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GALACTIC ABUNDANCES OF NEON, ARGON, AND CHLORINE DERIVED FROM PLANETARY NEBULAE

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ABSTRACT

Mean neon and argon to oxygen ratios are found from planetary nebulae to be Ne/O = 0.225 ± 0.01 and Ar/O = $7.0 \pm 0.5 \times 10^{-3}$. The mean Ar/Cl ratio is 21.3 ± 2.3, which results in Cl/O = $3.3 \pm 0.5 \times 10^{-4}$. The errors quoted are internal, and arise mostly from observational scatter. The accuracy of these nebular abundances is now limited by the calculated atomic data. The Ne/O ratio is probably the most accurate, and the Cl/Ar, Cl/O the least. The external error imposed by the Cl cross sections is probably less than $\pm 25\%$. If the three extreme halo planetaries are excluded, these ratios are constant among nebulae within the observational errors, so that the mean values have galactic significance. No variation in Ne/O with galactic position is seen, except that the halo planetary Ha 4-1 is a factor of 10 deficient in Ne compared with O. Comparison with other observations shows that these planetary abundance ratios are essentially solar. The observed ratios are in general agreement with the predictions of explosive nucleosynthesis; however, the measured Cl is a factor of 3–5 more abundant than the predicted values. The neon, argon, and chlorine abundances found in planetaries are apparently typical of the interstellar medium out of which the stars were formed. Since solar values for these elements are apparently not as well determined, the abundances presented here could be used to improve the compilations of "solar" or "local galactic" abundances.

Subject headings: nebulae: abundances — nebulae: planetary

I. INTRODUCTION

The chemical compositions of planetary nebulae reflect two processes: (1) galactic chemical evolution, which determines the material out of which the parent star was formed; and (2) stellar nuclear transformations and mixing in which the initial composition of the outer layers of the parent star can be changed. The results of both processes appear to be fairly well documented. Peimbert and Torres-Peimbert (1971) and Boeshaar (1975) demonstrated a large range of N/O in planetary nebulae, Kaler (1974) showed the existence of nebulae with high He/H, and Barker (1978) suggests a correlation between N/O and He/H. Presumably, freshly created He and N are mixed to the star's upper layers before the ejection of the nebula. The effects of galactic evolution appear to be seen in the variation of He/H with distance from the galactic center, *R* (D'Odorico, Peimbert, and Sabbadin 1976; Torres-Peimbert and Peimbert 1977, hereafter TPP; Aller 1976). D'Odorico *et al.* and TPP also suggest that O/H and N/H are functions of *R*. Radial abundance gradients are well known from other sources; for example, Searle (1971), Shields (1974), and Smith (1975) show that O/H and N/H decrease outward in the disks of spiral galaxies.

The interpretation of the compositions of planetary nebulae is complicated by the fact that both processes above may influence the more common elements, notably He and N, and it is difficult to separate the two. For this reason, the elements Ne, Ar, and Cl studied in this paper are of particular interest. They are produced in a star usually only under conditions of carbon or oxygen burning; and, while these processes may have been at work in the planetary nucleus, the burning has occurred so deeply within the star that it seems unlikely that many of the by-products could be mixed to the surface.

The range of O/H ratios observed is very large, up to a factor of 10. The studies mentioned above indicate that most of this variation is probably of galactic origin. The CNO processes at work within the star generally act to produce N, and if mixing to the surface does occur the O/H ratio should not be greatly affected. The abundances of O, Ne, Ar, and Cl should then primarily reflect the place of origin of the star.

It is generally believed that the overall galactic abundances of the heavier elements are determined by nucleosynthesis during explosive events; see, for example, Truran (1973) and Arnett (1973). Calculations of abundances of explosively produced elements have been made, for example, by Truran and Arnett (1970) and Woosley, Arnett, and Clayton (1973) (hereafter TA and WAC, respectively), who demonstrated substantial agreement with observation. The ratio Ne/O was predicted by Arnett (1969), and Ar/Si and Cl/Si (and thus Ar/Cl) by TA and WAC. Furthermore, Ar and Cl can be tied empirically to O through the measured solar Si/O ratio.

From an observational point of view, it is desirable

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to compute the abundances of Ne, Ar, and Cl with respect to O. The spectrum lines used to derive the abundances are all forbidden lines, and are all produced by the same mechanism of electron collision. The hydrogen lines are produced by recombination, however, and have different temperature and density dependences from those of the forbidden lines. Consequently, abundance ratios expressed in terms of O will be much less model-dependent than ratios expressed in terms of H. The study of these elements (particularly Ar) in nebulae is of importance because of the difficulty of deriving their abundances from stellar and other data.

In this paper, § II will describe the procedure used to derive ionic abundance ratios and the general method used to determine total abundances from the ionic abundances. In §§ III, IV, and V mean abundance ratios will be derived for Ne, Ar, and Cl, respectively. Section VI will consider the possible variations of abundances from the mean and the comparison of the measurements to other measured values and to predictions by theories of nucleosynthesis, and § VII, the broad conclusions.

II. IONIC AND TOTAL ABUNDANCES

a) *General Procedure*

In a nebula an element can exist simultaneously in a number of ionization stages. There are thus two distinct problems involved in the determination of nebular abundance ratios. The first is the actual calculation of ionic ratios; the second, the estimation of the abundances of the ions which are unobservable or for which reliable calculations cannot be made. Of the elements considered here, we can calculate ionic abundances from forbidden lines for O^+, O^{2+}, Ne^{2+}, Ne^{3+}, Ne^{4+}, Ar^{2+}, Ar^{3+}, Ar^{4+}, Cl^{2+}, and Cl^{3+}. Other ions are represented by permitted lines, but the mechanism for their formation (other than H and He) is often too complex to allow an abundance calculation. Of the ions listed above, it will be shown that Ne^{3+} and Cl^{3+} cannot be calculated reliably from [Ne IV] and [Cl IV]. In addition, Ar^{4+} calculations are suspect, and Ne^{4+} gives too large a scatter. Consequently, this study will concentrate on Ne^{2+}, Ar^{2+}, Ar^{3+}, and Cl^{2+}; calculations for Ne^{4+} and Ar^{4+} will be used mostly for confirmation purposes.

There are various ways of approaching the problem of missing ions. One is by a detailed modeling of a nebula to see how much of an ion is tied up in the various ionization states; see, for example, Harrington (1969). Another method makes use of coincidence in ionization potentials. For example, since O^{2+} and He^+ have nearly identical ionization potentials, it may be assumed (Seaton 1968) that

$$\frac{O^{3+} + O^{4+} + \cdots}{O^+ + O^{2+}} = \frac{He^{2+}}{He^+}, \quad (1)$$

where E^{n+} represents the abundance by number of ion E^{n+}. The general method was rather widely applied by Peimbert and Costero (1969) and by Peimbert and Torres-Peimbert (1971) to other elements.

Still another method was suggested by the author (Kaler 1973), which to some extent is dependent upon ionization coincidences, and which was applied at that time to Ne and Ar. The procedure involved looking for nebulae which have the largest Ne^{2+}/O or $(Ar^{2+} + Ar^{3+})/O$ ratios, and assuming that for these objects the large majority of Ne or Ar is in those stages. Analysis of O shows that up to ~90%–95% can be in O^{2+} for a given nebula. It is assumed that, for the nebulae in which Ne^{2+} and $(Ar^{2+} + Ar^{3+})$ is a maximum, only a similar small correction of less than 10% is required to go to total Ne/O and Ar/O abundance ratios. At the time of the earlier work it was not possible to decide whether the Ne/O and Ar/O ratios that were derived represented (1) true mean values, or (2) mean maximum values in the case that variation in Ne/O exists among nebulae.

In this paper the problem is approached by constructing empirical ionization curves as a function of nebular excitation for each ion studied, so that we can see for which stellar temperature (or nebular ionization level) a given ion has a maximum population. A small correction is then applied to the mean ionic abundances for nebulae of that excitation to derive a total element abundance. The restriction to nebulae of a limited ionization region also allows a limit to be set on the variation of element abundance.

