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[S II] IN NEBULAR SPECTRA, AND RELATIVE SULFUR-TO-OXYGEN RATIOS

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ABSTRACT

The relationships between the intensities of the λ6723 [S II] line and those of λ3727 [O II], λ6300 [O I], and λ6312 [S III] are examined for both planetary nebulae and diffuse nebulae in the Galaxy, the Magellanic Clouds, M101, and M33, and for supernova remnants in the Galaxy and M33.

The [S II]–[O II] relation in planetaries shares the characteristics of the relations between [O I] and [O II], [N I] and [N II], and O^+ and N^+. First, the [S II] line strengths for planetaries with higher central star temperatures ($\log T_* \geq 4.65$), which are mostly optically thin, are linearly related to those of [O II] over a range of two orders of magnitude. Second, the [S II]/[O II] ratio for optically thick planetaries with $\log T_* < 4.65$, which contain neutral helium, is negatively correlated with T_* in the same way as is N^+/O^+. For these objects the [S II]/[O II] ratio can be used to estimate effective blackbody central star temperatures by the relation $\log T_* = 4.325 - 0.147 \log [I(\lambda 6723)/I(\lambda 3727)]$. The [S II]/[O II] line ratios are probably also suppressed in the low-T_* nebulae at least in part because of increased homogeneity, as already shown by the suppression of the [O I]/[O II] ratio. The [S II] line strengths in planetaries are similarly related to those of [O I], and are related to roughly the cube of those of [S III].

The relations suggest that for planetaries without neutral helium, $S^+/O^+ \propto S/O$, which provides support for the reliability of $N^+/O^+ = N/O$, and thus indicates that $N^+/S^+ \propto N/S$. These sulfur relations are also true for diffuse nebulae, providing that one makes some modifications for central star temperature, or for $I(\lambda 5007)$ [O III]/$I(\mathrm{H}\beta)$. Because of very different conditions, the average [S II]/[O II] intensity ratio for SNR is 2.5 times that for diffuse nebulae of comparable [O III] strength, although at low [O III] strength, [S II]/[O II] in diffuse nebulae can be comparable to that in SNR.

There seems to be no detectable vertical S/O gradient within the Galaxy, nor is there a detectable radial gradient. The data indicate that the previously reported low S/O ratio in the halo planetary Ha 4–1 may be a result of the above relation between S^+/O^+ and T_*. The S/O ratio in the Magellanic Clouds and M33 is the same as that found in the Galaxy to within about ±10%, and in M101 to within about ±25%. There is no unambiguous evidence that S/O is anything but constant among the objects studied. This constancy allows the N/S ratio, and thus the N^+/S^+ ratio, to be a good indicator of N/O.

Subject headings: galaxies: Magellanic Clouds — nebulae: abundances — nebulae: planetary— nebulae: supernova remnants

I. INTRODUCTION

The behavior of the ionization of sulfur and of the S/O ratio is still in a state of some confusion. The problem in abundance work has been to allow for the S^{3+} and higher ionization states which are not optically detectable. The lack of information on higher ionization states has been alleviated in part by observation of the 10.51 μm [S IV] line by Dinerstein (1980*a*, *b*) and by Lester, Dinerstein, and Rank (1979*a*, *b*). However, for higher excitation nebulae a significant and unknown amount of sulfur can still be in S^{4+} and higher states, and total S/H or S/O is known for only a relatively small number of nebulae. In order to account for the unobserved ionization states, some authors use $S/O = (S^+ + S^{2+})/O^+$ (see Peimbert and Costero 1969), whereas others use $S/O = S^+/O^+$. Some, such as Sivan (1976), adopt $N/S = N^+/S^+$, whereas Hawley (1978*a*) and Hawley and Grandi (1977) claim that this relation is not correct. By using ionization models and comparisons with observations, Natta, Panagia, and Preite-Martinez (1980) suggest that $S^{3+}/S^{2+} = 0.10\ O^{2+}/O^+$ is a more accurate relation.

