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CHEMICAL ABUNDANCES AND THE PARAMETERS OF PLANETARY NEBULAE

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ABSTRACT

All known existing observations of spectral-line intensities of planetary nebulae have been compiled into a catalog which consists of 250 nebulae, including four well-observed H II regions. New electron densities have been calculated for most of these nebulae, and revised electron temperatures from the [O III] lines are given for 109 of them. The ratios He/H, O/H, and O^{2+}/H^+ are given for 80, 124, and nearly all the nebulae, respectively. A two-temperature model is assumed for the calculation of abundances, in which the low temperatures derived from the hydrogen lines and continuum are used for hydrogen and helium recombination coefficients, and the [O III] temperatures are used for the calculations involving forbidden lines. Various methods of calculating the abundance of the higher ionization stages of oxygen are evaluated, and the method of using the He^{2+}/He^+ ratio is found to give the most consistent results. The intensities of the [Ne IV] and [Ne V] lines suggest a high electron temperature near the central star. The [O III] electron temperatures are correlated negatively with the O/H ratio and positively with the temperature of the central star in accord with the currently accepted ideas of nebular heating and cooling. The mean [O III] electron temperature is 11500° K for nebulae without He II lines and 14000° K for those with He II lines. The mean O/H ratio is 5.35×10^{-4} and ranges from about 10^{-4} to 1.4×10^{-3}. The mean He/H ratio is 0.14 with a range of from 0.09 to greater than 0.2. The O/H ratio is negatively correlated with the He/H ratio, and is also correlated with population indicators such as radial velocity and height above the galactic plane in the sense that objects with high O/H have Population I characteristics and the nebulae of Population II have low O/H. In view of these results it would appear difficult to interpret the data in terms of "cosmic abundances."

I. INTRODUCTION

The three most abundant elements in the universe are hydrogen, helium, and oxygen. One of the most rewarding astronomical objects for the study of these abundances is the planetary nebula. The fundamental physical processes that take place in gaseous nebulae are reasonably well understood, and the calculations required to measure the above abundances are straightforward once the rates of atomic reactions and the atomic constants have been determined. The basic observations are the relative intensities of the nebular emission lines corrected for interstellar reddening. From these observations we can then calculate the two parameters which perhaps most characterize a nebula: the electron temperature and the electron density. The abundances of the elements in the nebula can then be calculated.

Very briefly, the helium and hydrogen lines are produced by electron-ion recombination, and the forbidden lines of oxygen by collisional excitation of metastable states by the electrons freed from the hydrogen and helium. The detailed derivations and formulations of the problem can be found in *Gaseous Nebulae*, chapters 4 and 5 (Aller 1956) and in a review article, "Planetary Nebulae," by Seaton (1960).

One of the first extensive lists of electron temperatures in nebulae was produced by Menzel, Aller, and Hebb (1941). They used the ratio of the auroral to nebular line intensities of [O III] and found values between 6000° and 10000° K. Since then numerous workers have improved the values of the atomic-collision cross-sections and transition probabilities, so that it is now known that the mean temperature is in the range of 10000–15000° K.

In the late 1930's and early 1940's, Menzel and his co-workers (*see* Menzel 1962) developed the first detailed theory of the production of the hydrogen lines, which allowed, among other things, the calculation of the electron densities of the planetaries. Menzel and Aller (1941) found values of the electron densities to be of the order of 10^4 cm^{-3} from the intensity of the Balmer continuum.

With the work of Goldberg (1941), Aller and Menzel (1945) measured a helium-to-hydrogen ratio of about 0.1. Mathis (1957) later found the mean ratio to be 0.185. The most extensive list to date is by Harman and Seaton (1966), who found a mean of 0.16. The first attempt at measuring the oxygen-to-hydrogen ratio was made by Menzel and Aller (1941), who estimated a value of about 10^{-4}. More recent calculations are summarized by Aller (1964) and Aller and Czyzak (1968), who give more refined abundances for these elements.

Even though the basic theory for the calculation of temperatures, densities, and abundances is relatively simple, a number of complications have arisen. First is the matter of the electron temperatures as computed from hydrogen radiations. The problem first became apparent in H II regions after the discovery of the radio recombination lines by Höglund and Mezger (1965). The strength of these lines with respect to the underlying free-free continuum indicates temperatures about half the value of those calculated from the forbidden lines. That the same effect holds in the planetary nebulae has been indicated by Lee (1968), Kaler (1968) who used the ratio of the Balmer continuum to Hβ, Thompson (1967, 1968), and others. Peimbert (1967) suggests that a nebula actually consists of high- and low-temperature regions, with the hydrogen emission coming mostly from the cooler regions and the forbidden-line radiation coming from the hotter regions. An apparent lack of a unique electron temperature obviously complicates the calculation of the O/H ratio, since the oxygen and hydrogen radiations may be produced at different temperatures in different regions. The situation is by no means clear, however, as different methods employing hydrogen emissions often give different temperatures. For example, Le Marne and Shaver (1969) get 12500° K for IC 418 from a careful radio-continuum study, whereas the ratio of the Balmer continuum to Hβ intensity from slit spectrograms yields only 4800° K.

A second important complication is that atoms in a nebula usually exist in several ionization stages at once. Since O^+ and O^{2+} emit forbidden-line radiation, the calculation of O^+/H^+ and O^{2+}/H^+ is relatively simple. But the higher ionization stages observed in the high-excitation nebulae are known only by their permitted spectra, and their abundances are difficult to calculate. Three methods are available for the calculation of the abundances of O^{3+}, O^{4+}, and O^{5+}. The first makes use of the permitted spectra under the assumption that these lines are emitted by the process by recombination. This is the method used by Burgess and Seaton (1960) and by Aller (1964). Second, we can construct an ionization curve for the higher stages by the use of Ne^{3+}, Ne^{4+}, and Ne^{5+}, and assume that this ionization function also applies to oxygen. This method has been applied by Seaton (1960) and most recently by Aller and Czyzak (1968). A third method, essentially the same as the second, is to use the He^{++}/He^+ ratio to estimate the $(O^{3+} + O^{4+} + \ldots)/(O^+ + O^{2+})$ ratio, as suggested by Seaton (1968*a*) and applied by Gebbie (1968). Unfortunately, the three methods give three different values for the O/H ratio.

The purposes of this paper are to assemble as many observational data as possible in order to reevaluate the electron temperatures and densities; to measure the relative abundances of hydrogen, helium, and oxygen in the light of the above calculations; and to try to reach some independent decisions as to the best way of making the calculations.

The intensities of the spectrum lines, their correction for interstellar reddening, and the choice of a low "hydrogen temperature" are discussed in § II. Sections III, IV, and V treat the calculation of nebular temperatures, He/H ratios, and O/H ratios, respectively. Section VI demonstrates the relations which exist between the O/H and He/H ratios and between the O/H ratio and the galactic and evolutionary characteristics of the nebulae. Finally, the results of this work are summarized in § VII.

II. LINE INTENSITIES

a) *The Catalog*

The basic data are, of course, the intensities of the spectrum lines. It is necessary that as much effort as possible be spent on obtaining high-quality observations of as many nebulae as possible. The spectra of a surprisingly high number of nebulae have been observed. Spectrophotometric measurements of nebulae go back to the turn of the century, but the modern work can be said to begin with the work of Berman (1930) and Aller (1941, 1951). In recent years, Aller and his co-workers, Chopinet (1962), O'Dell (1963*a*), and others have begun to use both photographic and photoelectric techniques to produce accurate, high-quality data which cover the spectrum extensively. The number of nebulae covered by the recent work is still relatively small, however, and is limited to the brighter objects. In order to provide a large quantity of data, the literature has been thoroughly searched for spectrophotometric observations of nebulae. Nearly all of these data have been assembled on punched cards in a catalog of nebular emission lines. This catalog currently contains observations of 243 planetary nebulae plus four H II regions and three possible H II regions, which are included in 568 separate sets of spectrophotometric observations.

The major problem in setting up the catalog is in the evaluation of the data, i.e., in a judgment as to whose observations should be used for a certain nebula, since in many cases two sets of observations of the same nebula may be in sharp disagreement. A number of criteria have been used to decide whether a given set of data should be included. These criteria are based upon expected line intensities such as the Balmer decrement, ratios of forbidden-line intensities (e.g., λ5007/λ4959), and so forth. The final decision is necessarily rather subjective. If two sets of data are both within the expected ranges, the sets are averaged. Generally speaking, the newer work takes precedence over the older. The earliest observations included in the catalog were made about 1940. In a great many cases the observations are extremely scanty (only the λ5007/λ4861 intensity ratio is observed), but even these contain valuable information and are included.

b) *Interstellar Reddening*

After the observations have been assembled, they must be corrected for interstellar reddening. We assume the form of the interstellar reddening function to be that published by Seaton (1960). This function is an average of the curves of Whitford (1948, 1958) and Divan (1954), and is in good agreement with the more recent functions published by Johnson (1965).

The main problem now is to obtain the reddening constant

$$c = \log \frac{I_c(H\beta)}{I_0(H\beta)} \tag{1}$$

for each nebula, where $I_c(\mathrm{H}\beta)$ and $I_0(\mathrm{H}\beta)$ are the true and observed fluxes of the Hβ line. By far the most accurate methods of getting c are by observations of the intensity ratios of the Paschen and Balmer lines of hydrogen, or by observations of the ratio of the radio-flux density (at optically thin wavelengths) to the Hβ flux. The latter method is valid at least as long as the radio-flux density is above the confusion limit. Where these observations are available, they are used to determine c. The details of the calculations can be found in Cahn and Kaler (1970).

When the direct observations of c by the Paschen/Balmer or radio/Hβ ratios are not available, the estimates of Cahn and Kaler (1970) are used. These estimates are based on the photometric method for determining distances (Minkowski and Aller 1954;

Shklovsky 1956; O'Dell 1962) and on a dust model of the Galaxy. The method is, of course, statistical in nature and is valid only for nebulae which are optically thin in the Lyman continuum, but a comparison between observed values of c and those calculated on the basis of the model gives excellent agreement (Cahn and Kaler 1970). For optically thick nebulae, the value of c derived by this means in an upper limit. If the nebula is optically thick but has b^{II} greater than 10° or so and is relatively distant, the reddening is computed from

$$c = 0.10 \csc |b^{II}| . \tag{2}$$

The Balmer-decrement method is used only when the nebula has no Paschen-line or radio observations and is not included by Cahn and Kaler (1970), or, in the case of optically thick nebulae in the plane of the Galaxy, when the value of c so calculated is less then that given by Cahn and Kaler (1970). The Balmer decrement is used only as a last resort when no other method is available. In order to get an accurate value of c from the Balmer decrement, the theoretical intensities must be known better than is now generally possible, since the wavelength region used is so short. Comparison of c measured by the radio/Hβ technique with that measured by the Balmer-decrement technique gives very poor agreement. When the Balmer decrement is used, the theoretical recombination values of Clarke (1965) are taken, and the assumptions are made that the angular-momentum states are degenerate and that Baker-Menzel case B applies. If no Balmer decrement is observed, either, the upper limit of Cahn and Kaler (1970), when given, is adopted. Where no value whatsoever is available, an average for the nebulae in that direction of space is assumed.

Once a value of c is chosen, the observations are then corrected in accordance with the relation

$$\log I_c(\lambda) = \log I_0(\lambda) + cf(\lambda) , \tag{3}$$

where $f(\lambda)$ is the reddening function, and I_c and I_0 are the corrected and observed relative intensities, respectively.