Ideally, the ionization curves should be plotted with the temperature of the central star (T_*) as the independent variable. Preliminary plots of Ne^{2+}/O and O^{2+}/O were made for which T_* was taken from Kaler (1976*a*, 1978*a*) for low-excitation nebulae, and newly calculated from the He II–Zanstra method (see Harman and Seaton 1964) for high-excitation nebulae. It was found that considerable scatter existed for the high-temperature objects, which was reduced if the ratio $He^{2+}/He^+ = Ex$ (which is in some sense a measure of T_*) were substituted for T_*. As support for this procedure, recent results on T_* by Pottasch *et al.* (1978) show that Zanstra temperatures for higher-excitation objects are often overestimated. Consequently, all subsequent ionization curves are plotted against $\log T_*$ where a value is available from Kaler (1976*a*, 1978*a*) (boxes in the figures), or else Ex (circles). The two scales are joined such that Ex becomes greater than 0 at $\log T_* = 4.75$. The larger the size of the symbol, the greater the relative weight of the point. The Orion Nebula and NGC 6523 are introduced as comparison points, and are represented by crosses. In instances where He^+ is not observed, the total He/H ratio is assumed to be

$$He/H = 0.166 - 0.00571R, \quad (2)$$

where R is the distance from the galactic center. Equation (2) is derived from the data presented by TPP and Kaler (1978*b*) where R is found from Cahn and Kaler (1971). Since the abundances are found from nebulae for which the abundance of He^{2+} is small, the results are very insensitive to the form of equation (2).

b) Ionic Abundances

This study required the calculation of ionic abundances for a large number of nebulae; well over 100 objects are considered. For most of these photometry is incomplete, so that only the simplest of models can be assumed. All observational data were taken from Kaler's (1976*b*) catalog (hereafter KC), Zipoy (1976), Lutz (1977), Kaler (1978*b*), TPP, Barker (1978), or Hawley and Miller (1978), corrected for reddening (see KC or the above papers). For each nebula, electron temperatures were calculated from the [O III] and [N II] lines (Seaton 1975), and electron densities from [O II], [Cl III], and [Ar IV] from the tables of Saraph and Seaton (1970, hereafter SS), without their recommended correction (see § II*c*); T_e[O III] was used for all ionic calculations except O^+, for which T_e[N II] was used. If T_e[N II] was not available, a modification of a finding by TPP was followed, whereby T_e[N II] $=$ T_e[O III] if $I(\lambda 4686) < 60$, and T_e[N II] $= T_e$[O III]/1.4 if $I(\lambda 4686) \geq 60$. If no temperature could be calculated, T_e was assumed as follows: $T_e = 10000$ K for $I(\lambda 4686)$He II $= 0$, $T_e = 12000$ for $0 < I(\lambda 4686) \leq 90$, $T_e = 18000$ for $I(\lambda 4686) > 90$. An electron density was chosen from that ion above for which the ionization potential was closest to the ion whose abundance is being calculated. If no density was available from the spectrum, a density was estimated from the Cahn and Kaler (1971) distance, modified for the correct extinction. Nebulae with densities greater than 10^4 were generally rejected, since the abundances are unreliable unless the density is known to high accuracy.

All abundances were first calculated with respect to H through the formula

$$\frac{E^{n+}}{H^+} = \frac{I(\lambda_F)}{I(H\beta)} \frac{N_e \alpha(H\beta)}{A(\lambda_F)} \frac{\lambda_F}{\lambda(H\beta)} \frac{N_T}{N_n} \qquad (3)$$

where N_n is the population of level $n = 2$ or 3 from which the forbidden line arises, λ_F is the wavelength of the forbidden line, the I's are line intensities, A is the transition probability, N_T/N_n is the ratio of the total abundance of ion E^{n+} to the population of level n, and $\alpha(H\beta)$ is the effective Hβ recombination coefficient. For p^2 and p^4 ions it was computed from the balance equations given by Aller (1956), the transition probabilities given by Garstang (1968) or Nussbaumer (1971), and the energy-averaged cross sections presented by Seaton (1975) or Osterbrock (1974). For p^3 ions N_T/N_n was calculated from the formulation and tables given by SS, Aller *et al.* (1970), Czyzak, Krueger, and Aller (1970), and Aller (1970). See these papers for cross-section references.

Since ionic and total ratios will be presented with respect to O, the total O/H ratio must be derived. Nebulae are not used unless both O^+ and O^{2+} are observed. The abundance of higher ionization stages is estimated from equation (1). He^+/H^+ and He^{2+}/H^+ ratios were calculated from the recombination coefficients of Brocklehurst (1971, 1972), where the $He^+(2\,^3S\text{–}n\,^3D)$ collisions are taken into account at one-third the rate, as predicted by Cox and Daltabuit (1971) (see Peimbert and Torres-Peimbert 1971). If He^+/H^+ is not observed, equation (2) is used to derive it. TPP and Barker (1978) suggest that the $2\,^3S\text{–}n\,^3D$ collisions are not important and that allowance should be made only for self-absorption from $2\,^3P$. Most of the calculations in this paper were made before this finding was made; since the absorption and collisional corrections are small and very similar and since data for the absorption correction are not generally available, the calculations were allowed to stand. No significant inaccuracy results.

c) Collision Cross Sections and Presentation of Results

The calculations of ionic ratios for the $3p^3$ ions Cl^{2+} and Ar^{3+} is complicated by the fact that two five-level atom solutions are available, which depend upon somewhat different target areas, Ω. An additional complicating factor is that in the calculation of total Ω, there are two approximations for the p-wave contribution: the exact resonance (ER) and the distorted wave (DW). See Saraph, Seaton, and Shemming (1969) for an explanation of these approximations. SS, for example, use the DW p-wave approximation, but suggest that the Ω's for Cl^{2+} should be increased by 50%, based upon the close-coupling calculations of Coneely, Smith, and Lipsky (1970). The DW–Ω's were used in the computation of both sets of five-level atom solutions, and this approximation was also used to compute the Ω's for Ar^{2+}. Czyzak (private communication) suggests that the ER p-wave contribution to the contribution to the total Ω be used instead of the DW contribution, as was done by Saraph, Seaton, and Shemming (1969) for the $2p^q$ ions. The relevant data are given by Krueger and Czyzak (1970). If the ER p-wave approximation is used, $\Omega(^4S\text{–}^2D)$ for Cl^{2+} is increased by 25%, and thus Cl^{2+}/O is decreased by 25%. The corrections to $\Omega(^4S\text{–}^2P)$, $\Omega(^2D\text{–}^2P)$ are ignored, since their effects on the population of the ^2D state are small. Note that this correction is similar to, although less than, that suggested by SS. For the ions Ar^{2+} and Ar^{3+} the Ω's are increased by 8% and 13%, respectively.

In this paper, the abundance ratios presented in Tables 1 and 3, and shown in Figures 6, 7, 9, and 10, are calculated with the DW–Ω's; Cl^{2+} and Ar^{3+} are shown as calculated directly from the tables of SS, without the ER correction. The data in these tables are averaged and converted to total element abundances. These abundances are then corrected for (1) the ER p-wave contribution, and (2) the other five-level atom solution, so as to produce an average of the two. The final corrected abundances are then presented in Table 5.

III. NEON

a) Abundance from Ne^{2+}, [Ne III]

The ionization curves for O^{2+} and Ne^{2+} are presented in Figures 1 and 2, respectively, in the form log O^{2+}/O (or log Ne^{2+}/O) versus (log T_*/Ex). Values of Ne^{2+}/O were calculated from λ3868, λ3967 of

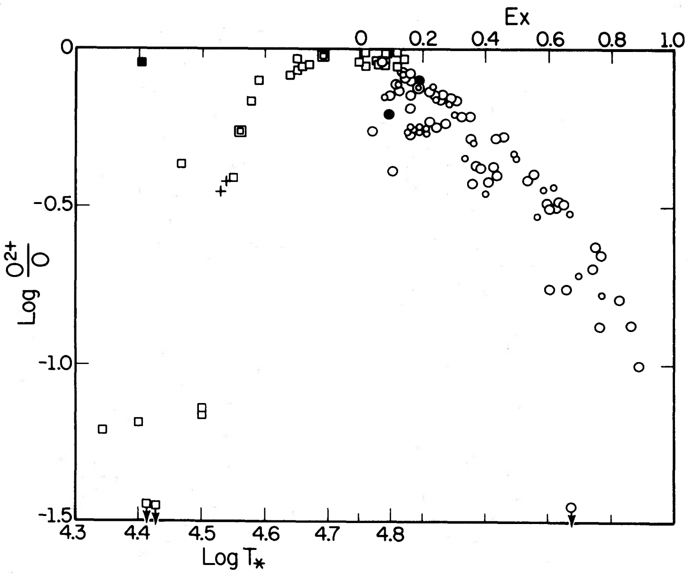

FIG. 1.—Log O^{2+}/O plotted against log T_* (*boxes*) or Ex (*circles*). The Orion Nebula and M8 are shown by crosses. The three halo planetaries are shown by filled symbols.

[Ne III]. The data for each nebula were examined in KC and the other sources, and anomalous values were removed. Note the similarity between the two curves. Both are characterized by a rapid rise and a plateau of relative constancy, followed by a slow steady decline. The Ne^{2+} curve reaches its peak at a slightly higher (T_*/Ex), as would be expected, because of its higher ionization potential.