From these various relations, a variety of conclusions have been drawn. Barker (1978*a*) finds no correlation between S/H in 20 planetaries and their kinematical properties and states that they have "essentially solar S abundances." With infrared [S IV] observations, Dinerstein (1980*a*, *b*) also suggests constant S/H. Talent and Dufour (1979) find little evidence for a radial Galactic S/H gradient, and suggest an S/O gradient. Smith (1975) and Shields and Searle (1978), however, find no evidence of such an S/O gradient in other galaxies. There is no evidence for variation in S/O among galaxies. Dufour and Harlow (1977*a*) show that S/O in the Large and Small Magellanic Clouds are "essentially identical" and are similar to that in the Galaxy. Pagel *et al.* (1978) indicate that S/O in the Clouds is "identical to what they are in Orion." Measurements of supernova remnants (SNR) by Dopita, D'Odorico, and Benvenuti (1980) show that S/O in M33 is the same as in the Sun. Natta, Panagia, and Preite-Martinez (1980) show that the mean S/H for a set of 41 planetaries is the same as that for Talent and Dufour's (1979) diffuse nebulae. However, the agreement in S/O between planetaries, diffuse nebulae, the Orion Nebula in particular, and the Sun is not always particularly good. Lester, Dinerstein, and Rank (1979*a*) find S/O = 0.055 in the Orion Nebula, and from Dinerstein (1980*a*, *b*) and Kaler (1980*b*), S/O for lower excitation planetaries equals 0.051. But the solar S/O from Lambert (1978) and Lambert and Luck (1978) equals 0.020, less than 2.5 times the nebular value. Finally, Natta, Panagia, and Preite-Martinez (1980) find that S/H in planetaries and in diffuse nebulae in general is significantly less than it is in Orion and in the Sun.

The correlations that can be found among the intensities of various nebular spectrum lines provide an especially simple means for the study of gaseous nebulae. There is now available in the literature a very large body of observations of spectral line intensities, which can supply data for a variety of such studies. As an example, Kaler (1980*a*) examined the relationships between the [O I] and [O II] and between the [N I] and [N II] lines observed in planetary nebulae. Relations involving [S II] can be similarly examined. The S^+ ion is particularly interesting in that it can be produced at photon energies less than that of the hydrogen Lyman limit, and so in some respects it may behave like neutral oxygen and nitrogen, and in others more like their singly-ionized states.

The generalizations made in the abundance studies cited above are often made within large errors, as much as a factor of 2, or are not quantitatively expressed. It is the purpose of this paper to provide a more detailed understanding of the behavior of [S II] and to use the [S II]/[O II] intensity ratio to improve significantly the error limits with regard to the variation of S/O. The lines of [S II] at λ6723 are strong and are extensively observed in both planetary and diffuse nebulae, the latter also in a variety of galaxies. The observational data are discussed in § II. The behavior of [S II] in planetaries and the S/O gradient perpendicular to the galactic plane are examined in § III. Diffuse nebulae, SNR, the radial Galactic gradient, and comparisons among galaxies are considered in § IV, and implications of this work regarding nitrogen abundances are discussed in § V. The relation between [S II] and [S III] is briefly taken up in § VI, and a summary is presented in § VII.