The reddening constants are computed on the basis of the electron temperatures found from hydrogen emissions. These temperatures are nearly all smaller than the electron temperatures calculated by the forbidden lines. It is still an open question as to whether these "hydrogen temperatures" represent physical values or not, but since they are derived from the hydrogen emissions which themselves are used to find c, they are employed. A value of 5000° K is assumed in the calculation of all reddening constants. Cahn and Kaler (1970) discuss this problem in detail, and give further arguments supporting the low-temperature assumption. Briefly, however, the adoption of the [O III] value of electron temperature as appropriate leads to unacceptably low values (including negative values) of c. *Even if the hydrogen temperatures are not physically real, they appear to be appropriate to the calculated recombination coefficients.*

A processing computer program has been written to average the observed line intensities, where appropriate, and to correct the line intensities for interstellar reddening. The values of the reddening constants chosen are in column (2) of Table 2, and the method used is indicated in the "Notes" column when c is not taken from Cahn and Kaler (1970).

The one remaining difficulty is in the possible variation of the ratio R of total absorption to selective absorption (see Johnson 1968). If c is measured from the Balmer decrement, the Paschen/Balmer ratio, or any method involving only optical lines, no problem arises. If R is not the normally chosen value of 3.0, the value of c will not be true total absorption; however, it will be correct with respect to the assumed reddening function, and the relative line intensities will be nearly properly corrected. This condition arises because the shapes of the reddening functions, even in regions where $R \neq 3$, are similar between 3000 and 15000 Å, as found from the work of Johnson (1965). In the majority of cases, however, where c is actually the true total absorption found from the radio/Hβ

ratio or the distance scale of Cahn and Kaler (1970), errors can arise since if $R > 3$ the line intensities will be overcorrected.

For the present purposes I will simply assume that $R = 3$ for all nebulae since, first of all, most nebulae are in the directions in which Johnson (1968) indicates that R is close to 3, and, second, the most important lines with which this paper is concerned are fairly close to Hβ and the effect of a change in R will be small. In any case, we do not know a specific value of R for each nebula, and we would have to choose a value on the basis of Johnson's (1968) $R(l^{\text{II}})$ function, which may not be valid for the higher values of b^{II}.

III. NEBULAR PARAMETERS

A number of quantities must be used to give even a brief description of a planetary nebula. The ones to be discussed here, and which are relevant to the abundance calculations made in the next section, are the electron density, the filling factor (the degree to which an assumed spherical nebula is filled with radiating material), and the electron temperature, both the values derived from the forbidden lines and those derived from the Balmer continuum or decrement.

a) Electron Densities

The simplest method of getting electron densities is from the ratio of the intensity of the λ3729 component to the λ3726 component of the [O II] doublet (Aller, Ufford, and Van Vleck 1949; Seaton and Osterbrock 1957). Where the observations are available and the density is within the proper range ($N_\epsilon < 10^5$ cm^{-3}), this method is used. The values have all been recalculated by using the latest values of the λ3727 ratio and the electron temperatures discussed below.

In the majority of the cases of [O II] doublet is unobserved or unresolved, and the electron density must be calculated from the observed Hβ flux and the known distance and radius of the nebula, in accordance with the formula

$$N_\epsilon = \left(\frac{3D^2F}{r^3\alpha_{42}h\nu\epsilon\beta}\right)^{1/2}, \tag{4}$$

where D is the distance, r the radius, α_{42} the Hβ recombination coefficient, ν the frequency of Hβ, F the Hβ flux corrected for interstellar extinction, ϵ the filling factor, and β the ratio of the number of electrons to hydrogen ions which is chosen to be 1.2. The recombination coefficient is a function of electron temperature, and the values derived from hydrogen [T_ϵ(H)] were chosen as appropriate. The values of α_{42} are taken from Pengelly (1964), and are fortunately almost independent of whether or not the angular-momentum states are degenerate. If no electron temperature is available, then $T_\epsilon(\text{H}) = 5000°$ K.

The distances and nebular radii are taken from Cahn and Kaler (1970). Where possible, they are computed by using the *observed* value of the reddening constant, rather than by using c from Cahn and Kaler's (1970) dust model. For the optically thick nebulae, the distance estimated from the reddening constant (the dust distance) is used, where available; otherwise, the electron density is a lower limit. The Hβ fluxes come from many sources, and have been taken from Cahn's catalog (Cahn and Kaler 1970).

The filling factor (based on a filled spherical nebula having unit filling factor) has been estimated in the cases in which a photograph of the nebula exists, after first assuming a three-dimensional form, such as a toroid or spherical shell. Where possible, the morphology of Greig (1967) has been used. If there is no appropriate photograph, the mean value of $\epsilon = 0.65$ is used. The primary sources of information for the filling factors were Curtis (1918), Westerlund and Henize (1967), Minkowski (1964), and Aller (1956). The distance scale of Cahn and Kaler (1970) uses a mean value of the filling factor. The distances were not corrected for the effects of the specific filling factor, since the distances also depend on the mean values of several other parameters.

The resulting filling factors and electron densities are presented in columns (3) and (4) of Table 2. If the λ3727 doublet was used, the reference from which it was taken is indicated by a double dagger. Fortunately, errors in N_ϵ enter into the electron temperatures and abundances in only a minor way.

b) Electron Temperatures

The subject of the electron temperatures can be divided into two parts: those found from hydrogen radiation, and those found from forbidden lines. The hydrogen temperatures are called T_ϵ(H) and are given in column (5) of Table 2. They are taken from the references given in § I, with some modification for improved reddening constants, and from the recent work of Aller, Czyzak, and Kaler (unpublished). The mean T_ϵ(H) is in the range of 5000°–6000° K.

The classical way of deriving the electron temperature is from the forbidden lines of oxygen by using the ratio of the intensity of λ4363 to that of λ4959 + λ5007. Many other forbidden-line ratios are available, but the [O III] lines are observed in by far the greatest number of nebulae, so that we will deal with them exclusively here.

Many studies of the electron temperatures have been made and many lists published (e.g., Aller 1956; Archipova and Kostjakova 1968). Generally, however, these temperatures are found in papers on individual nebulae and are widely scattered throughout the literature. In addition, the atomic constants have improved considerably in the last few years. Consequently, it seems desirable to recompute electron temperatures for all the nebulae for which there are observations, based on the best data, the new reddening constants and electron densities, and the new cross-sections of Czyzak, Krueger, Martins, Saraph, Seaton, and Shemming (1968) and of Saraph, Seaton, and Shemming (1969). The formula used is

$$R=\frac{I(4959)+I(5007)}{I(4363)}=7.1\,\frac{\exp\,(14300/T_\epsilon)}{1+2.8\times 10^{-4}N_\epsilon/\sqrt{T_\epsilon}}\,. \qquad (5)$$

The derivation can be found in Aller (1956). T_ϵ is solved for by iteration. Once a value is derived, a new N_ϵ is calculated if the [O II] lines are observed, and T_ϵ is solved for once again.

The values of T_ϵ so calculated are presented in column (6) of Table 2 as $T_\epsilon(F)$, and range from 8200° to > 20000° K.

For the purposes of the next section, N_ϵ, $T_\epsilon(F)$, and T_ϵ(H) are needed for all nebulae. If they are not available, the following values are adopted:

$$N_\epsilon = 10^3\ \text{cm}^{-3}\,,\quad T_\epsilon(\text{H}) = 5000°\ K\,,$$

$$T_\epsilon(F)=\begin{cases}11500°\ K\ (\text{no He II present})\\ 14000°\ K\ (\text{He II present})\,.\end{cases}$$

The actual mean electron density is 7×10^3 cm^{-3}, but the nebulae without *observed* values have lower surface brightnesses, so that a lower value of the electron density is more appropriate. If the observations are so limited that there is no knowledge on He II, then a value for T_ϵ of 14000° K was adopted, as most nebulae observed in detail exhibit He II lines.

Since the temperature of the central star is higher for those nebulae which show He II lines, a positive correlation between central-star temperature and $T_\epsilon(F)$ is indicated. This finding is consistent with the results of Archipova and Kostjakova (1968) and will be discussed more fully in § V.

IV. THE HELIUM-TO-HYDROGEN RATIO

The problem of the helium-to-hydrogen ratio is discussed fully by Seaton (1960) and by Harman and Seaton (1966). The basic difficulty is that, for a low-excitation planetary nebula, the outer parts of the region of ionized hydrogen may contain neutral helium, so that the He/H ratio is a lower limit to the true value. However, if a He^{2+} zone exists in the nebula, the He^+ and the H^+ zones are certainly coincident and the true ratio is observed. In measuring the He/H ratio, then, we must include only nebulae which have observable λ4686 (He II Pα) radiation. The He/H ratio is calculated from the equations

$$\frac{N(\mathrm{He}^{++})}{N(\mathrm{H}^+)} = \frac{I(4686)}{I(4861)}\frac{\alpha_{42}(\mathrm{H})}{\alpha_{43}(\mathrm{He}^+)}\frac{4686}{4861}, \tag{6a}$$

$$\frac{N(\mathrm{He}^{+})}{N(\mathrm{H}^+)} = \frac{I(4471)}{I(4861)}\frac{\alpha_{42}(\mathrm{H})}{\alpha_{4^2D,2^2P}(\mathrm{He})}\frac{4471}{4861}, \tag{6b}$$

$$\frac{N(\mathrm{He})}{N(\mathrm{H})} = \frac{N(\mathrm{He}^{++})}{N(\mathrm{H}^+)} + \frac{N(\mathrm{He}^{+})}{N(\mathrm{H}^+)}, \tag{6c}$$

where $\alpha_{42}(\mathrm{H})$ is from Pengelly (1964), and $\alpha_{4^2D,2^2P}(\mathrm{He})$ is from Pengelly (private communication).

The value of $\alpha_{43}(\mathrm{He}^+)$ is more difficult, as it depends upon the degree of collisional reshuffling among the angular-momentum states, which in turn depends upon the electron density. Seaton (1968*b*) has calculated the recombination coefficients for high density, low density, and for $N_\epsilon = 10^4$ cm^{-3}. Pengelly's (1964) values for low density have been multiplied by a constant to obtain the values for densities appropriate to planetary nebulae, the constant being the value found from Seaton (1968*b*) for $N_\epsilon = 10^4$ cm^{-3} extrapolated to $T_\epsilon(\mathrm{H}) = 5000°$ K. Since most of the helium is in the form of He^+, any error introduced by not taking the exact N_ϵ dependence into account will probably not be significant.

The electron temperatures suggested by hydrogen have been used in these calculations. Since the various recombination coefficients all have about the same temperature dependence, the He/H ratio is quite insensitive to temperature. As is pointed out in the next section, the region of the nebula near the central star is hotter than the outer parts, so that we might expect the He^{2+} to radiate at temperatures hotter than that given by $T_\epsilon(\mathrm{H})$. Since there is no direct knowledge on this point, $T_\epsilon(\mathrm{H})$ is still adopted. Again, any error introduced will not be large, for the reason given above and also because He^{2+} is generally less abundant than He^+.

The values of He/H are given in column (7) of Table 2, and the He^{2+}/H^+ ratio is given in column (8). Figure 1 shows histograms of the distribution of the He/H ratio for both the low-excitation and the high-excitation nebulae. The mean He/H ratio for nebulae with λ4686 present is 0.14, while the ratio for the nebulae with no λ4686 is lower, 0.13, in accordance with theory. In addition, the extreme low values belong to nebulae with no He II emission, NGC 40 and IC 418. Generally, nebulae with He/H $\gtrsim$ 0.25 were excluded from the statistics. More observations are needed to confirm whether the high He/H values are correct or whether they are due to observational error.