The mean maximum values of O^{2+}/O, Ne^{2+}/O are found by isolating the nebulae in the flat plateau, and averaging the individual values. For O^{2+}/O the nebulae for which log T_* is calculated in the range $4.64 < \log T_* < 4.8$ are averaged to find $\langle O^{2+}/O \rangle = 0.926 \pm 0.008$ (m.e.). For Ne^{2+}, two groups are isolated. The first consists of all those nebulae for which there is a measured log $T_* > 4.6$ or for which $0 < \mathrm{Ex} < 0.05$, and the second includes those for which $0.05 < \mathrm{Ex} \leq 0.2$. The mean Ne^{2+}/O is 0.218 ± 0.009 for group 1 and 0.197 ± 0.008 for group 2. The first group has the maximum Ne^{2+} ionization and will be used to find Ne/O, but both groups are useful in exploring for variations.

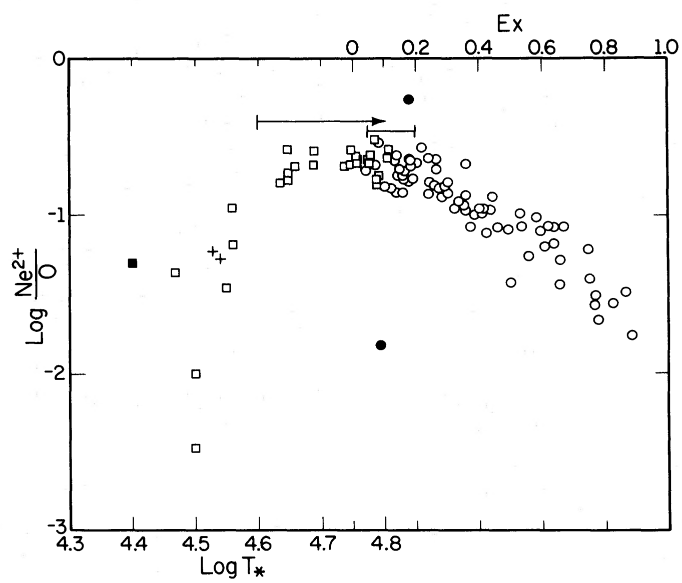

FIG. 2.—Log Ne^{2+}/O plotted against log T_* (*boxes*) or Ex (*circles*). Ha 4-1 is represented by a filled circle below the main curve, 108−76°1 by a filled circle above the curve, Ps-1 by a filled box, and the Orion Nebula and M8 by crosses. The horizontal bars show the regions for which averages were taken.

1978ApJ...225..527K

TABLE 1

ABUNDANCE DATA, O, Ne/O, Ar/Cl

Nebula (1)	log T_*/Ex (2)	10^4 O/H (3)	10^3 T_e (4)	O^{2+}/O (5)	Ne^{2+}/O (wt) (6)	Ar^{2+}/Cl^{2+} (wt) (7)	*R* (kpc) (8)
NGC:							
1535	0.16	1.85	13.5	...	0.178 (3)	22.1 (2)	11.4
2022	0.89	7.29	15.5	...	...	19.3 (4)	...
2346	0.20	2.90	12.9	...	0.178 (2)	...	11.1
2371	0.77	5.33	16.4	...	...	13.9 (2)	...
2392	0.63	4.55	14.2	...	...	19.0 (3)	...
2440	0.43	5.59	13.0	...	...	34.4 (2)	...
3132	0.11	6.91	9.9	...	0.152 (3)	...	10.0
3195	0.15	2.72	10.9	...	0.197 (2)	...	9.3
3242	0.28	4.23	11.3	...	...	10.3 (2)	...
3587	0.16	3.69	11.1	...	0.157 (3)	10.3 (1)	10.2
5882	4.79	4.77	9.3	0.945	0.234 (2)	34.2 (1)	8.2
6153	0.19	2.12	12.0*	...	0.222 (1)	...	8.5
6210	4.76	4.56	9.6	0.896	0.210 (2)	...	8.9
6309	0.49	3.38	13.5	...	...	25.1 (0)	...
6439	0.14	2.23	12.0*	...	0.216 (1)	...	4.0
6543	4.65	5.48	8.1	0.858	0.263 (3)	33.2 (3)	10.2
6565	0.08	3.12	11.3	...	0.296 (2)	...	5.5
6567	4.75	2.98	10.6	0.925	0.193 (3)	...	6.7
6572	4.78	3.48	10.5	0.894	0.239 (2)	21.2 (0)	8.7
6629	4.65	4.28	8.5	0.932	0.171 (2)	...	7.7
6644	0.12	3.64	12.6	...	0.150 (2)	...	15.5
6720	0.22	3.58	11.5	...	...	27.1 (0)	...
6778	0.12	1.28	12.6	...	0.226 (3)	...	7.7
6781	0.19	4.14	12.0*	...	0.149 (1)	...	9.3
6803	4.79	4.23	10.2	0.892	0.309 (2)	...	7.4
6807	4.78	2.36	11.7	0.952	0.212 (2)	...	...
6818	0.58	4.23	14.1	...	...	21.4 (0)	...
6826	4.67	3.25	9.7	0.901	0.181 (3)	22.4 (1)	9.9
6833	4.69	0.88	14.3	0.951	0.269 (2)	...	12.1
6879	0.19	1.76	13.2	...	0.227 (1)	...	8.6
6884	0.14	5.17	10.9	...	0.189 (2)	20.9 (0)	10.2
6886	0.36	4.89	12.9	...	...	39.7 (0)	...
6891	4.69	2.85	10.0	0.957	0.216 (2)	12.6 (0)	8.5
6894	0.16	2.88	12.0*	...	0.187 (1)	...	9.6
7009	0.12	4.27	10.4	...	0.238 (3)	19.9 (2)	9.2
7026	0.16	4.00	10.3	...	0.232 (2)	...	10.2
7027	0.35	5.88	11.7	...	...	21.0 (4)	...
7139	0.16	2.76	12.0*	...	0.144 (1)	...	10.4
7662	0.46	4.01	12.9	...	...	23.2 (1)	...
IC:							
351	0.40	4.31	12.3	...	...	18.3 (2)	...
418	4.50	8.25	9.4	...	...	12.8 (2)	...
2003	0.47	4.49	11.9	...	...	12.6 (3)	...
2165	0.36	3.70	13.4	...	...	17.1 (2)	...
3568	4.79	3.17	10.8	0.972	0.177 (3)	...	11.4
4406	0.05	5.31	10.7	...	0.192 (3)	...	8.5
4593	4.64	3.65	8.8	...	0.163 (3)	...	8.1
4732	4.81	1.23	15.8	...	0.261 (1)	...	3.8
4846	4.79	3.13	10.9	0.914	0.188 (2)	...	6.8
5217	0.13	3.67	11.3	...	0.208 (2)	19.4 (0)	12.2
Hu 1-1	0.14	7.33	10.7	...	0.137 (1)	31.8 (0)	17.0
Hu 1-2	0.59	1.34	19.4	...	...	20.5 (0)	...
J320	4.76	1.40	14.9	0.965	0.247 (2)	...	16.7
M1-4	0.07	2.42	11.6	...	0.216 (2)	...	...
Me 1-1	0.04	3.85	10.9	...	0.240 (2)	...	8.2
Me 2-2	4.66	1.78	11.3	0.931	0.218 (2)	...	...
PB 4	0.13	2.78	10.5	...	0.233 (2)	...	10.5
Sn −1	4.77	4.06	9.8	...	0.237 (2)	...	...
Vy 1-2	0.19	8.83	9.3	...	0.160 (1)	...	8.3
Means	...	...	...	0.926 ± 0.008	Group 1:† 0.218 ± 0.009 Group 2:‡ 0.197 ± 0.008 Group 3:§ 0.209 ± 0.008	20.1 ± 1.9	...

* Estimate.

† Nebulae for which log $T_* > 4.6$, Ex < 0.05.

‡ Nebulae for which $0.05 <$ Ex ≤ 0.2.

§ Same as group 1, except 9000 K $< T_e <$ 12000 K.

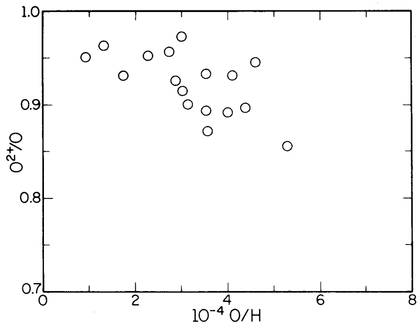

FIG. 3.—O^{2+}/O plotted against 10^{-4} O/H for nebulae on the plateau of Fig. 1 ($4.64 < \log T_* < 4.8$).

