the curves for similar nebulae. The result $N(Ne^{+})/N(Ne^{++}) = 2.2$ gives for the abundance of neon, $N(Ne) = 3.2\ N(Ne^{++}) = 1.01 \times 10^{-5}$ with an uncertainty of a factor of 2 where it is assumed that $Ne^0/Ne^{+} \ll 1$. This error is produced mainly from the determination of the relative abundance $N(Ne^{+})/N(Ne^{++})$.

In Table 3 the values of the relative abundances with respect to hydrogen are given. A major consideration is the uncertainty due to the electron temperature. The value derived here is larger than that found in other planetary nebulae. If this value is in error and is closer to the more typical 12000° K, then the oxygen abundance would be about nine times higher. The purely ionization-recombination case treated by Hummer (1963) would lead one to expect a lower temperature. The calculations of Daub (1963) would, however, predict a similar temperature for a nebula with many fewer cooling ions than is found in field planetaries.

IV. K648 AS A TYPICAL PLANETARY NEBULA

Although the range in characteristics of objects that are classified as planetary nebulae is rather large, there does seem to exist a discrete class of objects undergoing similar evolutionary patterns called the planetary nebulae. It is important to discuss in as thorough a manner as possible the characteristics of the nebula in M15 and to compare it with the field planetary nebulae.

The luminosity of the nebula has been estimated in two ways. (1) Küstner (1921) has measured the photographic magnitude to be 13.8. Using the average relation between the international photographic magnitudes of planetary nebulae and their flux in Hβ of $m_{\text{pg}} = -2.5 \log F(\text{H}\beta) - 15.8$ (O'Dell 1962) gives $\log F(\text{H}\beta) = -11.95$. (2) The spectral plates of K648 were compared with spectra of IC 4997 taken at the same zenith distance, entrance slit, spectrograph, and exposure time. Since the relative line intensities in IC 4997 are reasonably well determined for the brighter lines (O'Dell 1963*b*), estimates of the weaker IC 4997 lines that produced comparable densities to the bright hydrogen lines in K648 along with the known flux density in Hβ from IC 4997 were used to derive a flux $\log F(\text{H}\beta) = -11.91$. The surprisingly good agreement between the two independent approaches is probably fortuitous, since the inherent scatter of these methods is much greater. The value adopted for the luminosity is $\log F(\text{H}\beta) = -11.93 \pm 0.15$. Another important parameter in the discussion of planetary nebulae is the apparent diameter of the nebular disk. This size was estimated visually on a night of excellent seeing by means of the through-the-slit high-magnification viewing arrangement of the prime-focus spectrograph. Since the size of the entrance slit was accurately known, estimates of the seeing-disk size of the nebula and of nearby cluster stars of the same brightness could be made. The diameter of the stellar seeing disks was judged to be 0.4″, while the apparent diameter of the nebula was judged to be 1.1″. These values give for the true size of the nebula $2\,\varphi = \sqrt{(1.1^2 - 0.4^2)} = 1.0''$, where φ is the radius.

The mass of the nebular shell can easily be derived if one assumes that most of the material is contained in the filaments giving rise to the thermal recombination spectrum. Using recombination theory for hydrogen as studied by Burgess (1958) for an electron temperature of 19000° K gives $M/M_\odot = 1.35 \times 10_e\, F(\text{H}\beta) D_{\text{pc}}{}^2 N_e{}^{-1}$. Using the values $\log F(\text{H}\beta) = -11.8$ (the measured flux corrected for interstellar extinction), $N_e = 2.9 \times 10^3$, and $D_{\text{pc}} = 13000$ gives for the hydrogen mass $M = 0.12\, M_\odot$. From Section III we know the relative abundance of the next major contributor to the mass, helium, which enables us to derive for the total mass of the ejected shell $M = 0.21\, M_\odot$ with an uncertainty of a factor of 2. This compares quite favorably with the total shell mass derived for field planetaries of $0.20\, M_\odot$ (O'Dell 1963*a*). The magnitude of the central star of K648 was determined from seven direct plates taken with the 36-inch refractor and the 120-inch reflector. Iris diaphragm measures were made of photoelectric standards (kindly furnished by A. R. Sandage) and of stars of comparable brightness near K648. Due to the crowded field there, visual estimates of the brightness were made. A plate-filter combination was used such that the nebular emission lines did not contribute to the magnitude derived, and then a magnitude system conversion relation was calculated, using measures of other blue stars in this field, and applied. This value of $m_v = 14.37$ can be compared only with the older photographic magnitudes derived by Berman and others. Assuming that the central star is very blue ($B - V = -0.3$), using the magnitude system relations given by Arp (1961), taking $E_{B-V} = 0.1$, and using for the distance to the cluster the value 13 kpc, one derives an absolute magnitude $M_{\text{pg}} = -1.9$. This is quite similar to the value found for other planetary nebulae in their early stages of expansion. Stars evolving off of the main sequence in clusters very similar to M15 have masses of about $1.1\, M_\odot$ (Woolf 1962) which, due to the very rapid evolution following this phase, probably represents the same mass of the nebula-star system. Again this is very similar to the values derived for field planetaries of 1.1–1.3 $M_\odot$ (O'Dell 1963*a*).