V. THE OXYGEN-TO-HYDROGEN RATIO

The O/H ratio presents a difficult problem, but one which appears at least solvable. The O^{2+}/H^+ and the O^+/H^+ offer little difficulty. The forbidden-line intensities and the transition probabilities give us the populations of the metastable states. The ratio of the population of a metastable state to the ground state is then only a function of $T_\epsilon(F)$

and N_ϵ, through the equations given by Aller (1956, chap. 5). The ratio of $O^{2+}(^1D)$ to H^+ is given, for example, by

$$\frac{N[O^{2+}(^1D)]}{N(H^+)} = \frac{[I(5007) + I(4959)]}{I(4861)} \frac{\alpha_{42}(H)}{A(^1D\text{–}^3P)} \frac{4994}{4861}, \quad (7)$$

where $N[O^{2+}(^1D)]$ is the population of the ^1D term. The relations between the term populations, T_ϵ, and N_ϵ as given by Aller (1956) were then programmed, and the values of $N(O^{2+})/N(H^+)$ and $N(O^+)/N(H^+)$ were computed from the line catalog after correcting the line intensities for interstellar reddening. The only deviation of this paper from earlier analyses is that the forbidden-line temperature $T_\epsilon(F)$ was used for calculations involving the metastable terms of oxygen, whereas T_ϵ(H) was used for α_{42}(H). A similar procedure has been recently used by Peimbert and Costero (1969) in an analysis of H II regions. Since recombination is more efficient at low temperatures, this has the effect of

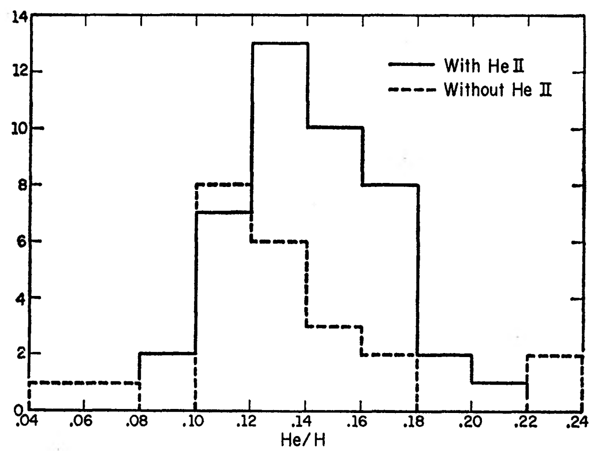

FIG. 1.—Distribution of the values of the He/H ratio for nebulae with He II lines and without He II lines.

raising $N(O^{2+})/N(H^+)$ and $N(O^+)/N(H^+)$ by about a factor of 2. It might be argued that the lower temperature of T_ϵ(H) is more appropriate to O^+ radiation than is $T_\epsilon(F)$ since the O^+ radiates in the outer region of the nebula. At least, this would be so if the temperature variation were in the form of a smooth gradient and if we were sure that T_ϵ(H) was a physically meaningful quantity. Given these uncertainties, it appears safer to assume that $T_\epsilon(F)$ is the more appropriate quantity for O^+. In any case, since O^+ usually contributes little to the oxygen abundance, any errors made will be very small.

Since neutral oxygen has the same ionization potential as hydrogen, there should be little neutral oxygen in regions of ionized hydrogen, so that it can be neglected.

As mentioned in § I, the biggest difficulty is in allowing for the higher ionization stages of oxygen, O^{3+}, O^{4+}, and O^{5+}. The original way of doing this was by constructing a curve of fractional ionization against ionization potential for a given element, notably neon, which has forbidden lines observable for Ne^{2+}, Ne^{3+}, and Ne^{4+}. This can be done for as many elements as possible and all the curves normalized. The values of O^{3+}/O^{2+}, etc., can then be read off the curve. This method is discussed by Aller (1956), Seaton (1960), and more recently by Aller and Czyzak (1968). The processing program used in the current work computes Ne^{2+}/H^+, Ne^{3+}/Ne^{2+}, and Ne^{4+}/Ne^{2+} at the values of $T_\epsilon(F)$ given in Table 2. Values of O/H computed in this way are given in Table 1, and are designated "Neon O/H."

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The second method makes use of the permitted lines of O^{3+}, O^{4+}, and O^{5+}. One of the difficulties here is that the supposedly recombination lines of O III are confused with the radiation produced by the Bowen fluorescent mechanism (Bowen 1934). Burgess and Seaton (1960) devised a way of separating the two components, and then proceeded to calculate values of O^{3+}/H^{+}. Recombination coefficients were also worked out for O^{4+} and O^{5+}. This method was exploited quite fully by Aller (1964). The processing program for the line catalog automatically computes the abundances of the higher ionization stages in accordance with the theory of Burgess and Seaton (1960); the results for those nebulae for which the appropriate O III lines are observable are given in Table 1, and are designated "Rec. O/H."

TABLE 1

RESULTS OF VARIOUS METHODS OF COMPUTING O/H, EXCITATION INDICATORS, AND THE ELECTRON TEMPERATURE OF THE INNER REGIONS

Nebula	Helium O/H ($\times 10^3$)	Neon O/H ($\times 10^3$)	Rec. O/H ($\times 10^3$)	10^{-3} T_*	$\frac{He^{2+}}{He^{+}}$	$I(4686)$	10^{-3} T_{in}
NGC 1535	0.45	...	0.80	...	0.18	22	...
NGC 2022	0.68	2.1	0.32	91	...	116	...
NGC 2440	0.71	7.1	1.45	High	0.87	63	40
NGC 3242	0.88	1.8	1.07	93	0.42	33	15
NGC 6543	0.91	0.91	1.14	66	0.0	0	...
NGC 6572	0.54	0.54	0.54	62	0.0	0	...
NGC 6886	1.47	5.1	...	...	...	46	...
NGC 7009	0.41	1.48	0.73	81	0.77	17	16.5
NGC 7026	0.53	1.62	1.04	98	0.12	21	...
NGC 7027	0.57	3.4	3.46	High	0.36	48	26
NGC 7662	0.72	2.8	1.84	100	0.97	67	22
IC 289	...	26	...	...	...	96	...
IC 2165	0.53	2.7	1.61	High	0.39	45	40
IC 3568	0.43	0.43	0.43	32	0.001	1	...
IC 4642	...	2.2	...	...	...	122	...
IC 4997	0.06	0.06	0.09	55	0.0	0	...
IC 5217	0.46	...	0.86	74	0.09	13	...
VV 5	0.57	7.0	...	...	2.5	96	26
VV 267	0.17	0.90	0.71	High	0.90	91	50
J 900	0.62	1.3	...	...	0.47	57	...

Seaton (1968*a*) has pointed out that when the O/H ratio is calculated in the above manner, the results correlate with nebular excitation, a situation which should not exist and which implies a systematic error. He suggests that the observable permitted lines of atoms heavier than helium contain a strong component due to photoexcitation by radiation from the central star, and are not due to recombination. He suggests the relation

$$\frac{He^{2+}}{He^{+}} = \frac{O^{3+} + O^{4+} + \ldots}{O^{+} + O^{2+}}, \tag{8}$$

which is somewhat the same as using only helium to construct an ionization curve. The method is simple, however, since He^{+} has the same ionization potential as O^{2+}. In the case in which there is neutral helium, i.e., no He II lines, there is little O^{3+}, a conclusion supported by the fact that there are very few nebulae which exhibit O III lines but no He II lines. The O/H ratios calculated on the basis of equation (8) are presented in Table 1 as "Helium O/H" for those nebulae which have had O/H calculated in the other two ways.

As can be seen from Table 1, these three methods give three different values, with the values computed by using the neon ionization curve being consistently the highest, and the values computed from the He^{2+}/He^{+} ratio the lowest. For purposes of comparison three indicators of nebular excitation are given in Table 1: the temperature of the central star, T_*, from Harman and Seaton (1966), He^{2+}/He^{+}, which should be proportional to T_*, and the intensity of the λ4686 He II line on the basis of $I(H\beta) = 100$. The three values of O/H are plotted against T_* in Figure 2. The stellar temperatures of NGC 2440, NGC 7027, IC 2165, and VV 267 are not known, but they must be greater than 10^5 ° K on the basis of (1) their excitation, (2) the fact that no star is directly observable, and (3) the work of Kaler (1967). The values of O/H found by using He^{2+}/He^{+} are the only ones not correlated with central-star temperatures, and are the only ones to have the same values as for low-excitation nebulae.

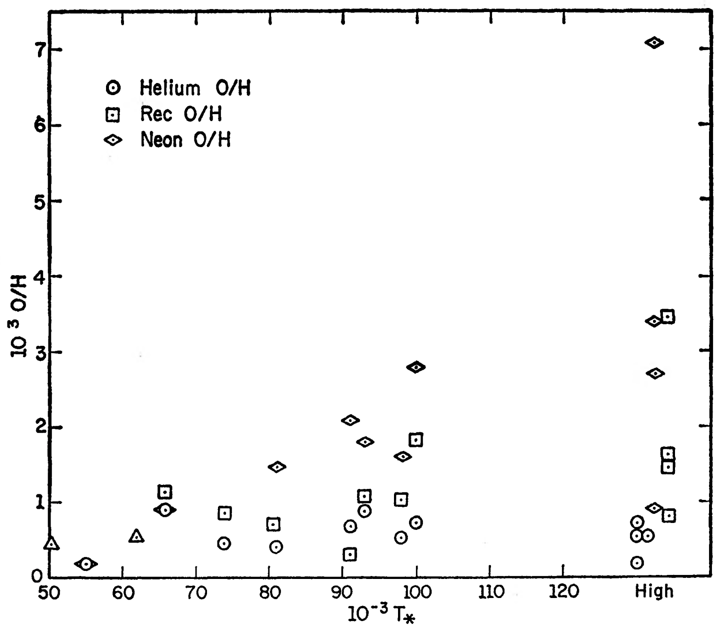

FIG. 2.—The O/H ratio as computed from three different methods as a function of central star temperature.

An examination of Table 1 shows that this argument is supported by the other two excitation indicators.

Perhaps the clinching argument in favor of the helium method is presented in Figure 3, in which $T_\epsilon(F)$ is plotted against "Helium O/H" for three ranges of He^{2+}/He^{+}. Correlations among all three quantities are readily apparent. The correlation between $T_\epsilon(F)$ and O/H as found in this manner was first discovered by Gebbie (1968). At that time it was ascribed to observational error. It is true that a systematic error in either $I(\lambda 4363)$ or $I(\lambda 5007)$ would produce a similar graph, but it seems inconceivable that an error that large could occur in the observations. The values of $I(4363)$ in the bulk of the modern work should be accurate (and are reproducible) to 10–20 percent. In any case, no separation due to nebular excitation level would be present.

It seems much more likely that the correlations represent a cause and effect between the heating and cooling rates of the nebula and the resultant electron temperature. The He^{2+}/He^{+} ratio is determined to a great extent by the temperature of the central star. Other things being equal, the He^{2+}/He^{+} ratio should be an indicator of heating. For a given nebular excitation, or central-star temperature, we then see that, as the O/H ratio increases, the electron temperature decreases, an observation which is understandable in terms of the fact that oxygen provides most of the nebular cooling. Also, the abundances of the other heavier elements probably decrease as well. For a given heating rate, as the coolant is removed, the temperature must increase. Using the crudest sort of approximation, let us assume that collisional excitation to the metastable terms of oxygen provides all the cooling. From Aller (1956) we see that the rate of collisional excitation is proportional to $\exp(-h\nu/kT_\epsilon)/\sqrt{T_\epsilon}$. In order to maintain constant cooling as T_ϵ varies, the total number of excitations per second must be maintained and thus O/H $\sim [\exp(-h\nu/kT_\epsilon)/\sqrt{T_\epsilon}]^{-1}$. This function (fitted to the low-temperature end of the curve) is plotted in Figure 3, and roughly fits the form of the observed plot for a given He^{2+}/He^{+} ratio.