The data upon which these means are based are given in Table 1, which gives, in column order: (1) nebula; (2) $\log T_*$ or Ex; (3) 10^{-4}O/H; (4) T_e[O III]; (5) O^{2+}/O; (6) Ne^{2+}/O; (7) Ar^{2+}/Cl^{2+}; and (8) R(kpc), the distance from the galactic center projected onto the plane, calculated and modified from Cahn and Kaler (1971). Column (7) will be discussed later. The numbers in parentheses are subjective weights assigned to the values. The weighted means are given at the bottom of each column.

Since (1) the ionization curves for Ne^{2+} and O^{2+} are similar, and (2) the ionization potentials are similar, it will be assumed that $\langle O/O^{2+}\rangle = \langle Ne/Ne^{2+}\rangle$. Before a value of Ne/O is derived, however, a more subtle ionization effect must be explored. Figure 3 shows O^{2+}/O from Table 1 (those nebulae on the plateau) plotted against O/H. A distinct correlation is present; O^{2+}/O is highest when O/H is smallest. As O/H decreases, so does the cooling rate, and the electron temperature increases. O^{2+}/O should correlate with T_e as well. It does, but the correlation with O/H is better. A likely at least partial explanation of the correlation is that as T_e increases, the O^{2+} to O^+ recombination coefficient decreases, so that more oxygen exists in the O^{2+} state. Ne^{2+}/O for both groups is plotted against O/H in Figure 4. The effect may be marginally present. In order to reduce the error caused by this ionization effect, the nebulae used in the analysis should be restricted to a range of electron temperatures. We therefore define a group (3) for the Ne^{2+}/O ratios in Table 1 which is the same as group 1 except that $9000\ K < T_e < 12000$ K. The mean for this group is 0.209 ± 0.008. The mean of O/O^2 for a nebulae with this temperature restriction is the same as in Table 1. Thus, Ne/O = $\langle(Ne^{2+}/O)\rangle/\langle(O^{2+}/O)\rangle = 0.209$ (the average for group 3)/0.926 = 0.225 ± 0.01 (the mean abundances are compiled in Table 4).

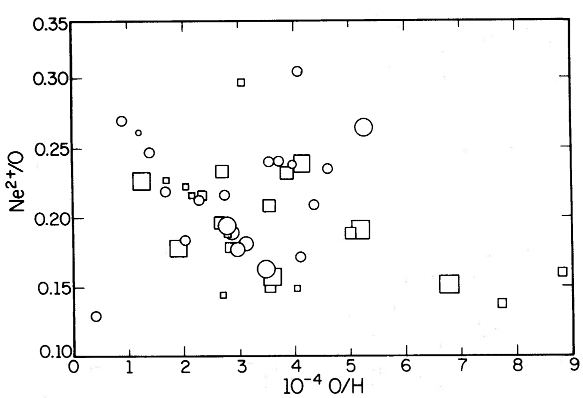

FIG. 4.—Ne^{2+}/O for the two groups of Table 1, for which Ne^{2+}/O is near maximum, plotted against 10^{-4} O/H. Groups 1 and 2 are indicated by circles and boxes, respectively.

Does the scatter within the ionization curve represent real Ne/O abundance variations, or does it represent only observational error, compounded with error in the extinction constant c, and the electron temperature? From Table 1 we find that the mean expected percentage error for any individual point is $\pm 18\%$ and $\pm 20\%$ for groups 1 and 2, respectively. These figures are about the error that one would normally expect, and it is concluded that Ne/O = 0.225 is probably close to a true mean value for galactic planetaries. The Ne^{2+}/O ratios have been examined for systematic error by plotting the data of Table 1 against extinction; no correlation is found.

Two further points are to be made here. First, the three halo planetaries Ps-1 (K648, in M15), Ha 4-1, and $108-76°1$ (see Boeshaar and Bond 1977) are generally anomalous. For these three objects, abundance data are taken directly from Hawley and Miller (1978). Ps-1 (denoted by a filled box at $\log T_* = 4.40$ in Figs. 1 and 2) is considerably higher than the mean ionization curves. Presumably, the mass of Ps-1 is so low (see Peimbert 1973) that the nebula is optically thin, and $\log T_*$ is only a lower limit. Ha 4-1 and $108-76°1$ are shown in Figure 2 as filled circles at Ex = 0.08 and 0.18, respectively. Ha 4-1 is well below the curve; it appears that Ne/O is down by a factor of 10 from the galactic value. (Hawley and Miller 1978 point out that both Ne and O are deficient with respect to H.) The planetary $108-76°1$ is above the curve, but Hawley and Miller (1978) indicate that the λ3868 line is uncertain (Boeshaar and Bond 1977 give similar, uncertain results). Possibly this halo nebula has a normal Ne/O.

Second, note that the Orion Nebula and NGC 6523 fit the ionization curves well, implying that the ⟨Ne/O⟩ found from galactic planetaries is the same as that of the galactic disk. This contention is supported by the agreement with the solar value (see § VI).

The value of Ne/O derived here is considerably below the figure of 0.41 derived by Kaler (1973). The difference is due to improved observations of I(λ3868), better extinction coefficients, and proper allowance for observational error. TPP, Barker (1978), and Aller (1976) find Ne/O = 0.257, 0.224, and 0.20, respectively. The difference between this analysis and those of the above authors is that here it is assumed that $\langle Ne/Ne^{2+}\rangle = \langle O/O^{2+}\rangle$ for the maxima of the ionization curves, whereas a usual method is to assume that $Ne/Ne^{2+} = O/O^{2+}$ for individual nebulae. Examination of Figures 1 and 2 shows that this

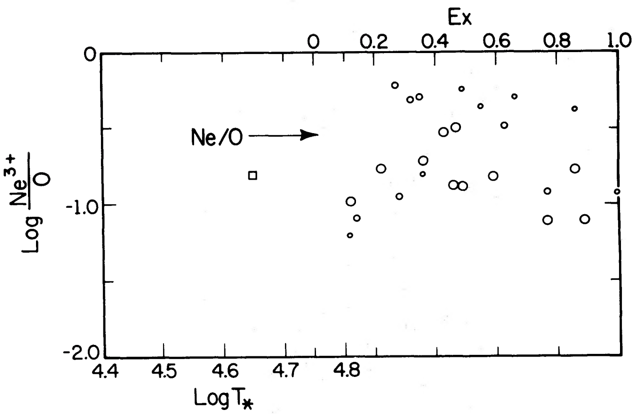

FIG. 5.—Log Ne^{3+}/O plotted against log T_* (*boxes*) or Ex (*circles*). The value of Ne/O found from Ne^{2+}/O is indicated by an arrow. The size of the symbol is proportional to the weight of the point.

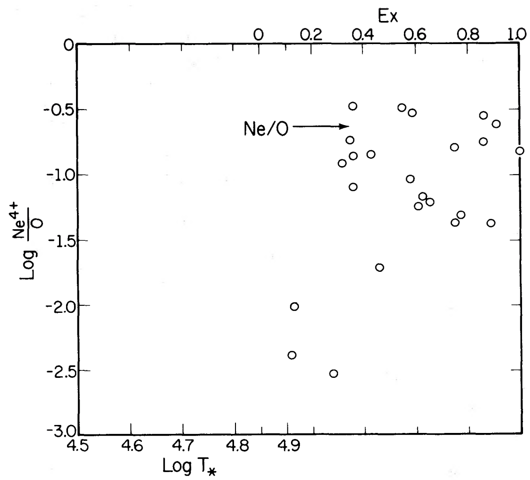

FIG. 6.—Log Ne^{4+}/O plotted against log T_* (*boxes*) or Ex (*circles*). Ne/O from Ne^{2+} is indicated by an arrow.

latter approximation underestimates Ne/O. The approximation is good to better than 10% for higher-excitation nebulae, but it can be severely in error for lower-excitation objects (log $T_* < 4.6$).

b) Ne^{3+} *and* Ne^{4+}

Figures 5 and 6 show ionization curves for Ne^{3+} (derived from λλ4724, 4725 [Ne IV]) and Ne^{4+} (from λλ3345, 3425 [Ne V]). Both curves show the characteristic rise to a peak, then a fall. The value of Ex (peak) becomes progressively higher as the ionization stage of neon increases. The value of Ne/O derived above is indicated on both graphs. The mean curves should stay below this level. If Ne/O is found from $Ne^{2+} + Ne^{3+} + Ne^{4+}$ (which in principle it could be), the resulting mean value of Ne/O derived is higher, between 0.35 and 0.40. Note, however, the large scatter of the points. The [Ne IV] lines are quite weak, and the Ne^{3+} abundance is very sensitive to T_e. These auroral lines increase in strength by a factor of 20 between $T_e = 10000$ and 15000 K. This ion and especially Ne^{4+} have high ionization potentials and are formed in regions different from O^{2+}, so that the electron temperature used in the calculations may not be applicable. It seems best to ignore the results for Ne^{3+} altogether. If we combine the results of Figures 2 and 6 at, say, Ex = 0.8, and assume that $\langle Ne^{3+}/O\rangle = \frac{1}{2}(\langle Ne^{2+}/O\rangle + \langle Ne^{4+}/O\rangle)$, Ne/O ≈ 0.28. Given the uncertainty of the data and possible temperature effects, this figure should be regarded as a confirming result.