TABLE 1

DATA SOURCES

Planetary Nebulae
a) *Galactic*
[a]Aller and Czyzak (1979)
Aller, Czyzak, Craine, and Kaler (1973)
[a]Barker (1978*b*)
Czyzak and Aller (1979)
Czyzak, Aller, and Kaler (1971)
Czyzak, Buerger, and Aller (1975)
Hawley (1978*b*)
Hawley and Miller (1977; 1978*a*, *b*, *c*)
Kaler, Aller, Czyzak, and Epps (1976)
[a]Kondratyeva (1978, 1979)
Liebowitz (1975)
O'Dell (1963)
Peimbert and Torres-Peimbert (1971)
[a]Torres-Peimbert and Peimbert (1977, 1979)
Zipoy (1976)
b) *Magellanic Clouds*
Dufour and Killen (1977)
Aller, Keyes, Ross, and O'Mara (1980)
Supernova Remnants
a) *Galactic*
Davidson (1979)
Miller (1974)
[a]Dopita, D'Odorico, and Benvenuti (1980)
b) *M33*
[a]Dopita, D'Odorico, and Benvenuti (1980)
Diffuse Nebulae
a) *Galactic*
Aller and Liller (1959)
Danzinger (1974)
[a]Hawley (1978*a*)
Mendez (1967)
Peimbert and Costero (1969)
Peimbert and Torres-Peimbert (1977)
[a]Peimbert, Torres-Peimbert, and Rayo (1978)
[a]Talent and Dufour (1979)
b) *Magellanic Clouds*
Aller, Czyzak, Keyes, and Boeshaar (1974)
[a]Dufour (1975)
[a]Dufour and Harlow (1977*a*, *b*)
[a]Pagel, Edmunds, Fosbury, and Webster (1978)
Peimbert and Torres-Peimbert (1974, 1976)
c) *M101*
Hawley (1978*b*)
Shields and Searle (1978)
[a]Smith (1975)
d) *M33*
[a]Dopita, D'Odorico, and Benvenuti (1980)
Smith (1975)

[a]Major source.

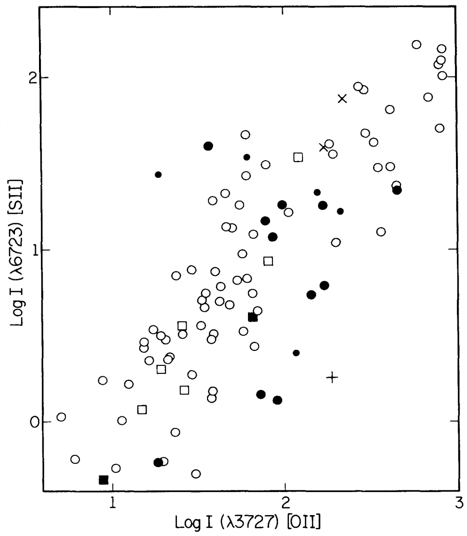

FIG. 1.—Log $I(\lambda6723)$[S II] plotted against log $I(\lambda3727)$[O II] for planetary nebulae. *Open symbols*, log $T_* \geq 4.65$ and $He^{2+}/He > 0$; *closed symbols*, log $T_* < 4.65$; *circles*, galactic planetaries; *boxes*, SMC; X's, LMC; *cross*, Ha 4–1.

II. THE OBSERVATIONAL DATA

The spectrum lines used in this study are the blended nebular [S II] and [O II] doublets at λ6723 and λ3727, respectively, the principal member of the nebular [O I] triplet at λ6300, and the auroral [S III] singlet at λ6312. The line intensities were taken from the references listed in Table 1. Nebulae in the Galaxy, the Magellanic Clouds, M101, and M33 were considered. The criterion for inclusion was that for any given comparison between two lines, both lines had to be observed in a given nebula by a given author, in order that stratification effects be avoided. All of the observations of diffuse nebulae and SNR were made photoelectrically, as were the large majority of those of planetaries. Corrections for interstellar reddening were taken either from the authors' papers, or from Kaler (1976*a*).

Multiple observations of nebulae are common. They may be made by a variety of observers, or by one observer who examines several regions within the object. In the results that are presented in the succeeding tables and figures, each nebula is treated as one data point; multiple observations are averaged to provide characteristic line ratios for that nebula. In the figures, the mean line strengths on the scale $I(H\beta) = 100$ are plotted against one another, which will introduce a small weighting error if stratification is severe. But mean line ratios for a particular kind of object [e.g., $\bar{r}(S)$ in planetaries, where $r(S) = I(\lambda6723)/I(\lambda3727)$], are the means of the averages of the multiple observations. No attempt has been made to weight the observations.