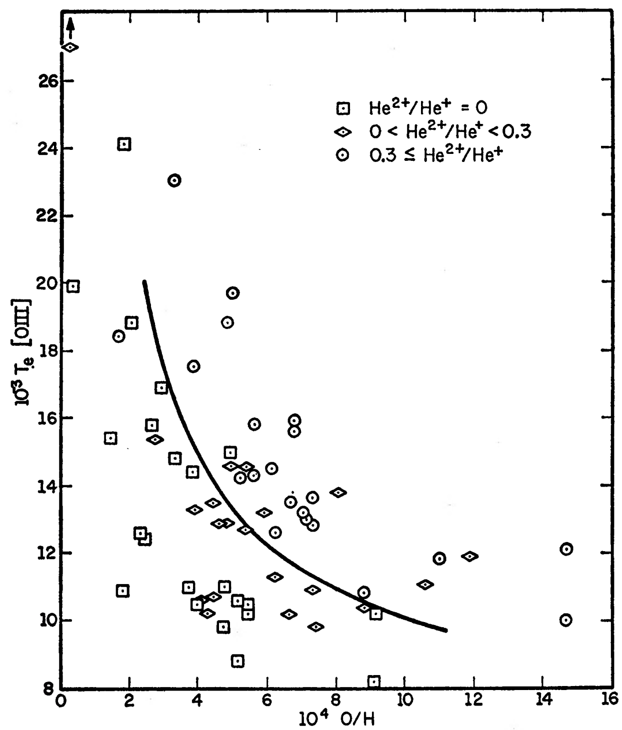

FIG. 3.—Relation between the electron temperature as computed from the [O III] lines and the O/H ratio, plotted for three values of nebular excitation. *Solid curve*, expected relation if O^{++} provides most of the cooling.

We can also see from Figure 3 that, for constant O/H, as He^{2+}/He^{+} increases, $T_\epsilon(F)$ increases, a result alluded to in § III. For a given $T_\epsilon(F)$, as He^{2+}/He^{+} increases (heating), O/H must increase (cooling). If the He^{2+}/He^{+} method did not give the proper value of O/H, it is unlikely that such a correlation would exist.

Finally, the detailed examination of NGC 7662 by Harrington (1969) shows that the helium method gives good results. *From this point on,* O/H *refers to that value found by the helium method.* These values of O/H are presented in column (9) of Table 2.

Seaton (1968*a*) has explained why the recombination-line method will not work for getting the O/H ratio (which, by the way, is an argument against the neon method, as one would expect it to give lower values than the recombination method, not higher).

If the He^{2+}/He^{+} method of computing the $O^{3+} + O^{4+}$ abundance is correct, the [Ne IV] and [Ne V] lines are abnormally strong. The most likely explanation for this effect is that the electron temperature is higher in the inner regions of the nebula where the high-excitation neon lines are formed, a fact which has been suggested by Flower (1968) and Harrington (1968). Aller and Czyzak (1969) indeed show that such a situation exists and adopt a higher inner electron temperature in calculating neon abundances. If we draw an ionization function for oxygen and use it to predict the Ne^{3+}/Ne^{2+} ratio, we can compute the electron temperature necessary to reproduce the observed [Ne IV] intensities. The procedure is very crude, as it requires an extrapolation of the ionization curve to 64 eV, the energy required to produce Ne^{3+}. The temperatures so derived are listed in the last column of Table 1 as T_{in}. Considering the large errors involved, the value for NGC 7662 agrees in substance with that suggested by Harrington (1969). The value of T_{in} is correlated with T_*, as would be expected. The one discordant note is that the electron temperature found from the [K V] lines in NGC 7027 (from observations by Aller, Bowen, and Minkowski 1955), which are produced at 61 eV, is about 14000 °K, the same as the [O III] temperature. Ne^{3+} certainly extends closer to the central star than does K^{4+}, however, because of the ionization potentials of the next higher stages. It is not possible to do this analysis for [Ne V], as there is no a priori way of telling the abundance of Ne^{4+}.

Unfortunately, there is no way of checking these values by ground-based observations. Observations of the auroral line of [Ne V] at λ2972 or the nebular line of [Ne IV] at λ2439 are of great importance.

Of the observed spectrum lines which are used in this study, one of the hardest to observe is the λ4471 He I line. (In some few cases, λ5876 is used instead.) Since λ4686 of He II is capable of being much stronger than λ4471, if the latter is present and λ4686 is not, we can assume that λ4686 is absent or very weak.

In many cases, however, λ4686 is observed, but no λ4471. A further step based on λ4686 alone is then needed to obtain the contribution of O^{3+}, etc. The case wherein both O^+ and O^{2+} are observed is treated first. From the nebulae with complete observations $I(\lambda 4686)$ was plotted against $(O^{3+} + O^{4+})/(O^+ + O^{2+})$ so that $(O^{3+} + O^{4+})$ could be found the $I(\lambda 4686)$ intensity. Since the resulting curve is quite good, the O/H values found from it should be reliable, and they are used in the statistics in the next sections. The values of O/H so derived are marked with an asterisk in Table 2.

In the case where neither λ4471 nor λ3727 of O^+ was observed, the uncertainty in O/H will be much larger. To get values for these nebulae, $\Sigma_n O^{n+}/O^{2+}$ was plotted against $I(\lambda 4686)$ for the well-observed objects. This graph shows much scatter, due to the varying contributions of O^+. In this case, the lower envelope of the distribution of points was used for the O^{3+} calibration; consequently, the values of O/H derived are lower limits, but probably not by more than 40 percent. These values are marked by a dagger in Table 2. These methods work as long as $I(\lambda 4686) \lesssim 90$; there are too few points above this to establish a reliable curve.

In a large number of cases, the only observations were of the [O III] and Hβ lines, so that all that could be found was the O^{2+}/H^+ ratio, of course based on a mean electron temperature. From the higher-quality observations it is found that the dominant ion is nearly always O^{2+}; the median value of O/O^{2+} is 1.3. The O^{2+}/H^+ ratio is given in column (10) of Table 2.

The distribution of the values of O/H is given in Figure 4 for three cases: (1) where everything necessary is observed, (2) where the strengths of both helium lines are known, and (3) where at least λλ4686 and 3727 are observed or are known to be small or zero (Hβ and either λ5007 or λ4959 are nearly always observed). The lowest histogram includes only those points with observed T_ϵ(H). The middle one includes these as well as all other reliable O/H except those with asterisks and daggers. The top histogram includes the points with asterisks. The top and middle histograms are essentially the same; the bottom one shows a flatter distribution. It is hard to say how much of this is caused by observational selection. All three distributions peak at $O/H = 5 \times 10^{-4}$. The mean

O/H given by the bottom histogram is 5.8×10^{-4}; that given by the middle histogram is 5.35×10^{-4}.

The largest uncertainty is in the lack of $T_\epsilon(H)$ for most nebulae.

VI. RESULTS AND CORRELATIONS

a) Population Separation

One of the interesting findings of the above two sections is the wide variation in the He/H and the O/H abundance ratios: He/H varies by over a factor of 2, and O/H by a factor of 10. It would be interesting to see whether there is any connection between the chemical composition and the galactic orbit of the nebula, or between the chemical composition and population type. This kind of relation is, of course, well known for the

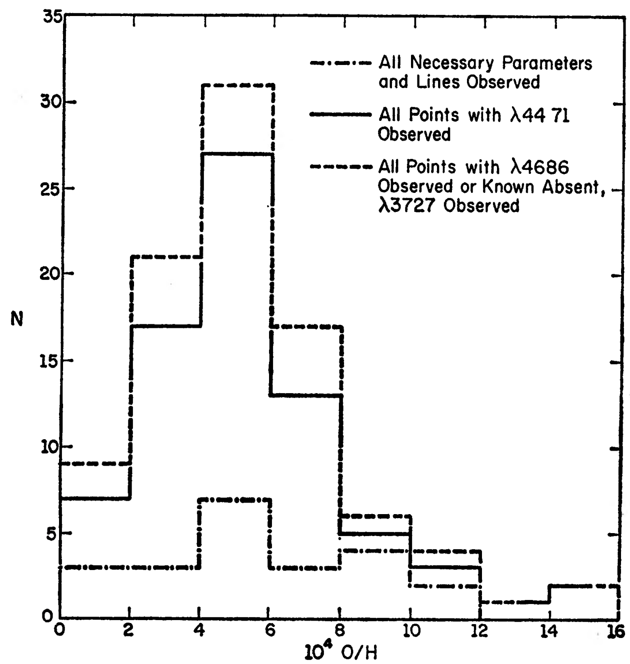

FIG. 4.—Distribution of the values of the O/H ratio for three classes of precision

metal/hydrogen ratio (Eggen, Lynden-Bell, and Sandage 1962) and for the cyanogen abundance (Yoss 1962), such that the Population II stars tend to have lower abundances of the elements heavier than helium.

Unfortunately, the planetary nebulae are generally so distant and hard to observe that their proper motions are unreliable, except for a very few. We are then left with only two indicators of population type: the radial velocity, v_r, and the present height above the galactic plane, Z. The directly observed radial velocity is a poor quantity, however, because of observational selection effects. Often studies of nebular spectra are concentrated in particular regions of the sky. A better indicator is the difference, ΔV_r, between the radial velocity that would be expected on the basis of purely circular motion about the galactic center and the radial velocity actually observed. We know the position of the optically thin nebulae from Cahn and Kaler (1970). The nebulae are then assumed to orbit the Galaxy parallel to the plane and about the rotation axis of the Galaxy. The expected radial velocity is then computed under the assumption of the basic solar motion quoted in Mihalas and Routly (1969). The assumed rotation curve of the Galaxy is the polynomial of Contopoulos and Strömgren also quoted in the above reference.

Table 2

The Nebulae, their Parameters, Helium to Hydrogen and Oxygen to Hydrogen Ratios

(Galactic Planetary Nebulae)