IV. ARGON

a) *General Remarks*

Argon can be treated similarly to neon, yet it presents a rather different set of problems. First, we can deal effectively with two or even three ions instead of one: Ar^{2+}, through the λ7135, λ5191 [Ar III] lines, Ar^{3+} through the λ4740 [Ar IV] line, and Ar^{4+} through λ7005 [Ar V]. These lines are considerably weaker than the λ3868 [Ne III] line, so that errors are correspondingly higher. The problem of error is compounded by the fact that, of the nebulae for which both [Ar III] and [Ar IV] lines are measured, we must rely on auroral (λ5191 [Ar III]) line measurements for about one-third. This line is quite weak, and the abundance derived is more sensitive to T_e than that derived from the nebular line. The dependence is nowhere nearly as great as it is for the [Ne IV] auroral line, however, since the excitation potentials of the ^2P and ^2D states of Ar^{2+} are half those for Ne^{3+}. Consequently, we should be able to rely on auroral [Ar III], even though we apparently cannot on [Ne IV].

b) *Electron Temperatures from* [Ar III]

For 13 nebulae plus the Orion Nebula there is sufficient information to derive the electron temperature from the [Ar III] lines. These temperatures, derived from the formula given by Kaler *et al.* (1976, hereafter KACE), are given in column (2) of Table 2,

TABLE 2

ELECTRON TEMPERATURES FROM [Ar III]

	$10^{-3}T_e$ (K)		
NEBULA	[Ar III]	[O III]	[N II]
NGC:			
2392......	13.8	14.2*	13.7
2440......	13.1	13.0	8.6
3242......	12.7*	11.3	12.5
6543......	8.3	8.1	...
6572......	11.9	10.5	13.0
6826......	10.5	9.7	8.4
7009......	11.9	10.4	8.3
7027......	11.3	11.7	...
7662......	14.8	12.9	...
IC:			
418......	10.1*	9.6	8.1
2003......	17.8	11.9	16.3
2165......	16.4	13.4	8.3
4997......	27.4	26.3	19.5
Orion.......	14.2	9.5	9.3

* Note limiting values on Fig. 7.

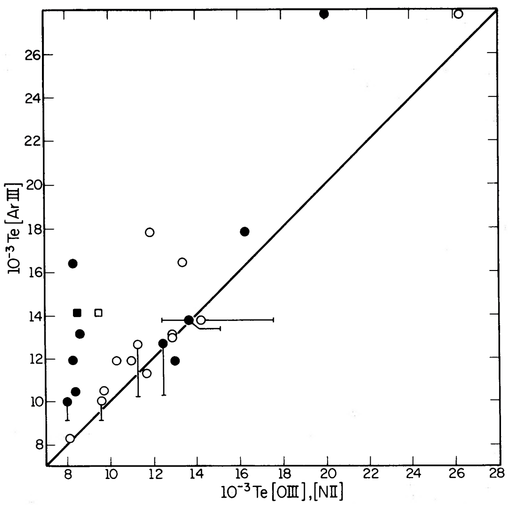

FIG. 7.—$10^{-3}T_e$ from [Ar III] plotted against $10^{-3}T_e$ from [O III] (*open circles*) and $10^{-3}T_e$ from [N II] (*filled circles*). The Orion Nebula is represented by boxes. The solid line is the 1:1 line.

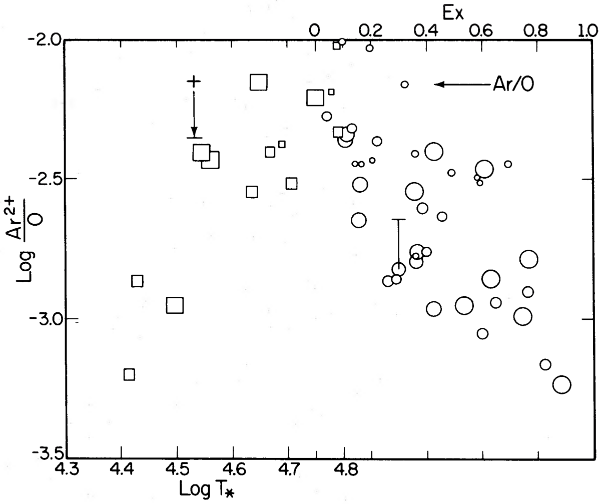

FIG. 8.—Log Ar^{2+}/O plotted against log T_* (*boxes*) or Ex (*circles*). The Orion Nebula is shown by a cross; the lower limit is from the more accurate nebular line. The final Ar/O is shown by an arrow.

together with the [O III] and [N II] temperatures in columns (3) and (4) for comparison. The temperatures are presented graphically in Figure 7, where T_e[Ar III] is plotted against T_e[O III] (*open circles*) and T_e[N II] (*filled circles*). The Orion Nebula points are shown by boxes. The [Ar III] temperatures agree better with T_e[O III] than with T_e[N II], and with a few exceptions, the agreement is quite good, especially considering the weakness of the [Ar III] auroral line and the fact that the auroral and nebular lines are usually measured by different observers.

Because [Ar III] temperatures are not available for all the nebulae considered, and because of the good general agreement between [O III] and [Ar III], the [O III] temperatures are used in all subsequent calculations.

c) Abundances of Ar *from* Ar^{2+}, Ar^{3+}, *and* Ar^{4+}

The ionization curves for Ar^{2+}, Ar^{3+}, and Ar^{4+} are shown in Figures 8, 9, and 10. The Ar^{2+} abundances were derived from both the auroral and nebular lines, with the nebular lines given double weight. Ar^{3+} is the abundance as derived from SS. As was the case with neon, the three ionization curves are complementary, with the peak of the curve shifting to higher log T_*/Ex as the ionization stage increases. As Ar^{2+} drops, Ar^{3+} increases, and as Ar^{3+} drops, Ar^{4+} increases. Since there are so few data for Ar^{4+} and since Ar^{4+}/O is uncertain, Ar^{2+} and Ar^{3+} will first be treated together; Ar^{4+} will be added later for confirmation.

The curve for the sum of the two ions, $Ar^{2+}/O + Ar^{3+}/O = Ar^{2,3+}/O$, is shown in Figure 11. Note here now that the peak of the curve is much flatter, although we can still see the rise at low T_* resulting from ionization of Ar^+ to Ar^{2+}, and the fall at high He^{2+}/H^+ from Ar^{3+} ionization to Ar^{4+}. This curve is analyzed by the same method employed for Ne^{2+} in § III*a*. The abundance of $Ar^{2,3+}$ is at a maximum for nebulae with log $T_* > 4.75$, but with Ex < 0.25, a region which includes nine nebulae.

The relevant abundance data are presented in Table 3, where the columns give: (1) nebula; (2) log T_*/Ex; (3) T_e[O III]; (4) Ar^{2+}/O; (5) Ar^{3+}/O; and (6) Ar^{4+}/O. No correction for the ER *p*-wave approximation is yet applied. The values for $Ar^{2,3+}/O$ for the nine nebulae at the peak of Figure 9 are given in column (7) with an estimate of the weight in parentheses. The weighted

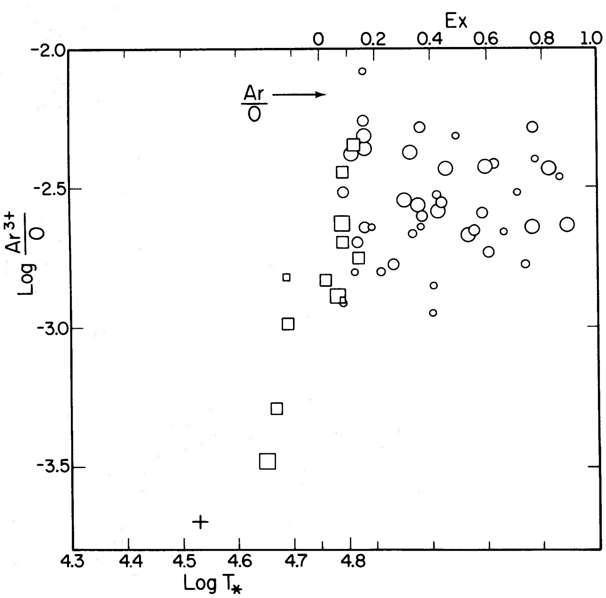

FIG. 9.—Log Ar^{3+}/O plotted against log T_* (*boxes*) or Ex (*circles*). The Orion Nebula is shown by a cross. The final Ar/O is shown by an arrow.