III. [S II] IN PLANETARY NEBULAE

a) *General Remarks*

The data relevant to planetary nebulae are plotted in Figures 1 through 6. Figure 1 presents log $I(\lambda6723)$ [S II] plotted against log $I(\lambda3727)$ [O II]. The nebulae are divided into two classes based upon central star temperature (T_*): those with log $T_* \geq 4.65$ (the majority of which are optically thin), and those with log $T_* < 4.65$, which contain a significant amount of neutral helium (Kaler 1978*a*). The values of T_* were taken or derived from the procedures of Kaler (1976*b*, 1978*b*). Magellanic Cloud planetaries and Ha 4–1 are indicated separately; see the caption to the figure. Nebulae are plotted without regard to density. The S^+ and O^+ ions have similar critical densities for ^4S–^2D collisional de-excitation, so that increasing density affects both ions in the same way (see Kaler 1980*a*). An empirical check also shows no density-dependent effects.

The high-T_* galactic nebulae define a nearly straight line where the log of the [S II] line strength is directly proportional to that of [O II] over a range of a factor of 100. The least-squares analysis for galactic planetaries is presented in the first row of Table 2, where column (1) gives the category of nebula, column (2) presents $\bar{r}(S)$, where again $r(S) = I(\lambda6723)$ [S II]/$I(\lambda3727)$ [O II], columns (3) and (4) show the standard deviation for an individual point and the mean error of the mean respectively, and column (5) gives the number of objects considered. Column (6) gives the correlation coefficient, and then columns (7) and (8) give the slopes for least-squares fits, where all the error is considered first to be all in the *y*-axis, then all in the *x*-axis. (Data for SMC planetaries are given separately in row 2.) The scatter in Figure 1 is too large to be due to observational error and must be largely intrinsic, so that the

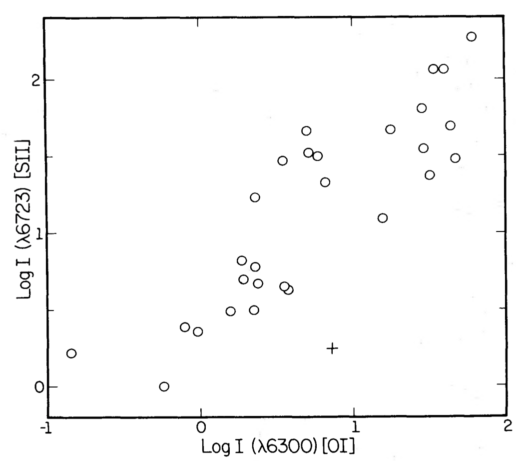

FIG. 2.—Log $I(\lambda6723)$[S II] plotted against log $I(\lambda6300)$[O I] for galactic planetary nebulae with log $T_* \geq 4.65$ and log $N_e < 3.8$. The cross represents Ha 4–1.

TABLE 2

INTENSITY RELATIONS FOR SULFUR LINES

A. [S II]–[O II] (1)	$\left\langle \frac{I(\lambda 6723)}{I(\lambda 3727)} \right\rangle^{a}$ (2)	Std. Dev. (3)	m.e. (4)	n (5)	Corr. Coef. (6)	Slope $\sigma_x = 0$ (7)	Slope $\sigma_y = 0$ (8)
Galactic planetaries							
$\log T_* \geq 4.65$	0.172	±0.128	±0.015	69	0.88	0.99	1.28
$4.40 \leq \log T_* < 4.65$ ...	0.083	±0.070	±0.022	10	0.70	1.13	2.29
SMC planetaries							
$\log T_* > 4.65$	0.134	±0.087	±0.035	6	...	...	...
Galactic diffuse							
All	0.152	±0.075	±0.015	25	0.59	0.82	2.37
$4.45 < \log T_* < 4.65$ ...	0.114	±0.032	±0.008	18	0.68	0.61	1.34
LMC[b] diffuse	0.102	±0.028	±0.008	13	0.87	0.92	1.22
SMC[b] diffuse..........	0.090	±0.031	±0.008	14	0.56	0.44	1.44
M101[b] diffuse	0.116	±0.036	±0.014	7	0.70	1.33	2.7
M33[b] diffuse	0.123	±0.039	±0.016	6	0.74	0.90	1.64
Galactic SNR	0.291	±0.067	±0.034	4	...	...	...
M33 SNR.............	0.301	±0.092	±0.027	12	...	...	...