Nebula	c	ε	10^{-3} N_ϵ (cm^{-3})	10^{-4} T_ϵ(H) (°K)	10^{-4} T_ϵ(F) (°K)	$\frac{He}{H}$	$\frac{He^{2+}}{H^+}$	10^4 $\frac{O}{H}$	10^4 $\frac{O^{2+}}{H^+}$	Pop.	ΔV (km sec^{-1})	Notes	Refs.
NGC 40	0.97	0.40	1.63			0.043		1.96	0.012	I	0	1,24	MA,LILL,SO‡,OS‡,AUV‡
246	0.00	0.60	0.16				0.119		0.63	I	48	6	M
650	0.43	0.38	0.42		1.20		0.060	13.3*	5.00	I	12	24	M,MO‡
1501	1.14	0.60	0.54				0.036	5.2†	3.70	I	-49		M,COAL
1514	0.72	0.17	0.61		1.40		0.026	5.4†	4.12	II	-78		M,C
1535	0.13	0.22	4.48		1.35	0.139	0.021	4.48	3.77	II	34		AW‡,MA,LILL,OCB
2022	0.80	0.22	3.14		1.56	0.145	0.111	6.8	1.56	I	15	10	AW‡,OD63,VV1
2346	1.37	0.60	0.67		1.46	0.166	0.033	4.97	2.59	I	-7		AKI‡
2371	0.58	0.45	0.53		1.97	0.151	0.107	5.00	1.71	I	-7		O,M,OD62,C
2392	0.43	0.14	9.59		1.88	0.112	0.057	4.85	2.06	I+	-58	24	MA,LA,OS‡,O
2438	0.58	1.00	0.18						3.20	I	-47		OD63
2440	0.66	1.00	1.92	0.73	1.32	0.132	0.061	7.06	3.56	I	-42		CAK1‡,OD63
2452	0.61	0.15	0.75						3.67	I	-13		OD63,AKI‡
2610	0.66	0.94	0.31						1.18	I	-51		OD63
2792	1.35	1.00	2.98		1.75	0.307	0.102	3.90	2.47	I			AF,WB
2818	0.82	0.22	0.64		2.30		0.081	3.30†	1.41	I	37		J,OD63
2867	0.17	1.00	17.5		1.00	0.112	0.036	14.7	8.76	I	-4		AF
2899	1.80	0.30							2.76				WB
3132	0.44	0.09	0.72		1.09	0.146	0.016	7.36	4.36	I	15		AF,AKI‡,WB
3195	0.32	0.30	0.24		1.11		0.020	4.9*	2.64				AF,WB
3211	0.90	1.00	1.40		1.31		0.068	10.2*	5.10	I	21		AF,WB
3242	0.33	0.22	3.23	0.57	1.08	0.105	0.031	8.81	6.13	I	8		CAKF‡,LILL,COAL,OS‡
3587	0.02	0.60	0.23		1.12		0.026	6.5*	3.93	I	-9		M,COAL,OS‡
3918	0.14	1.00	7.50		1.18	0.138	0.047	11.0	6.86	I	20		AF
4071	0.64	0.10	0.92						2.06				WB
4361	0.34	0.50	0.33		2.34		0.100		0.50	I	-14	6	HAC,OD62
5307	0.62	0.70	0.77		1.27	0.133	0.026	5.40	4.21	II	-100		AF
5315	1.70		13.1						2.08	I			WB
5873	0.38	1.00	2.68		1.21		0.034	6.5†	4.61				WB
5882	0.66	1.00	4.38						2.97	I	-24		WB
5979	1.52		3.72						2.83	I			WB
6058	0.15	0.22	0.28		1.90		0.062	4.1†	2.11	II	-4		M,C,COAL
6072	0.98	0.70	0.24						3.71	I	-22		OD63
6153	1.31	0.15	5.56		1.54	0.127	0.025	2.77	2.14	I			AF
6210	0.16	1.00	6.55		1.02	0.167	0.005	6.68	6.07				LA,C,CPDA,LILL,AUV‡,AH‡
6309	1.04	0.70	4.06				0.082	8.2*	3.57	I			AW‡,COAL
6326	0.88		2.22		1.93		0.035	3.8*	2.65	II	-61		AF,WB
6369	2.20	0.60	4.35		1.25			5.66†	5.66	II		1,21	M,OD63
6439	1.40	1.00	5.92				0.015	3.5†	2.87	II			M,OD63
6445	1.21	0.88	1.33		1.38	0.164	0.032	8.08	3.98	I	-21	24	AKI‡,M,OD63
6537	2.09	1.00	17.6		2.06		0.077	4.9†	2.18	I	17		M,VV1,COAL
6543	0.22	0.30	7.99	0.37	0.82	0.110		9.10	8.50	I	38		CAK2‡,OCB,CPDA,LILL
6563	0.62	0.28	0.72						2.65	I	22		OD63
6565	0.00	0.35	0.80	0.61	1.04	0.140	0.021	8.84	5.28	I	10	2,18	OD63,VV3,AKI‡
6567	0.69	1.00	5.96		1.06	0.131		5.17	4.90	II	-126		A,M,COAL
6571	0.20		7.50				0.031	6.1*	4.40				A,M
6572	0.31	1.00	9.46	0.61	1.05	0.102		5.44	5.03	I	2		SO‡,AK2,OPC,OCB,CPDA,LILL
6578	0.97	1.00	0.83					5.19†	5.19	I	26	2,21	M
6629	1.03	1.00	3.58	0.61	0.88	0.129		5.14	4.56	I	-17		AKI,VV3
6644	0.24	1.00	20.3	0.81	1.44	0.164	0.022	3.85	3.21	II		2,26	AKI‡,VV3
6720	0.29	0.32	0.99		1.32	0.111	0.014	5.93	3.27	I	16		LA,COAL,OSSH,MO‡
6741	1.57	0.45	11.4		1.36	0.186	0.050	7.32	5.64	I	-31	27	AW
6751	1.18	0.88	1.40		1.55		0.206		1.93	I	36	6,7	VVI,COAL
6772	0.87	0.30	0.23					5.3*	3.45	I	6		M,OD63
6778	0.92	0.20	2.85		1.79	0.272	0.019	1.53	1.28	II	-67	11	A,VV1,M,COAL
6781	0.63	0.50	0.14			0.106	0.023	6.01	3.59	I	-6		AKI,M,COAL
6790	0.33	1.00	86.0	0.26	1.19	0.121	0.017	11.9	11.9	I	-49		AKI

* O^{3+}/H^+ estimated from $I(\lambda 4686)$.

† $(O^+ + O^{3+})/H^+$ estimated from $I(\lambda 4686)$.

‡ Source of the λ3727 doublet ratio; N_ϵ computed from this ratio.

Table 2 (Contd.)

Nebula	c	ε	10^{-3} N_e	10^{-4} T_e(H)	10^{-4} T_e(F)	$\frac{He}{H}$	$\frac{He^{2+}}{H^+}$	10^4 $\frac{O}{H}$	10^4 $\frac{O^{2+}}{H^+}$	Pop.	ΔV	Notes	Refs.
NGC 6803	0.88	1.00	9.69	0.49	0.98	0.126	0.005	7.43	6.69	I	-7		AKI‡,A,LA,LILL
6804	1.15	0.94	0.77				0.071	4.7†	2.21	I	7		M,C,COAL
6807	0.95	1.00	19.5		1.69	0.151		2.93	2.72	II	89		A
6818	0.24	0.22	4.27		1.70		0.073	7.0*	2.98	I	11	7	LA,A,VV2
6826	0.18	1.00	2.41		1.05	0.112		3.97	3.78	I	-5		LA,O,OCB,CPDA, LILL,CAK3‡
6833	1.10	1.00	100	0.68	1.54	0.150		1.48	1.36	II			AKI‡,OD63
6842	1.07	1.00	2.25						2.33	I	6		OD63
6853	0.14	0.40	0.42		1.35	0.151	0.045	6.70	3.16	I	48		AKI,C,M,OSSH,OS‡
6879	1.09	1.00	4.01		1.46		0.025	3.1*	2.43				VV2,COAL
6881	1.99	1.00	9.94		1.51				3.58	I			M
6884	0.74	1.00	10.7	0.41	1.11	0.128	0.019	10.6	8.54	I			AKI‡,A,COAL
6886	1.38	1.00	4.16		1.21	0.101	0.044	14.7	7.13	I			A,COAL
6891	0.41	1.00	3.67	0.21	1.02	0.118		9.16	8.77	I	-47		AKI,A,COAL
6894	1.13	0.60	0.49			0.096	0.020	5.64	2.79	I+	56		AKI,M,COAL
6905	0.55	0.60	0.53		1.43			4.2*	2.69	I	7		A,M,COAL
7008	0.71	0.40	7.50		1.33	0.173	0.029	3.92	2.69	II	67	8	AS‡
7009	0.24	0.30	6.13	0.97	1.06	.140	0.018	4.11	3.51	I	51		AK1,OPC,OCB,LILL, SO‡
7026	0.99	0.90	5.06		1.12	0.182	0.020	5.29		I	28	19	ACU‡,A,OCB,CPDA
7027	1.22	1.00	14.7		1.43	0.169	0.045	5.67	3.97	I	-24		ABW,OCB,CPDA,LILL AUV‡
7048	1.10	0.60	0.40						2.66	I	47		OD63
7139	0.23	0.50	0.05				0.018	3.8*	2.53	II	63		M,OD63
7293	0.09	0.24	0.20					2.65	1.85	I	13	1	M,OS‡
7354	1.96	0.22	5.81				0.055		3.57	I			M,A,OD63
7662	0.40	0.90	4.69	0.58	1.30	0.128	0.063	7.18	3.60	I			AKB‡,CPDA,LILL, OCB
IC 289	1.40	0.35	0.86		1.59		0.091		1.17	I	5	6	AKI,OD63
351	0.67	1.00	1.98		1.41	0.123	0.054	7.35	4.10			12	AW,VV1,CPDA
418	0.33	0.26	41.7	0.48	1.10	0.064		3.72	0.68	I			AK3,O,CPDA,LILL, SO‡
1747	1.19	0.35	5.23		1.29	0.192	0.019	4.88	4.11	II	61		VV1,C,OD63
2003	0.70		3.71		1.28	0.148	0.057	7.33	3.72			24	A,OD63
2149	0.54	0.71	14.7		1.24	0.113		2.47	1.61	I	36		K,O,A,LA,CPDA,LIL
2165	0.92	1.00	4.39	0.58	1.42	0.151	0.043	5.27	3.59	I			KAC,CPDA,
2448	0.43	1.00	2.38		1.26	0.119	0.037	6.25	4.25				AF,WB
2501	0.87		64.0						2.61	I	-28		WB
2553	1.10	1.00	2.34						3.69	I			WB
3568	0.24	1.00	5.67	0.81	1.02	0.145	0.001	4.28	4.17	II	10		LACD‡,CPDA
4191	1.80								4.07				WB
4406	0.40	0.70	0.59			0.120	0.005	5.34	2.94	I	7		AF
4593	0.27	0.97	2.64			0.125		2.92	2.59	II			A,CPDA,LILL,OS‡
4634	0.71	1.00	3.04		1.02	0.101		5.45	4.91	I			LA,A,COAL
4642	0.76	0.22	0.91		2.12		0.116		0.93	II	-91	6	AWR,AF
4732	0.19	1.00	1.26		1.48	0.175		3.37	3.33	II	-213	2	A,LA,OD63
4846	0.74	1.00	1.37	0.55	1.10	0.125		4.79	4.56	II		17	AKI‡,A,OD63
4997	0.54	1.00	690	1.20	1.88	0.139		2.04	1.23	II	69	20	AK2,O,OD62
5117	1.47	1.00	32.7		1.46	0.129	0.020	5.43	4.24	I			A,R,VV1,OD63
5217	0.96	1.00	8.68		1.29	.166	0.013	4.62	4.08	II	84		ACU,COAL
VV 2	1.31		1.00		1.07	0.265	0.014	4.24	3.57			2,13	VV1,R
3	1.42		6.54		1.49	0.57	0.029	5.69	3.15	I		14	
5	0.86		4.94	0.47	1.58	0.127	0.091	5.65	1.48	II	-49		AK1,R,VV1
8	0.42	1.00	100.			0.38	0.049	1.03	0.61			15	O,R,VV1,OD66
11	1.30		100		1.13	0.091	0.009	6.24	5.10	I		2	AKI‡
30	1.11		5.91					5.55	3.75			1	VV1
60	0.68	0.70	0.90				0.030	2.9*	2.20				AF,WB
73	1.55	0.22	3.65				0.030	4.8*	1.95	I			AF,WB
75	0.43	0.88	1.01						2.19				WB
78	1.74	0.15	2.86						5.40				WB
108	1.72		15.4						0.72				VV3
110	0.37		1.79						2.71	II	83		OD63
116	1.70	0.70	2.42		1.51	0.159	0.066	6.78	3.82	I		2	AKI,OD63
129	0.28		1.81		1.86		0.045	2.9*	1.59	II	126	7	R
136	1.60								1.89			4	VV3
153	1.69		7.46						1.07				VV3
157	1.60								0.90			4	VV3
171	0.54		.7.47		3.10	0.128	0.008	0.26	0.24				A,VV2,OD62
174	1.83		17.4						0.84				VV3
177	1.77		15.5						1.63				VV3

Table 2 (Contd.)