This similarity in all arguments greatly strengthens the thesis that the nebula in M15 represents the same phenomena that we observe in the field planetary nebulae.

V. COMPARISON OF THESE RESULTS WITH OTHER MEMBERS OF M15

In order to compare the results of Section III with the determination of the metal abundances in the other cluster members, one should first emphasize the fact that these nebular lines produced accurate results only for helium and oxygen, while the methods of the study of the atmospheres of the stars largely deal with the "true" metals, e.g., Fe, Si, Mg, etc. There is no firm basis for arguing that the oxygen abundance derived here is not representative of the metal abundances in the nebula, and therefore throughout the rest of this discussion, we shall use the terms "metal deficiency" and "oxygen deficiency" interchangeably unless otherwise noted.

There are several lines of evidence that the globular cluster M15 was formed from a metal-deficient cloud of material. The photographic, integrated spectra of the cluster indicates that metallic lines are only weakly present. The cluster spectra was classified as Type I by Morgan (1956) and Type *c* by Deutsch, both of these types representing the weakest metal line strength class of the globular clusters studied. The mean period of the RR Lyrae variable stars in the cluster is 0.65 days (Preston 1959), placing it among the longest period group and therefore in that group with the lowest metal abundance. Similarly, the difference in magnitude between the horizontal branch and the M giants is $3^{m}15$, a value as large as that in the other very metal-deficient globular clusters. On the basis of an incorrect abundance-equivalent width relation and the neglect of Rayleigh scattering as an important source of opacity, A. J. Deutsch (1963) has questioned the accuracy of the older estimates of the metal deficiencies in globular clusters as being too extreme. Evidently these criticisms are well founded, although the Rayleigh scattering opacity correction is not very large in the stars studied in this type of a cluster. Wallerstein (private communication) has calculated the abundances in similar metal-weak stars from weak lines, which should be insensitive to the mode of damping. These calculations indicate a deficiency of a factor of 100. One may then say that there is strong evidence that the original metal deficiency of M15 was about 100 times relative to the Sun.

TABLE 4

COMPARISON OF RELATIVE ABUNDANCES*

Object	He/H	O/H	Ne/H	Ne/O	$(O/H)/(O/H)_{\odot}$
M15(K648)	0.18	1.54×10^{-5}	1.01×10^{-5}:	0.65	0.016
Planetary nebulae	.173	0.59×10^{-3}	2.4×10^{-4}	0.40	0.62
Sun	....	0.95×10^{-3}	....	....	1.00
B stars	.16	0.59×10^{-3}	5.2×10^{-4}	0.88	0.62
Orion nebula	0.143	0.34×10^{-3}	5.4×10^{-3}	1.59	0.36

* By number.

Fortunately, the oxygen abundance relative to hydrogen in the atmosphere of the Sun can be determined with good accuracy from the strengths of the hydrogen lines and the red oxygen-forbidden lines. This method has most recently been applied by Osterbrock and Rogerson (1961) who found a value $N(O)/N(H) = 1.4 \pm 0.3 \times 10^{-3}$. This value is higher than the previous results for the Sun where a lower oxygen abundance was derived, $N(O)/N(H) = 0.95 \times 10^{-3}$ (Aller 1961). The former value may be criticized as being 40 per cent too large, since there was poor agreement with the average in one of the three lines measured, and we shall therefore use the older value of 0.95×10^{-3}. The present results for K648 are compared in Table 4 with these results for the Sun. Also given in Table 4 are the mean results of the studies of the atmospheres of several B stars (Aller 1961). It is seen that there is a deficiency of oxygen of 61-fold relative to the Sun where the accuracy of $N(\mathrm{O})/N(\mathrm{H})$ is very good, about 20 per cent, and 38-fold relative to the young B stars where the accuracy of $N(\mathrm{O})/N(\mathrm{H})$ is much less. Although indicating a smaller deficiency than the results of the studies of the spectra of the cluster stars would indicate, the two results are certainly within the probable error of the methods and can be taken as confirming one another.