B. [S II]–[O I]	$\left\langle \frac{I(\lambda 6723)}{I(\lambda 6300)} \right\rangle^{a}$	Std. Dev.	m.e.	n	Corr. Coef.	Slope $\sigma_x = 0$	Slope $\sigma_y = 0$
Galactic planetaries $\log T_* \geq 4.65$	3.69	±2.91	±0.55	28	0.87	0.80	1.06

[a] Mean of averages for individual nebulae.

[b] $4.45 < \log T_* < 4.65$, excluding the extreme low points for LMC and SMC.

true least-squares slope should fall roughly between the two extremes, or about 1.11. Thus over a factor of 100, $I(\lambda 6723)$ is directly proportional to $I(\lambda 3727)$ to within a factor of about 1.6, which implies the same manner of proportionality between S^+ and O^+, and a slope of 1 is within the allowable range. Further evidence below and in the next section implies that the slope is indeed close to 1.

Real deviations in r(S) from the mean are seen. For example, NGC 6720 and NGC 7293 are observed at six and eight points, respectively, by Hawley and Miller (1977) and Hawley (1978*b*). All points are consistently below the average of all nebulae, with mean r(S) for these two nebulae being 0.086 ± 0.016 and 0.018 ± 0.009, down by a factor of 2. It is possible that this reduction is an abundance effect, although in view of the final conclusions of this paper it seems unlikely. Clearly, it is necessary to understand fully the ionization of these nebulae, including effects of charge exchange.

Since the line strengths of [O I] and [O II] correlate linearly (Kaler 1980*a*), we would expect those of [S II] and [O I] to correlate as well. Figure 2 shows that indeed they do, where only the high-T_* group is shown. Since [O I] shows effects of collisional de-excitation only at high densities (see Kaler 1980*a*), the $I(\lambda 6300)/I(\lambda 6723)$ ratio is density-sensitive, so only nebulae with $\log N_e < 3.8$ are shown in Figure 2. The mean ratio and the data pertaining to the least-squares fit with [O I] are given in the last row of Table 2. Since λ6300 is weaker than λ6723, and is subject to larger error, the true slope is probably closer to that in column (7), and supports the linear relation between the strength of [S II] and that of [O II]. An average of all four slopes (from [O II] and [O I]) yields a mean slope of 1.03, which strengthens the concept of the overall linearity between S^+ and O^+.

b) *The Low-T_* Nebulae*

The low-T_* set of nebulae, those with neutral helium, are plotted as filled symbols in Figure 1. Those for which $\log T_*$ is estimated from $I(\lambda 5007)/I(H\beta)$ are indicated by half-size points. As a group, these nebulae show a much larger scatter than do the high-T_* nebulae, although a correlation is still evident. About half of the galactic objects show depressed [S II] strengths, while for three nebulae, [S II] is clearly enhanced. Two of these three, M1–67 and He 2–138, have the lowest values of $\log T_*$, which is <4.40 for both. M1–67 is of particular interest, as Pismis and Recillas-Cruz (1979) suggest from its velocity field that it may be a type of symmetrical H II region more associated with nebulae like NGC 6164-5.

This beha' is reminiscent of that of N^+/O^+ for low-T_* nebulae. Kaler (1979) showed that for low-T_* nebulae, N^+/O^+ is negatively correlated with $\log T_*$.