Nebula	c	ε	10^{-3} N_e	10^{-4} $T_e(H)$	10^{-4} $T_e(F)$	$\frac{He}{H}$	$\frac{He^{+2}}{H^+}$	10^4 $\frac{O}{H}$	10^4 $\frac{O^{2+}}{H^+}$	Pop.	ΔV	Notes	Refs.
VV 181	1.60								1.18			4	VV3
194	1.68		3.45						2.26	I			VV1
201	2.20		100					5.22	1.36	I		7,22	VV1
202	2.57		100					2.87	1.07	II		1	VV1
203	0.00		1.00				0.032	0.66*	0.46			2,7	VV1
208	0.53		31.7		0.98	0.100		4.73	2.43				A,OD62
210	0.42	0.98	0.45					1.52†	1.52	II	26	1,21	VV1
223	1.60								2.09			4	R
230	0.00		1.00		1.58			1.54†	1.54			1,2,21	R
231	1.55		1.00		1.97			1.31	1.31			1,2,21, 28	VV1
237	0.22		100		1.50	0.126		4.97	4.36	I	42		A,R,OD63,AKI‡
238	0.21		1.36		1.19	0.232		1.81	1.50	I	35	2	VV1,R
240	0.06		1.00		1.59		0.033	1.80	1.66	I		2,7	VV1,R
267	0.12	1.00	4.56	1.00	1.84	0.205	0.097	1.67	0.83			5	AW,OD63
286	0.77		100	0.48	2.41	0.151		0.68	0.60	I		2,25	AKI‡',A,OD63
He 7	0.79	1.00	0.31					4.51	4.04			1	LK
16	1.80	1.00							4.25				WB
18	1.52	1.00	0.78						4.46				WB
22	1.41	1.00	1.30						2.21				WB
26	1.10								3.60				WB
28	1.88	1.00	1.48						4.33				WB
29	1.42	0.60	0.87						0.51				WB
36	1.80	1.00					0.115		3.02			6	WB
43	1.21	0.70	0.67				0.120					6	WB
51	1.15	1.00	1.27						2.20				LK
54	1.78	1.00	1.44						1.62				WB
68	1.80								0.30				WB
71	1.10								0.21				WB
73	2.38		11.9						4.00				WB
86	1.80								2.34				WB
95	1.39	1.00	1.79						0.64				WB
97	0.73								1.78			3	WB
103	1.94	1.00	1.00						2.26				WB
106	1.80								1.29				WB
107	2.59	1.00	4.28						0.15				WB
108	0.81	1.00	1.02						0.29				WB
115	1.39		3.69						1.31	I	37	2	WB
117	2.84		8.20						1.92	I		2	WB
118	0.19								3.53	II		2	WB
123	2.23		1.65						0.48	II	-76		WB
124	7.55		283						2.79				WB
125	1.49		1.37							I	30	2	WB
127	1.15		1.00					0.52†	0.31			2,21	WB
128	0.90								0.34			2	WB
129	1.19		8.79						0.37	II		2	WB
131	0.49		28.3						0.04				WB
132	2.23	1.00	0.93						1.92	II	94		WB
133	0.34		0.59						0.40			2	WB
134	0.49											2	WB
136	0.57								3.68	II		2	WB
138	0.70		4.83										WB
140	1.84	0.70	4.38								63	2	WB
141	1.98		0.98		1.74		0.049	4.3†	2.64	I	-5		WB
142	1.28		4.94							I	14	2	WB
143	0.34		0.35						5.42			2	WB
145	3.13	0.22	4.87						3.17				WB
146	1.91	1.00	0.98						6.53	II	-80		WB
149	0.00		0.35						2.49	II	205	2	WB
151	0.57									II		2	WB
152	2.18	1.00	4.42		1.50		0.100		2.19			6	WB
153	0.49	0.35	0.64						2.44	I	-53	2	WB
154	1.66	0.10	5.14						0.08	I	-13		WB
155	1.40	1.00	0.83						2.77				WB
156	0.00											2	WB
158	1.31		2.57						1.44	II			WB
159	2.22	0.70	1.61						2.71	I	41		WB
160	3.61		5.34						2.37				WB
161	0.26	1.00	0.20						0.95	I	-6	2	WB
162	1.00	1.00										2	WB
163	1.01	0.95	0.35						2.56	I	0		WB

Table 2 (Contd.)

Nebula	c	ε	10^{-3} N_e	10^{-4} T_e(H)	10^{-4} T_e(F)	He/H	He^{2+}/H^+	10^4 O/H	10^4 O^{2+}/H^+	Pop.	ΔV	Notes	Refs.
He 164	2.05	0.95	1.28		1.67		0.056	3.8†	2.10	I	41		WB
165	1.17	1.00	0.33						1.79	I	-1		WB
169	2.19	1.00	0.94						1.64				WB
170	0.05								3.06			2	WB
172	0.97		1.00		3.10				1.26			2	WB
177	1.09								0.24			2	WB
182	0.33		1.00		1.46				0.69			2	WB
185	0.00		100						0.26			3	WB
186	0.40		100				0.038	0.53†	0.36			2	WB
187	1.80								0.89				WB
195	0.49								0.37			2	WB
CD -23° 12238	0.24		1.74		1.57		0.077	7.7†	2.94	II		7	VV1,OD63
CD -32° 14673	1.12		1.60		1.69			1.53†	1.53	II		1,2, 21	LA
BD +30°3639	1.74	1.00	100			0.182	0.018	2.09	.009			23	O,VV2,COAL
Anon 22^h29^m	0.00		1.00		1.26	0.224		2.33	2.11			2	A
HD 3300 36	1.80								2.57				WB
J 320	0.57	1.00	2.01		1.58	0.169		2.63	2.56	II			A,MA,CPDA
J 900	1.78	1.00	18.3		1.45	0.169	0.054	6.16	3.33	I			A,LA,CPDA
K 648	0.25	1.00	5.48		1.99	0.118		0.37	0.23	II	-123	9	OP
M2 - 11	1.60								1.72			4	VV3
M3 - 20	1.60								0.68			4	VV3
M3 - 27	0.60							1.4†	1.17			3	K68
Small Magellanic Cloud													
N 6	0.21								2.59			3	WB
38	0.21								2.77			3	WB
40	0.21								2.20			3	WB
42	0.21								0.55			3	WB
43	0.26		1.00		0.99	0.156			3.45			2	WB
44	0.88		1.00		1.16				4.00			2	WB
47	0.21								0.94			3	WB
68	0.26								1.09			2	WB
70	0.19								1.47			2	WB
81	0.00		1.00		1.37	0.203			2.02			3	WB
87	0.26								1.81			3	
Large Magellanic Cloud													
P 1	0.16								2.35			3	WB
7	0.00		1.00		1.79				2.14			3	WB
8	0.26								2.37			2	WB
9	0.16								2.69			3	WB
17	0.65								3.10			2	WB
18	0.26		1.00		1.31		0.029	5.0†	3.73			3	WB
19	0.16								2.20			3	WB
20	0.16								3.57			3	WB
24	0.16								2.09			3	WB
25	0.19		1.00		1.78		0.029	3.0†	2.27			3	WB
26	0.65								2.94			2	WB
29	0.00		1.00		1.18		0.024	7.7†	6.02			3	WB
32	0.16								1.89			3	WB
33	0.16								4.96			3	WB
35	0.00		1.00		2.23		0.044	2.1†	1.45			3	WB
38	0.16								4.60			3	WB
39	0.16								4.19			3	WB
42	0.16						0.024	5.4†	4.22			3	WB
H II Regions													
NGC 604	0.34		0.056		0.90	0.120		3.39	1.50				ACW‡
1976	0.36		5.00		0.92	0.101		4.29	2.45				KAB,AL,OS1‡
30 Dor	0.34		0.61		1.05	0.072		3.32	2.60				FA
η Car	0.77		0.62		0.99	0.109		2.40	1.23				FA‡
IC 1470	0.84		0.50		1.00	0.158		1.19	1.19			16,21	C
NGC 7635	0.82		0.50		1.00							16	VV1
He 113	1.80		0.50		1.00							16	WB

EXPLANATION OF TABLE 2

Col. (1).—Name of the nebula, beginning with NGC and IC numbers. The other catalogs used, in order, are: VV, first catalog of Vorontsov-Velyaminov (1953); He, Henize numbers (Perek and Kohoutek 1967); J, K, M2, and M3, see Perek and Kohoutek (1967); N and P, see Webster (1969*a*).

Col. (2).—c, reddening constant.

Col. (3).—ϵ, adopted filling factor: that fraction of a sphere having the radius of the nebula which is filled with radiating matter.

Col. (4).—N_ϵ, electron density in 10^3 cm^{-3}.

Col. (5).—T_ϵ(H), electron temperature from the hydrogen lines in 10^4 ° K.

Col. (6).—$T_\epsilon(F)$, electron temperature from the [O III] lines in 10^4 ° K.

Col. (7).—He/H, the helium-to-hydrogen ratio.

Col. (8).—He^{2+}/H^+, the ratio of doubly ionized helium to ionized hydrogen.

Col. (9).—O/H, oxygen-to-hydrogen ratio times 10^4.

Col. (10).—O^{2+}/H^+, ratio of doubly ionized oxygen to ionized hydrogen times 10^4.

Col. (11).—Population type. Population II has either $Z > 800$ pc *or* $\Delta V_r > 60$ km sec^{-1}.

Col. (12).—ΔV_r, the difference between the observed radial velocity and that expected on the basis of circular galactic orbits.

Col. (13).—Notes.

Col. (14).—References, sources from which the observations were taken.

NOTES TO TABLE 2

1. Lines at λλ4471 and 4686 are not observed, but enough lines are observed to know that λ4686 is very weak, so that no correction to the O^{2+}/H^+ ratio is required.
2. Reddening constant from Balmer decrement.
3. Reddening constant from $c = 0.10 \csc |b^{II}|$.
4. Reddening estimated from reddening of nearby nebulae.
5. T_ϵ(H) of VV 267 estimated from Balmer decrement.
6. I(4686) too high to make accurate correction to O^{2+}/H^+ ratio.
7. I(4471) observed, but value is much too high to be realistic. O/H ratio based on λ4686 intensity. If $I(\lambda 4686) = 0$, then $O/H = (O^+ + O^{2+})/H^+$.
8. The λ3727 ratio is close to limiting high-N_ϵ value on low dispersion; this value of N_ϵ adopted.
9. K648 is in M15, whose distance was taken as 10.5 kpc (Arp 1965).
10. Line at λ5876 used to compute He^+/H^+. Large discrepancy between AW and VV1. Mean value used.
11. Large discrepancy between λ5876 and λ4471. Values in table apply to λ5876 which looks more realistic. If we adopt λ4471, He/H = 0.27, O/H = 1.51×10^{-4}.
12. Large discrepancy in λ4471 between VV1 and AW. VV1 chosen as more realistic.
13. Large discrepancy in λ4471 between observers. Mean value assumed. O/H ratio not significantly affected.
14. I(λ4471) very large, but both A and VV1 agree!
15. Peculiar object. N_ϵ probably higher; T_ϵ not measurable. Probably not a planetary nebula.
16. Values of N_ϵ and T_ϵ assumed. Perek and Kohoutek (1967) state that Henize 113 is not a planetary.
17. The radio data, which are very poor, give $c = 0$. Cahn's upper limit seems much more reasonable, as $b = 10°$, and IC 4846 is probably quite distant, so a cosecant law can be used.
18. Value of O/H is a lower limit. Radio observations give $c < 1.17$. If $c = 1.17$, then T_ϵ(H) = 2500° K, $T_\epsilon(F)$ = 12100° K, He/H = 0.171, O/H = 14.4×10^{-3}.
19. Large discrepancy in He^+/H^+ between A and ACU. Mean value adopted. If A is chosen, He/H = 0.139.
20. N_ϵ and T_ϵ from Aller and Liller (1966). T_ϵ is variable.
21. Forbidden line of [O II] at λ3727 not observed.
22. I(λ4686) unrealistically high and incompatible with O^{2+}/O^+ ratio.
23. Very approximate; parameters poorly known.
24. Values of O/H and He/H are the means of the ratios measured in various regions of the nebula.
25. The O/H ratio is quite uncertain: Observers disagree on the value of I(λ5007), and there is wide range in allowed values of $T_\epsilon(F)$, T_ϵ(H), and N_ϵ. Even with extreme values, though, O/H is low.
26. The upper limit to c is 1.08; then T_ϵ(H) = 3000° K, $T_\epsilon(F)$ = 16700° K, He/H = 0.168, O/H = 5.5×10^{-5}.
27. AW value of I(λ5007) chosen, as the new results agree closely with A. COAL value higher. If mean chosen, O/H = 9.98×10^{-4}.
28. Same as VV230?