VI. COMPARISON OF THE HELIUM ABUNDANCE WITH THAT IN OTHER GALACTIC OBJECTS

Although it is very difficult to determine the He/H abundance in late-type stars (Osterbrock and Rogerson 1961), this ratio can be determined with comparative ease in gaseous nebulae. This means that here we are able to compare accurately the abundance in K648 with the abundance in the present interstellar medium and the old, disk-population, objects, the planetary nebulae.

TABLE 5

OBSERVED RELATIVE LINE INTENSITIES IN NGC 1976

λ	6563	5876	5007	4861	4471	4340
$F\lambda/F_{\mathrm{H}\beta}$	3.64	0.199	3.26	1.00	0.041	0.425

TABLE 6

He/H RATIOS DETERMINED FROM PUBLISHED STUDIES OF NGC 1976

Source	He Lines Measured	He/H	Wt	$C_{\mathrm{H}\beta}$
Aller and Liller	5876 4471 4026	0.193	2.5	0.53
Mathis	5876	.146	1.0	.51
Mendez	5876 4471 4026	.100	2.5	.62
O'Dell	5876 4471	0.142	2.0	0.49

We shall first consider the helium abundance in H II regions. The brightest northern galactic nebula NGC 1976, the Orion Nebula, has been studied most extensively by the accurate method of photoelectric photometry (Aller and Liller 1959; Mathis 1962; Mendez 1963). None of these studies was made with high positional accuracy so that each region, and hence each study, must be considered separately in the application of reddening corrections. Dut to the lack of agreement in the relative intensities of the helium lines, it was considered necessary to make another, independent, study.

Spectrophotometric measures of the relative line intensities in a region 20″ west of the Trapezium were made during August, 1963, with the Mount Wilson Cassegrain photoelectric spectrograph on the 60-inch telescope. The methods of observation and data reduction were very similar to a previous study made with this equipment and will not be discussed here (O'Dell 1963*b*). The results of this photometry are given in Table 5.

The effects of selective wavelength scattering in the Orion Nebula and in the path of the light to the Sun are very considerable. We have chosen here to correct the measured relative line intensities using Seaton's (1960) tabulated reddening function and comparison of the observed Hα/Hβ/Hγ ratios with planetary nebulae after correction for reddening. This method may be criticized on two grounds; that deviations from a "normal" reddening curve exists (Hallam 1959) and that the ratio of the intensities of Paschen to Balmer lines arising from the same upper principal energy level can provide better estimates. The first criticism is met by the fact that only a small wavelength range is used here in the determination of the relative helium abundance (λ 4026–λ 5876), thus making the errors in the ratios of the lines with λ 4861 small. We have chosen to not use the method of Paschen/Balmer ratios since the fluxes from these lines are weak and hence the errors in the relative intensities are probably great. As Mendez (1963) has shown, one can derive the reddening function, and hence the true relative intensities, if accurate measures for these lines exist. Even after consideration of these uncertainties, the absorption corrections are probably accurate to a few per cent.

The results for the determination of $N(\mathrm{He}^+)/N(\mathrm{H}^+)$ in NGC 1976 are given in Table 6, where $C_{\mathrm{H}\beta}$ is the logarithm of the absolute absorption at λ 4861, derived above. The weights were assigned according to the scheme where measures of λ 5876 and λ 4471 were each worth 1 and measures of λ 4026 were worth 0.5. The actual relative abundances were calculated from the equations:

$$\frac{N(\mathrm{He}^+)}{N(\mathrm{H}^+)}=1.00\,\frac{I(5876)}{I(4861)}=2.44\,\frac{I(4471)}{I(4861)}=4.76\,\frac{I(4026)}{I(4861)}\,.$$

The weighted average, 0.143, is higher than that in previous studies, but should be accurate to ±0.02. This value is incorporated in Table 4, where the relative abundances of the metals are taken from Aller and Liller (1959).