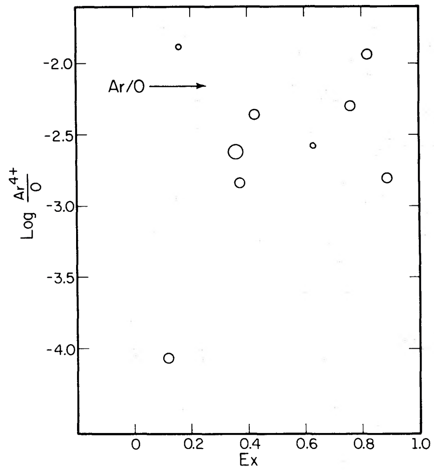

FIG. 10.—Log Ar^{4+}/O plotted against Ex. The final Ar/O is shown by an arrow.

mean, given at the bottom of column (7), is 6.96 ± 0.43×10^{-3}.

The $Ar/Ar^{2,3+}$ correction is somewhat uncertain. It will be small, since two ions are considered. Little Ar will be in Ar^{4+}, as is evident from Figure 10. The span in ionization potentials from Ar^{2+} to Ar^{4+} is reasonably similar to that for Ne^{2+} and O^{2+}, so that the O/O^{2+} correction is assumed. Thus, from the Table 3 data, $Ar/O = \langle(Ar^{2,3+}/O)\rangle/\langle(O^{2+}/O)\rangle = 6.96 \times 10^{-3}/0.926 = 7.52 \pm 0.47 \times 10^{-3}$. The error for the ratio from a single nebula is ±17%, which can clearly be accounted for by observational scatter. There is no change if the nebulae are restricted to the temperature range 9000 K < T_e < 12000 K.

The Orion Nebula is denoted by a cross in Figures 8, 9, and 11. The lower end of the bar is the value from the more reliable nebular line. The fit onto the curves

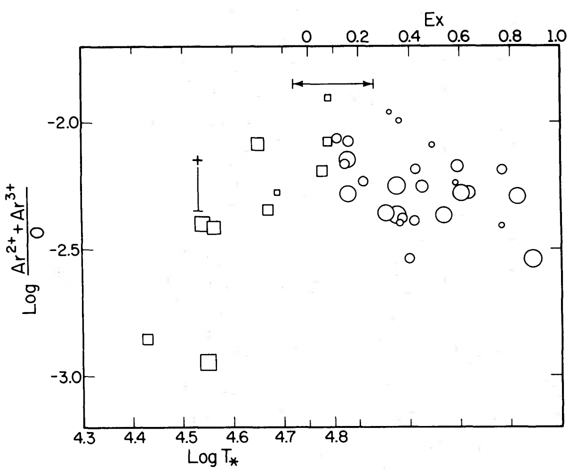

FIG. 11.—Log $(Ar^{2+} + Ar^{3+})/O$ plotted against log T^* (*boxes*) or Ex (*circles*). The Orion Nebula is shown by a cross; the lower limit uses the nebular line of Ar^{2+}. The horizontal bar shows the region for which averages were taken.

is satisfactory, implying that the Ar/O derived from planetaries is similar to that of the galactic disk.

The Ar^{3+} abundances are calculated with the tables of SS. If they are recalculated with the tables of Czyzak, Krueger, and Aller (1970), Ar/O is increased by 6%. The average of the two then yields $Ar/O = 7.74 \pm 0.44 \times 10^{-3}$. If now the target areas for Ar^{2+} and Ar^{3+} are increased for the ER *p*-wave approximation, according to § II*c*, Ar/O is decreased to 7.0 ± 0.5×10^{-3}. For comparison, Aller (1976) finds $Ar/O = 4.7 \times 10^{-3}$. From the discrepancy between the approximations used for the target areas, the external error imposed by them is probably of the order of ±10%.

The [Ar V] lines, from which Ar^{4+}/O is derived, give some confirmation to the above figure, although there is some evidence that the atomic data for Ar^{4+} may be in error (see § V). The sum of the three ions should give the best results, but there are problems with using Ar^{4+}. The electron temperature appropriate to it is not really known. More important, it exists only in nebulae where there is considerable O^{3+}. Equation (1) for O^{3+} is probably accurate as long as He^{2+}/He^+ is small, but its accuracy is uncertain when $He^{2+} \approx He^+$. Therefore O/H is not well known for these objects. Nevertheless,

$$\sum_{n=2}^{4} Ar^{n+}/O$$

is presented in column (8) of Table 3, and averaged at the bottom. NGC 3587 is excluded, as Ar^{4+} is anomalously high, probably due to observational error. He^{2+}/He^+ is shown in column (9). Values of Ar^{4+}/O are used only when $He^{2+}/He^+ < 1$. We are now left with only four nebulae (NGC 2440, 3918, 7009, and 7027) whose weighted mean gives $Ar/O = 7.89 \pm 0.87 \times 10^{-3}$. Since three ionization stages are considered,

$$Ar\Big/\sum Ar^{n+} = 1\,.$$

The agreement between the two values helps confirm the method, and the correction from $Ar^{2,3+}$ to the total Ar/O.

d) *An Ionization Problem*

From § III we saw that approximately 93% of the O could be in the O^{2+} state. However, examination of Figures 8 and 9 with respect to total Ar/O (denoted by an arrow) shows that only about half of the Ar can be in either the Ar^{2+} or Ar^{3+} state. We might expect that O^{2+} and Ar^{3+} would behave similarly, since their ionization potentials are not very different, and the spans (that is, ionization potential [I.P.] for O^{3+} minus I.P. for O^{2+}) are the same, yet they behave quite differently. The lower and upper ionization potentials for Ne^{2+} are actually closer to those for Ar^{3+} than they are to those of O^{2+}. The question then arises as to which ratio, O/O^{2+} or Ar/Ar^{3+}, is more appropriate to Ne/Ne^{2+}. Evidence comes from the

TABLE 3

Ar AND Cl^{+++}

Nebula (1)	log T_*/Ex (2)	10^3 T_e (3)	10^3 Ar^{2+}/O (4)	10^3 Ar^{3+}/O (5)	10^3 Ar^{4+}/O (6)	10^3 $Ar^{2,3+}/O$ (7)	(wt)	$\Sigma Ar^{n+}/O$ (8)	He^{2+}/He^+ (9)	10^3 $Cl^{3+}(A)/O$ (10)	10^3 $Cl^{3+}(N)/O$ (11)	$Ar^{3+}/Cl^{3+}(A)$ (12)	$Ar^{3+}/Cl^{3+}(N)$ (13)
NGC:													
1535......	0.16	13.5	2.26	4.81	...	7.07	(3)	...	...	...	...	...	...
2022......	0.89	15.5	0.59	2.31	1.59	...		4.49	8.5	...	...	...	...
2392......	0.63	14.2	1.36	3.88	2.64	...		7.88	1.6	...	...	...	...
2440......	0.43	13.0	3.96	2.59	4.34	...		10.89 (1)	0.74	3.13	...	0.83	...
2610......	0.77	16.8	1.27	5.23	5.02	...		11.52	3.4	...	...	...	...
3587......	0.16	11.1	2.97	2.26	12.7	5.23	(3)	...	0.20	...	...	...	...
3918......	0.37	11.8	1.71	2.47	1.46	...		5.64 (2)	0.60	...	...	...	...
4361......	0.83	19.8	0.78	4.92	11.5	...		17.2	4.9	...	...	...	...
5882......	4.79	9.3	4.75	3.60	...	8.35	(2)	...	...	...	...	...	...
6572......	4.78	10.5	5.11	1.31	...	6.42	(2)	...	...	...	...	...	...
6720......	0.22	11.5	4.30	1.56	...	5.86	(2)	...	...	...	...	...	...
6741......	0.32	11.1	...	...	...	...		...	...	1.43	...	3.08	...
6818......	0.58	14.1	...	...	...	...		...	...	2.08	...	1.56	...
6884......	0.14	10.9	3.52	3.33	...	6.85	(2)	...	...	3.02	...	1.10	...
7009......	0.12	10.4	4.43	4.27	0.086	8.71	(2)	8.79 (2)	0.13	2.27	0.857	1.88	4.98
7027......	0.35	11.7	2.96	2.64	2.41	...		8.01 (3)	0.54	2.73	0.565	1.01	4.67
7662......	0.46	12.9	...	...	...	...		...	...	2.37	1.33	1.56	2.78
IC:													
2003......	0.47	11.6	...	...	...	...	...	...	...	3.93	...	0.69	...
2165......	0.36	13.5	...	...	...	...		...	...	2.45	...	1.10	...
3568......	4.79	10.8	10.1	2.44	...	12.5	(0)	...	...	...	...	...	...
5217......	0.13	11.2	3.64	4.35	...	7.99	(2)	...	...	...	...	...	...
Hu 1-2......	0.59	19.4	...	...	...	...		...	...	2.75	...	1.34	...
Means..........						6.96 ± 0.43		7.89 ± 0.87		2.26 ± 0.21	0.92 ± 0.22	1.42 ± 0.22	4.14 ± 0.69