REFERENCE KEY TO TABLE 2

A: Aller (1951)
ABW: Aller, Bowen, and Wilson (1963)
ACU: Aller and Czyzak (unpublished)

ACW: Aller, Czyzak, and Walker (1968)
AF: Aller and Faulkner (1963)
AH: Andrillat (1955)
AK1: Aller and Kaler (1964*a*)
AK2: Aller and Kaler (1964*b*)
AK3: Aller and Kaler (1964*c*)
AKB: Aller, Kaler, and Bowen (1966)
AKI: Aller, Czyzak, and Kaler (unpublished)
AL: Aller and Liller (1959)
AS: Aller (1969)
AUV: Aller, Ufford, and Van Vleck (1949)
AW: Aller and Walker (1965)
AWR: Aller and Wares (1969)
C: Chopinet (1962)
CAK1: Czyzak, Aller, and Kaler (1968*a*)
CAK2: Czyzak, Aller, and Kaler (1968*b*)
CAK3: Czyzak, Aller, and Kaler (unpublished)
CAKF: Czyzak, Aller, Kaler, and Faulkner (1966)
CPDA: Capriotti and Daub (1960)
COAL: Collins, Daub, and O'Dell (1961)
FA: Faulkner and Aller (1964)
HAC: Heap, Aller, and Czyzak (1969)
J: Johnson (1960)
K: Kaler, Lee, Aller, Czyzak, and Yoss (unpublished)
K68: Kohoutek (1968)
KAB: Kaler, Aller, and Bowen (1965)
KAC: Kaler, Aller, and Czyzak (1968)
LA: Liller and Aller (1963)
LACD: Lee, Aller, Czyzak, and Duvall (1969)
LILL: Liller (1955); Liller and Aller (1954)
LK: Kohoutek (1964)
M: Minkowski (1942)
MA: Minkowski and Aller (1956)
MO: Minkowski and Osterbrock (1960)
O: O'Dell (1963*a*)
OCB: Osterbrock, Capriotti, and Bautz (1963)
OD62: O'Dell (1962)
OD63: O'Dell (1963*b*)
OD66: O'Dell (1966)
OP: O'Dell, Peimbert, and Kinman (1964)
OPC: O'Dell (private communication)
OS: Osterbrock (1960)
OS1: Osterbrock (1955)
OSSH: Osterbrock and Stockhausen (1961)
R: Razmadze (1961)
SO: Seaton and Osterbrock (1957)
VV1: Vorontsov-Velyaminov *et al.* (1965*a*)
VV2: Vorontsov-Velyaminov *et al.* (1965*b*)
VV3: Vorontsov-Velyaminov *et al.* (1965*c*)
WB: Webster (1969*a*)

The observed radial velocities are taken from Perek and Kohoutek's (1967) catalog, which includes the work of several people, and from Webster (1969*b*). The resulting ΔV_r's are given in column (12) of Table 2 for the optically thin nebulae.

The Z-distances were computed from the work of Cahn and Kaler (1970), again for the optically thin nebulae and for those thick nebulae for which they have computed "dust distances" from the reddening constants.

Figures 5 and 6 show O/H plotted against ΔV_r and Z, respectively. A separation for these data is quite evident, as the high O/H nebulae have low values of Z and ΔV_r, and those nebulae with high Z and ΔV_r all have low O/H. The values of O/H with daggers (no O^+/H^+) are not included.

The distributions of both high and low O/H (divided at 6×10^{-4}) for ΔV_r and Z are given in Figure 7. All show reasonable Gaussian fits except for low O/H versus Z. In both cases the dispersion of the distribution for high O/H is about half that of the low

O/H distribution. The dispersions are given in Table 3. An F test applied to the ΔV_r distributions shows significance for a real difference between the 1 percent and the 5 percent levels. There appears to be little doubt that the abundances are population dependent.

It is interesting to note that this result was anticipated by Johnson (1954), who related the λ4959/λ4861 intensity ratio to Z. The existence of a separation has also been alluded to by O'Dell, Peimbert, and Kinman (1964) from observations of K648 in M15.

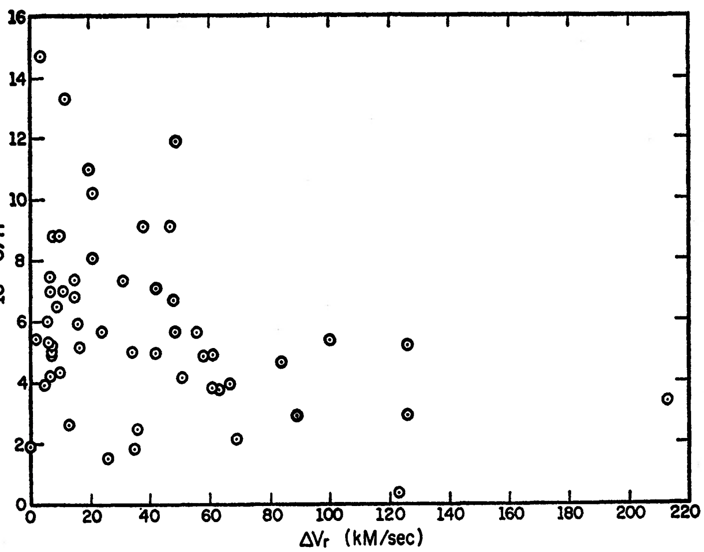

FIG. 5.—Relation between the O/H ratio and ΔV_r, the absolute difference between the radial velocity and the radial velocity expected on the basis of circular motion.

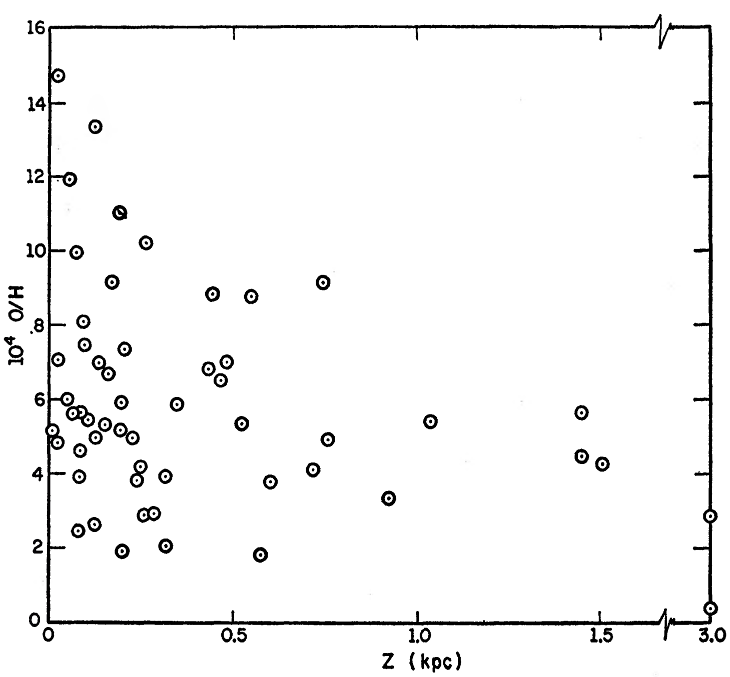

FIG. 6.—Relation between the O/H ratio and height above the galactic plane, Z

In order to make the population separation even more convincing, the nebulae have been divided into Populations I and II. Any object having either $\Delta V_r > 60$ km sec^{-1} or $Z > 800$ pc was called Population II. If neither of these criteria was satisfied, the nebula was called Population I. These divisions, of course, do not necessarily correspond to the classical population divisions; rather, they are a redefinition of population for the purposes of this paper, but they are certainly related to the classical types. The type adopted for each nebula is given in column (11) of Table 2. More nebulae are available than in the case of Figures 6 and 7 since in many instances it was possible to make a population decision even though only an upper limit of the distance was available. Distributions of O/H for each type are plotted in Figure 8. The difference between the two is markedly apparent; the difference in the distributions is significant at the 1 percent confidence level. Again the O/H marked with daggers are excluded. The separation must be even more extreme when we realize that the sample called Population I contains some Population II objects. The mean values for each population are given in Table 3.

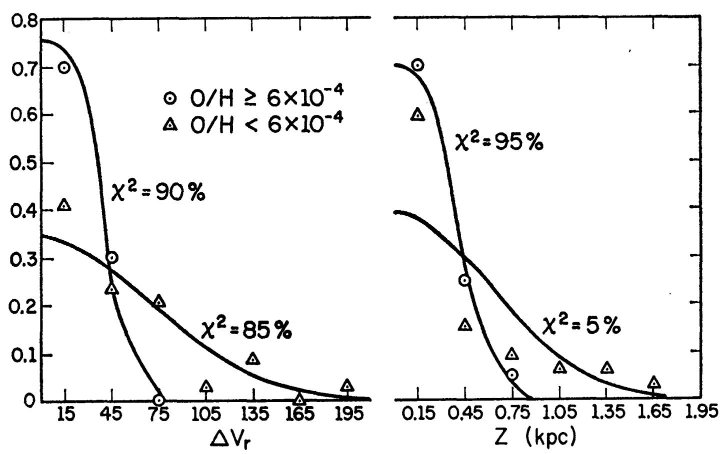

FIG. 7.—Distributions of the O/H ratios in ΔV_r and Z for O/H $\geq 6 \times 10^{-4}$ and O/H $< 6 \times 10^{-4}$, together with the best Gaussian fits.