The relative helium abundance, as determined from the published measures of line intensities for fourteen planetary nebulae (Liller and Aller 1963; O'Dell 1963*b*), is also given in Table 4. The spread in these fourteen nebulae about the average of 0.173 is very close to that expected from the uncertainties of the measurements; that is, there is no strong evidence for large deviation of the helium abundance in the planetaries, although variations of ±0.03 may exist. The oxygen abundance was taken from Aller (1961, p. 75). The relative abundance of neon has been calculated separately based on the new photoelectric data (Liller and Aller 1963; O'Dell 1963*b*). One may conclude that there seems to be no difference between the planetary nebulae and the B stars.

It is interesting to note that in the planetary nebula NGC 6644, also observed at Mount Wilson in August, 1963, which has an unusually large radial velocity ($V_r = +193.9$ km/sec) and lies in the direction of the galactic center ($l^{\mathrm{I}} = 336°$, $b^{\mathrm{I}} = -8.7°$), was found to have $N(\mathrm{He})/N(\mathrm{H}) = 0.14 \pm 0.03$. This is of particular interest since this object belongs to the group of planetaries that have highly eccentric orbits and travel close to the galactic nucleus.

VII. DISCUSSION

This agreement of the determinations of the relative helium abundances in these rather diverse objects should be investigated more fully. Qualitatively it may be argued that the high helium abundance in the interstellar medium-young stars and in the shell of the planetary nebulae merely reflects the fact that hydrogen burning has occurred in evolved stars, originally of low helium abundance, enriching their outer layers which are eventually returned to the interstellar medium. This would lead to the interpretation that the original helium abundance in M15 was much lower and that the large abundance found in K648 represents the enrichment by nucleogenic processes.

If one is to accept this idea of great enrichment, one must deal with considerations of the total amount of energy released during the formation of the helium known to be present in the Galaxy at this time. If the primordial Galaxy were formed of only hydrogen, then the present abundance of helium (He/H = 0.17) would argue for the release of 5.5×10^{62} ergs. Averaged over 10^{10} years, this would call for an absolute bolometric galactic magnitude of -24.3. Any attempt to explain this as the result of rapid helium formation at an early phase of the evolution of the Galaxy would require even greater luminosities. This brightness is much greater than the present luminosity of the Galaxy (probably about the same as M31 with $M_B = -20.4$) and is larger than the observed galaxies (Sandage 1963). This problem, discussed in detail by Burbidge (1958, 1962), is eliminated if one assumes a much higher helium abundance for the Galaxy at the time of formation of the field stars.

There are two other lines of evidence that large helium abundances exist in the outer parts of stars that were formed early in the development of the Galaxy. The models for the RR Lyrae variable SU Draconis constructed by Christy (1963) indicates that the abundance ratio is $N(\text{He})/N(\text{H}) = 0.205$. Although this ratio is rather uncertain, his probable errors do not allow a value smaller than 0.106. The presence of helium lines in the spectra of the luminous blue stars found in globular clusters also argues for the presence of helium in the outer parts of these stars. Traving's (1962) analysis of B29 in the globular cluster M13 gave $\text{He/H} = 0.5\ (\text{He/H})_{\tau\ \text{Sco}}$ while helium lines are clearly visible in a similar star in M15.

These facts, taken together with the observations that the helium abundance in the nebulae surrounding highly evolved stars in the field planetary nebulae and the planetary in M15 is high, argue strongly that the original helium abundance in the Galaxy, or at least the abundance since the time of formation of the stars that we now observe, was non-zero and probably about $N(\text{He})/N(\text{H}) = 0.14$. Variations of 50 per cent are certainly possible (Eggen 1963). As has been pointed out by many previous investigators, such a large original helium content would substantially decrease the computed age of the oldest globular clusters. One may also conclude that, on the basis of these measures of K648, the rate per star, of metal enrichment by evolving stars of slightly greater than 1 $M_\odot$, must be very small.

The conclusion, that the original abundance of helium in the globular cluster M15 was very similar to that now found in the interstellar medium, must remain uncertain at this time since much of the evidence is circumstantial. It is of course possible to set upper limits to the amount of mixing of the heavy-element-enriched core of the star with the outer one-fourth of its mass.

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