ionization curves. Note from Figures 1 and 2 that Ne^{2+}/O and O^{2+}/O both rise very quickly as T_* increases, implying rapid conversion of the singly ionized state to the doubly ionized state. Oxygen then stays at above 90% O^{2+} for a considerable range of T_* before O^{3+} begins to be formed at somewhat under $T_* = 60000$ K. Neon is even more stable in the Ne^{2+} state (over a wide range of T_*) than O is in the O^{2+} state. It appears from Figure 2 that Ne^+ is nearly all ionized to Ne^{2+} at $T_* = 40000$ K, and Ne^{3+} does not really become significant until $T_* = 63000$ K. Note that neither Ar^{2+} nor Ar^{3+} (Figs. 8 and 9) behaves in this fashion. Ar^{3+}/O peaks at Ex ~ 0.3 (whereas Ne^{2+}/O peaks below the formation of He^{2+}), and no stable plateau is evident. The fact that Ne^{2+}/O behaves so much more like O^{2+}/O than it does like Ar^{3+}/O implies that the oxygen-derived correction factor of 1.08 is indeed appropriate.

V. CHLORINE

a) Cl^{2+}/O *and* Cl/Ar *from* [Cl III]

Two ionization stages, Cl^{2+} and Cl^{3+} (from [Cl III] and [Cl IV]), are observed for chlorine, and we would expect to be able to proceed with the calculation of Cl/O much as we did for Ar/O. However, it will be shown in § V*b* that the [Cl IV] lines give anomalous results, and that the true Cl^{3+}/O cannot be derived. Consequently, only Cl^{2+} is available for analysis. As pointed out in the last section, only about half of the Ar can at any time be in either Ar^{2+} or Ar^{3+}. The close similarity of ionization potentials of Ar and Cl suggests that very much the same would be true for Cl, thus meaning that a large correction would be required to go from Cl^{2+}/O to Cl/O.

The ionization curve for Cl^{2+} (from SS) is shown in Figure 12. Note that the slope of the linear part of the curve (above $\log T_* = 4.6$) is very similar to that of Ar^{2+}/O in Figure 8. Over this entire range of excitation the two curves are within a few percent of one another. This similarity in ionization is consistent with the close similarity of ionization potentials. It seems very likely, then, that the Cl/Cl^{2+} ratio should be nearly the same as the Ar/Ar^{2+} ratio, so that instead of directly deriving Cl/O, we can find Ar/Cl, which should be equal to Ar^{2+}/Cl^{2+} to a few percent (assuming no scatter in the observed intensities).

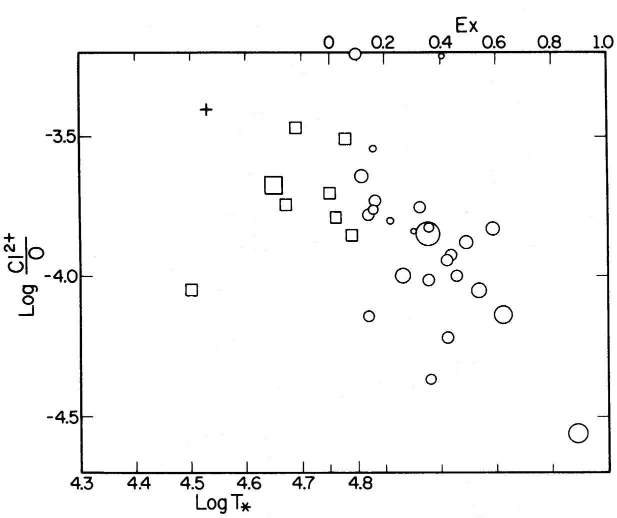

FIG. 12.—Log Cl^{2+}/O plotted against $\log T_*$ (*boxes*) or Ex (*circles*). The Orion Nebula is shown by a cross.

The values of Ar/Cl = Ar^{2+}/Cl^{2+} (without the ER correction) derived for 27 planetaries are presented in column (7) of Table 1. The relative weight or reliability of the measurement (from a subjective judgment of the data) is given in parentheses. The weighted mean value of Ar/Cl is 20.1 ± 1.9 (m.e.). The error for an individual point is ± 38%, not inconsistent with the probable errors of these weak line intensities.

The Cl^{2+} and Ar^{2+} data sometimes come from different observers. As a check, Ar/Cl was recalculated in the case where both ions were observed by only one observer; the result is Ar/Cl (from SS) = 23 ± 1.4. The data come entirely from TPP, KACE, and Aller and Walker (1970); three-quarters of the data come from the last, who did not observe the nebular line of [Ar III]. The average presented in Table 1 is probably the more reliable, since it makes greater use of the much more accurately observable [Ar III] nebular line.

The Ar/Cl ratio for Orion is 17.4 if all data are used, 11.3 if [Ar III] nebular is used, and 21.9 if only Aller and Walker (1970) data are used. The Orion result is clearly very similar to that for the planetaries.

An average with those values calculated from Aller *et al.* (1970) gives Ar/Cl = 18.4 ± 2.0. If the ER correction is now applied to the above ratio (8% increase for Ar^{2+}, 25% for Cl^{2+}), the final value for Ar/Cl = 21.3 ± 2.3. With Ar/O = 7.0×10^{-3}, Cl/O = $3.3 \pm 0.5 \times 10^{-4}$. This value is recommended. Given the comparison between the DW and ER approximations, Cl/O may be uncertain by as much as ± 25%.

If the *s*-process was active in the star before the ejection of the planetary, the Ar/Cl ratio could be decreased (Truran and Iben 1977). If Ar/Cl is altered by processed matter brought to the surface, then we would expect it to correlate with N/O or He/H, since nitrogen and helium are commonly enriched by stellar processes in nebulae (see § I). Plots of Ar/Cl against N/O and He/H, where the latter are taken from Kaler (1978*b*, *c*), show no such correlation. It is therefore concluded that the initial Ar and Cl abundances have not been changed by the star, and that the Ar/Cl and Cl/O derived here are the correct galactic values.

b) Cl^{3+} *from* [Cl IV]

The [Cl IV] lines are reasonably well represented in planetaries. The auroral line is observed in 11 objects, and the nebular line in three of these. The value of Cl^{3+}/O derived from auroral (A) and nebular (N) transitions are given in columns (10) and (11) of Table 3. From Figure 9 we see that Ar/Ar^{3+}, and thus $Cl/Cl^{3+} \approx 2$. If this correction is applied to column (10) of Table 3, Cl/O from Cl^{3+} is about 10 times

TABLE 4

ABUNDANCE SUMMARY

Ratio (1)	Nebulae*: This Paper (2)	Solar: Ross and Aller (1976) (3)	Solar: Withbroe (1976) (4)	Solar System: Cameron (1973)† (5)	Other Observed (6)	Nucleosynthesis Calculations: O-burn TA‡ (7)	Nucleosynthesis Calculations: O-Si-burn WAC‡ (8)	Nucleosynthesis Calculations: C-burn Arnett (1969) (9)
Ne/O	0.225 ± 0.01	0.054 ± 0.018	0.058	0.16	0.21 (+0.10, −0.5)[a]	...	...	0.16
					0.16 ± 0.03[b]	...	...	...
10^3 Ar/O	7.0 ± 0.5	1.45 (+0.9, −0.6)	2.24	5.5	...	8.4	8.2	...
Ne/Ar	32 ± 3	37	26	29.4	27.6[c]	...	...	20§
					24.1[d]	...	...	...
Ar/Cl	21.3 ± 2.3	3.2	4.9	20.6[e]	...	65	105	...
				17.9[f]	...	...	...	...
10^4 Cl/O	3.3 ± 0.5	4.6 (+6.9, −2.8)	4.6	2.65[e]	1.8 (+2, −1)[g]	1.3	0.78	...
					4.6 (+6.9, −2.8)[h]	...	...	...

* Errors quoted are internal mean errors. Estimates of errors imposed by uncertainty in Ω from DW–ER comparison are Ar/O, ±10%; Ne/Ar, ±10%, Ar/Cl, ±25%; Cl/O, ±25%.

† Values of Ar found by interpolation between Si and Ca.

‡ Authors give ratios to Si; Ar and Cl related to O through Si/O given by Ross and Aller 1976 and Withbroe 1976.

§ Derived from Ne/O from Arnett 1969 and the mean Ar/O of TA and WAC.