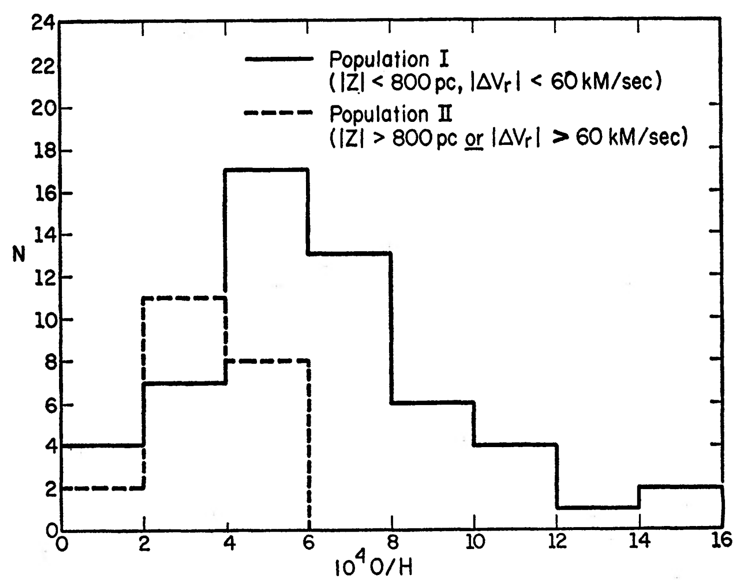

FIG. 8.—Distribution of the values of the O/H ratio for Population I and Population II nebulae

There are not enough population II nebulae with measured He/H values to give really significant results, but the mean He/H for Population II is higher than For population I, for nebulae both with and without He II lines. (see Table 3). This result is particularly interesting with regard to the correlation described below.

b) The Relation Between Oxygen and Helium

The O/H ratio is plotted against the He/H ratio in Figure 9, with the population types as noted in the figure. The two are related to one another through an inverse correlation. At first glance it would appear that we have an envelope distribution, but a second glance shows that the Population II points all lie below the higher Population I points; also, the Population I sample contains some Population II nebulae. What we *may* have is two parallel correlations between O/H and He/H, with the Population II

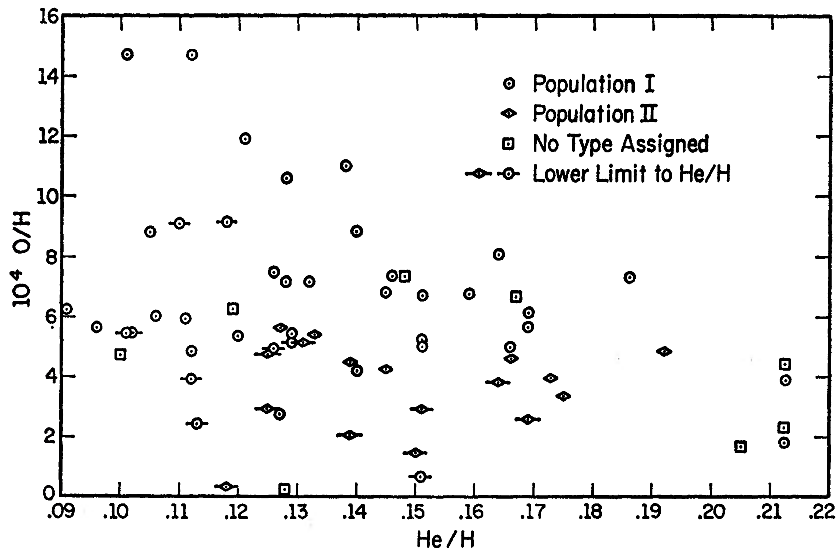

FIG. 9.—Relation between the O/H and the He/H ratios for all nebulae studied

having the lower O/H (and possibly the higher average He/H). At least, this hypothesis is consistent with the observations. The Population II points, however, do not exhibit a marked correlation.

The points of highest quality (those with measured values of T_ϵ(H) are plotted separately in Figure 10. The negative correlation here is much more noticeable. It is quite likely that scatter is introduced into Figure 9 because of the lack of T_ϵ(H).

One criticism which can be leveled at this correlation is that to some extent the O/H ratio depends on the strength of the He lines. If the intensity of λ4471 is systematically underestimated, we will indeed obtain a negative correlation between O/H and He/H. The error required is much too large, however, to account for the large variations found, especially since the O/H ratio is on the average only about 20–30 percent dependent on the helium lines.

c) Further Comments

Since T_ϵ(H) may in fact not be physically real, we should at least consider the effect of assuming that $T_\epsilon(F)$ holds throughout the nebula. We can ignore any effect on the reddening constant, as unrealistic values would have to be assumed, and the results are only slowly dependent upon changes in *c*. The largest effect is in the O/H ratio. If T_ϵ = 14000° K is assumed for the whole nebula, the mean O/H ratios would have to be reduced by a factor of 2.4. Since the effective recombination coefficients for helium and hydrogen all have about the same electron-temperature dependence, the He/H ratio will not be greatly changed. The assumption of a single high electron temperature will on the average raise the values of He/H by about 15 percent. Since all the points will be moved by similar factors in the same directions, the correlations will not be greatly altered, and the final conclusions will remain the same. This statement is true even for Figure 10 when the actual values of $T_\epsilon(F)$ are assumed to hold throughout the nebula.

One important source of error lies in the assumption of two distinct temperature regions. If in fact the nebula possesses a continuous temperature gradient, the [O III] λ4363 line will be produced in a region of higher temperature than will the [O III] λ5007 line as it requires higher collisional energies, and the value of $T_\epsilon(F)$ computed will be higher than is appropriate for the λ5007 line which is used in the abundance calculations. Thus the O/H ratio will be too low. The exact calculation requires detailed models which are not available, and which would not be appropriate to a wide survey of this

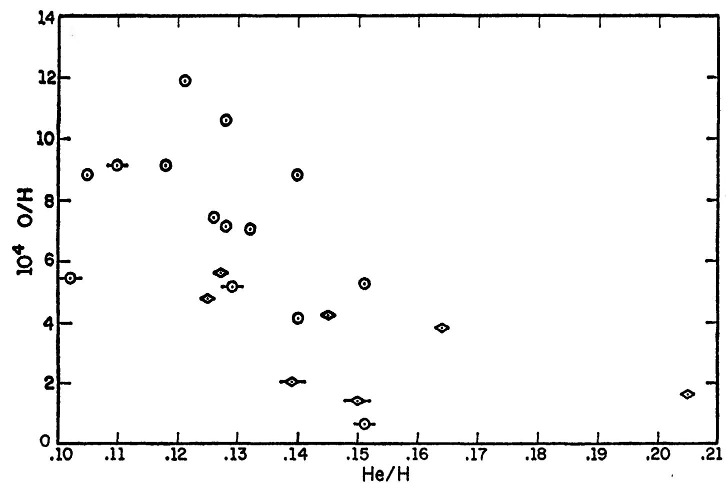

FIG. 10.—Relation between the O/H and the He/H ratios for nebulae for which a "hydrogen temperature" is observed.

sort. Consequently, the simple two-temperature model used here will have to suffice. In any case, if the model used here is not truly appropriate, at least all the O/H ratios will be changed by about the same amount, and the correlations and results will remain unchanged.

The oxygen-helium correlation will result in small systematic errors in the O/H ratios marked by the asterisk or dagger in Table 2. Since these values are found from the strength of the λ4686 line and not the ratio of λ4686 to λ4471, the helium abundance will enter into the calculation. There is no way to account for this error, however, so all we can do is acknowledge its presence. It should amount to only a few percent, in any case.

The average O^{2+}/H^+ ratios are given in Table 3 for both Population I and Population II and also for the Large and Small Magellanic Clouds. The ratio

$$\frac{(O^{2+}/H^+)(\text{Population I})}{(O^{2+}/H^+)(\text{Population II})} < \frac{(O/H)(\text{Population I})}{(O/H)(\text{Population II})}, \tag{9}$$

which implies that the excitation level of the Population I nebulae is somewhat greater than that of Population II, which in turn may represent a difference in the temperatures of the central stars. This result is suggested by Greig (1967) on other grounds.

The O^{2+}/H^+ ratio in the Magellanic Clouds is similar to that of the nebulae in the Galaxy, and is closer to the Population II value, but there are really insufficient data upon which to base a firm decision. Certainly, selection effects in our own Galaxy have a strong influence on the relative numbers of Population I and Population II nebulae observed.

It is interesting to note that four well-observed H II regions have O/H ratios less than those of the so-called Population I nebulae, an argument for the manufacture of oxygen in the central star. Peimbert and Costero (1969) have recently reobserved the Orion Nebula as well as M8 and M17, and find an average O/H ratio of 6×10^{-4} with a maximum of 7×10^{-4} in M17, still less than many of the Population I planetaries.

Following the completion of the analysis presented in this paper, Miller (1969) published an analysis of the high-latitude planetary 49+88°1, which is high above the galactic plane and exhibits a high radial velocity. On the basis of a unique electron temperature (14500° K), he found that O/H = 1.02×10^{-4} and He/H = 0.13. If we assume that T_ϵ(H) = 5000° K, O/H then increases to $\sim 2.5 \times 10^{-4}$ and He/H decreases to about 0.10. The abundances and galactic parameters of this nebula are consistent with the results presented in this paper.

VII. SUMMARY AND CONCLUSIONS

The principal conclusions reached in this paper are as follows for planetary nebulae:

1. The oxygen-to-hydrogen ratio should be based upon an ionization equilibrium established by the He^{2+}/He^+ ratio.
2. The electron temperatures near the central stars are quite high for high-excitation nebulae.
3. The oxygen-to-hydrogen ratio is dependent upon population type, decreasing toward Population II.
4. The helium-to-hydrogen and oxygen-to-hydrogen ratios are negatively correlated with one another.

The mean characteristics of the observed nebulae and the ranges over which the various values extend are given in Table 3. One of the interesting results of this work is the wide range of values for the oxygen-to-hydrogen and helium-to-hydrogen ratios. In order to explain this fact and the correlations mentioned in point 4 above, it is probably necessary to look at the interior nuclear processes of the star. The planetary nebula is, after all, not original interstellar matter, but represents a portion of a star which has probably undergone considerable chemical evolution. The first thought that comes to mind is that the low-helium nebulae have had their helium converted into oxygen (resulting in the high oxygen-to-hydrogen ratio) and other elements. The complete explanation is not a simple one, however, since the observed variation in the oxygen-to-hydrogen ratio requires a much smaller variation in the helium-to-hydrogen ratio than is present even if one considers the manufacture of all the other elements in addition to oxygen. The relation between the helium and the oxygen probably depends on the degree of chemical evolution in the preplanetary phase of stellar evolution, the degree of internal mixing, the amount of matter ejected from the star to form the nebula, and the star's original composition (into which the population type enters).

Because of all this, care must be taken in interpreting the mean values of Table 3 in terms of "cosmic abundances," especially since the mean values are weighted by observational selection because of the very limited observations of planetary nebulae near the galactic nucleus.

Since the oxygen-to-hydrogen ratio can be correlated with galactic parameters, perhaps the *limits* on the abundances can tell us something about the initial chemical composition of the Galaxy. We must again be careful, however, since the indication that we are dealing with evolved matter means that we must be able to show that in the limit the part of the star that was ejected did not take part in any thermonuclear processes.

The true limits on the abundances and the true mean abundances cannot be established without further observation, especially of nebulae in the direction of the galactic nucleus. In particular, we need many more data to evaluate properly the variation of the helium-to-hydrogen ratios of planetary nebulae in the Galaxy.

TABLE 3

MEAN VALUES OF PARAMETERS AND ABUNDANCES FOR PLANETARY NEBULAE

Quantity	Mean	Range
$T_\epsilon(F)$, with λ4686	14000° K	8200°–~25000° K
$T_\epsilon(F)$, no λ4686	11500° K	
T_{in}	30000° K	15000°–50000° K
He/H, with λ4686	0.140	0.09–>0.2
He/H, no λ4686	0.131	0.04–>0.2
He/H Population I, with λ4686	0.133	0.09–>0.2
He/H Population II, with λ4686	0.155	0.12–>0.2
He/H Population I, no λ4686	0.117	0.04–>0.2
He/H Population II, no λ4686	0.142	0.12– 0.17
O/H	5.35×10^{-4}	$\sim1\times10^{-4}$–14 $\times10^{-4}$
O/H Population I, with * values	6.23×10^{-4}	$\sim1\times10^{-4}$–14 $\times10^{-4}$
O/H Population II, with * values	3.63×10^{-4}	$\sim1\times10^{-4}$– 5.6×10^{-4}
O^{2+}/H^+ Population I	3.36×10^{-4}	...
O^{2+}/H^+ Population II	2.70×10^{-4}	...
O^{2+}/H^+, SMC	2.08×10^{-4}	...
O^{2+}/H^+, LMC	3.15×10^{-4}	...
O^{2+}/H^+, SMC + LMC	2.75×10^{-4}	...
H II, O/H	3.35×10^{-4}	...
$O/H>6\times10^{-4}$, σ_z	300 pc	...
$O/H<6\times10^{-4}$, σ_z	600 pc	...
$O/H>6\times10^{-4}$, $\sigma_{\Delta V_r}$	28 km sec^{-1}	...
$O/H<6\times10^{-4}$, $\sigma_{\Delta V_r}$	70 km sec^{-1}	...

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