REFERENCES.—[a] Solar corona; Acton, Catura, and Joki 1975. [b] Solar flare cosmic rays; Bertsch, Fichtel, and Reames 1972, used by Cameron 1973. [c] Three gas-rich meteorites; Marti, Wilkening, and Suess 1972. [d] Average of all meteorite values, same references as above. [e] Cl from Goles, Greenland, and Jerome 1967, from meteorites. [f] Cl from semi-equilibrium prediction by Cameron 1973. [g] Cl/H from B stars (Bruhweiler 1977), compared with O/H (Ross and Aller 1976; Withbroe 1976). [h] Molecular sunspot spectra; Hall and Noyes 1972, used in "solar" above.

higher than that derived from Cl^{2+}, and is higher than Cl/O derived from other sources (see § VI). Cl/O derived from column (11) is a factor of 4 too high. The ratio Ar^{3+}/Cl^{3+} is shown in columns (12) and (13) and is much smaller than Ar^{2+}/Cl^{2+}. By another approach, we can derive electron temperatures for these three nebulae, where we use the formulation in KACE, and find 16100 K, 35000 K (see the above reference), and 17000 K, respectively, well above the [O III] values. The [Cl IV] lines give higher estimates of Cl/O than do the [Cl III] lines. The [Cl III] results are adopted because (1) they give better agreement with other observations, and (2) the auroral and nebular [Cl IV] lines themselves give very discordant results. The problem may be due either to blends or to inaccurate atomic data. Since both the auroral and nebular lines give high results, it seems likely that the atomic data are in error.

As one further interesting piece of information, KACE find $T_e = 21600$ K from [Ar V] for NGC 7027, far above the [O III] value of 11200 K. Since the [Cl IV] and [Ar V] lines come from ions on the same isoelectronic sequence, some doubt is cast on [Ar V]. The evidence indicates that the atomic data for the heavier $3p^2$ ions may be in error. (Note that T_e from [S III] from KACE appears to be a good value.)

VI. SUMMARY AND COMPARISONS

a) Summary of Measurements

A summary of the various ratios involving Ne, Ar, and Cl is given in Table 4. Column (1) gives the ratio, and column (2) gives the adopted measurement with its error. The errors are formal mean errors of the mean, and do not include any systematic effects which may be present, such as those introduced by temperature fluctuations, by errors in collision strengths, or by unrecognized ionization effects. The internal precision of the measurements is high, and for argon and chlorine the abundances may be the best available galactic values.

Other observational conclusions are as follows:

1. The [Ne IV] lines give poor results for Ne^{3+} and should not be used except in models where small T_e variations can be taken into account.
2. Electron temperatures from [Ar III] are in substantial agreement with those from [O III]; the agreement is better than with T_e[N II].
3. The [Cl IV] lines (in the $3p^2$ isoelectronic sequence) cannot be interpreted accurately in terms of Cl^{3+}, perhaps because of inadequate atomic data. [Ar V] may also be affected.
4. The ionization of Ar^{3+} is inconsistent with that of O^{2+} (and, it is assumed, also of Ne^{2+}) in that Ar cannot be fully ionized to Ar^{3+}.
5. O^{2+}/O (and possibly Ne^{2+}/O) is correlated with O/H, showing an ionization effect to be present. This ionization effect will produce an unevaluated systematic error in Ne/O (which is expected to be small) which limits the ultimate accuracy of the method.

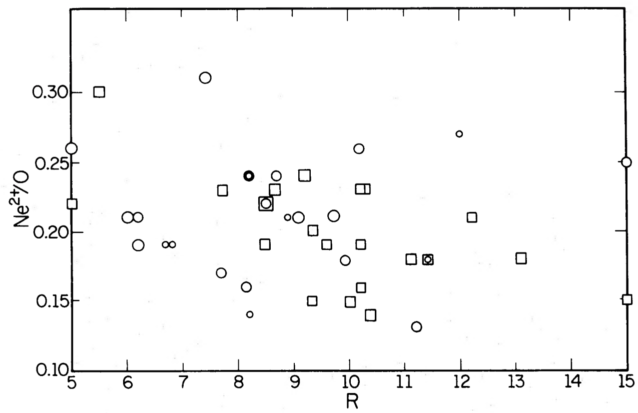

FIG. 13.—Ne^{2+}/O for the two groups of Table 1 plotted against R, the distance of the nebula from the galactic center. Groups 1 and 2 are indicated by circles and boxes, respectively.

b) Variations among Nebulae

Both Ne^{2+}/O and Ar/Cl were plotted against distance from the galactic center projected onto the plane, R, and against distance from the galactic plane. No correlations can be seen, except for the low Ne/O of Ha 4-1 which is very far from the galactic plane. Figure 13 shows Ne^{2+}/O for both groups plotted against R. Any systematic variation of Ne^{2+}/O versus O/H, if present at all, is probably an ionization effect. As mentioned in § V, Ar/Cl shows no variation with O/H. The variation in Ne^{2+}/O, $Ar^{2,3+}/O$, Ar/Cl among nebulae can be accounted for by observational scatter. Any true variation is lost within this scatter.

c) Comparison to Other Results

Columns (3) through (6) of Table 4 give other values of the ratios of Ne, Ar, and Cl for comparison with the nebular measurements. Columns (3) and (4) give solar ratios, taken from the compilations of Ross and Aller (1976) and Withbroe (1976). Column (5) gives solar system abundances as compiled by Cameron (1973), which include meteorite data. Column (6) presents a sampling of recent measurements.

The Ne/O and Ar/O of the two solar compilations are down by a factor of 4 from the nebular measurements; the solar and nebular Ne/Ar are in good agreement, however. Ne and Ar are difficult to analyze in the Sun, and there is a wide range of values among various observers. The most recent result for Ne/O, by Acton, Catura, and Joki (1975), is very close to the nebular result. The solar-nebular comparison for Cl is very satisfactory.

The nebular ratios compare well with Cameron's (1973) solar system compilation (some of these values include the measurements given in col. [6]). Note that the nebular Ne/Ar ratio is very close to that derived from meteorites (see col. [6]). The nebular Ar/Cl is close to Cameron's (1973) estimate. The Cl/O is also close to the Cl derived from meteorites and falls between the solar measurement and that derived from Bruhweiler's (1977) measurement of Cl/H in B stars.

d) *Comparison to Theoretical Predictions of Explosive Nucleosynthesis*

Columns (7) and (8) of Table 4 contain theoretical ratios of the elements predicted on the basis of explosive oxygen burning (TA) and explosive oxygen/silicon burning (WAC). These references give Ar/Cl directly, and the ratios of both these elements to silicon. The Ar/O and Cl/O ratios presented in Table 4, columns (7) and (8), come from their Ar/Si, Cl/Si multiplied by the solar Si/O ratio given by Ross and Aller (1976) and Withbroe (1976). The Ar/Cl calculations have physical significance and can be compared with the planetary observations. TA and WAC underestimate Cl by factors of about 3 and 5, respectively, but in this kind of calculation that could be considered agreement. The Ar/O and Cl/O calculations in columns (7) and (8) are not as significant, since stars formed from matter mixed with explosive products would not be expected to have these ratios. Nevertheless, note the agreement. Note also that Cameron's (1973) theoretical prediction of 17.9, in which Ar was found by interpolation between Si and Ca and Cl was produced by a semi-equilibrium calculation, agrees reasonably well with the observed value. The Ne deficiency of Ha 4-1 is also consistent with the explosive origin of neon, since this object probably represents an earlier stage of galactic evolution.

Column (9) contains a prediction of Ne/O which results from Arnett's (1969) calculations of explosive carbon burning, which is close to the observed value. A predicted value for Ne/Ar is derived by comparing Arnett's (1969) Ne/O with TA's and WAC's Ar/O. Although this prediction may have limited physical meaning, the result is remarkably close to that observed from nebular and solar sources.

VII. CONCLUSIONS

Mean neon, argon, and chlorine to oxygen ratios have been calculated for galactic planetary nebulae. Except for one halo planetary, there is no evidence for variation involving ratios of these elements.

The nebular ratios of these elements are consistent with (1) solar and solar system ratios, (2) ionic abundances in galactic diffuse nebulae, and (3) predictions from explosive nucleosynthesis. This consistency and the lack of variation implies that the Ne, Ar, and Cl to O ratios found in planetaries are the same as the original stellar ratios, and are typical of local galactic, or solar, abundances. The term "local galactic" in this context means the disk within a few kiloparsecs of the Sun and the inner halo. The majority of planetaries discussed here range from about 6 to 12 kpc from the galactic center and up to about 2 kpc from the galactic plane, although three-quarters of them are within 1 kpc. The values presented in this paper seem generally more accurate than values derived from most other sources, and should be used in galactic or cosmic abundance compilations. They are probably more typical of true solar abundances than are the more difficult solar measures themselves.

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