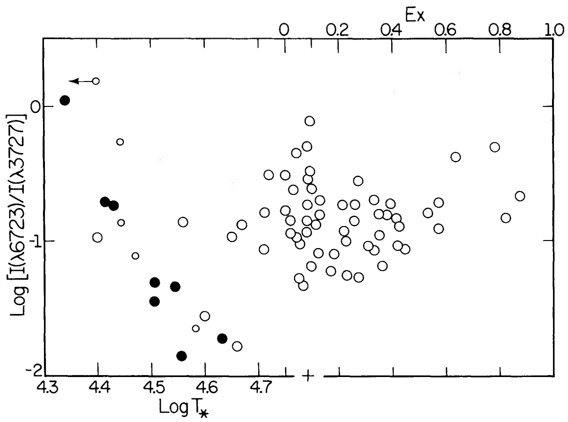

FIG. 3.—Log r(S) = log{I(λ6723)[S II]/I(λ3727)[O II]} plotted against log T_* or Ex = He^{2+}/He for galactic planetary nebulae. The cross represents Ha 4–1. The half-size circles indicate that log T_* was estimated from I(λ5007), and the filled circles show nebulae with the best determinations of T_*.

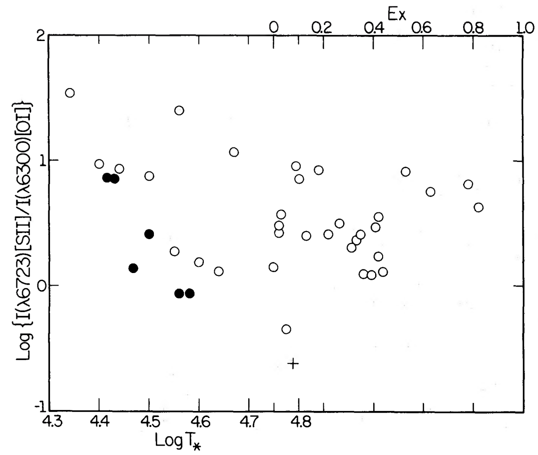

FIG. 4.—Log{I(λ6723)[S II]/I(λ6300)[O I]} plotted against log T_*, Ex = He^{2+}/He for galactic planetary nebulae. The cross represents Ha 4–1. The filled circles show nebulae with log N_e > 3.8.

Log r(S) is plotted in Figure 3 against log T_* and Ex = He^{2+}/He for galactic objects, the same way as for log N^+/O^+ in Kaler's (1979) Figure 2. A comparison between the two figures shows striking similarities. Values of r(S) also anticorrelate with log T_* for log T_* < 4.65. Both r(S) and N^+/O^+ show little correlation with Ex, and proceeding downward from high Ex, there is a sudden drop in both minimum r(S) and N^+/O^+ at the high-temperature end of the correlation with log T_*. Figure 4 shows a similar, although not so clear-cut, behavior for the log I(λ6723)[S II]/I(λ6300)[O I] ratio. This ratio again correlates negatively with log T_* for log T_* < 4.65, which supports the correlation of Figure 3. Note that the anomalous point in this correlation in Figure 4 at log T_* = 4.56, which is IC 2149, is also high in Figure 3.

The phenomenon is more clearly seen in Figure 5 where log r(S), log [I(λ6723)/I(λ6300)] and log N^+/O^+ [from Kaler (1979), and computed from Aller and Czyzak (1979) and Kondratyeva (1978, 1979)] are all plotted against log[I(λ5007)/I(Hβ)] for nebulae with log T_* < 4.65. Note the striking similarity of slopes.

Since N^+/O^+ decreases as T_* increases, we might expect to see analogous changes in the strengths of the neutral lines. Figure 6 shows log r(O) = log{I(λ6300)[O I]/I(λ3727)[O II]} and log r(N) = {I(λ5199)[N I]/I(λ6584)[N II]} from Kaler (1980a) plotted against log T_* for log T_* < 4.65. The number of observations is small, and the scatter is large. But from the available data, we see that r(N) shows a positive correlation with log T_*,

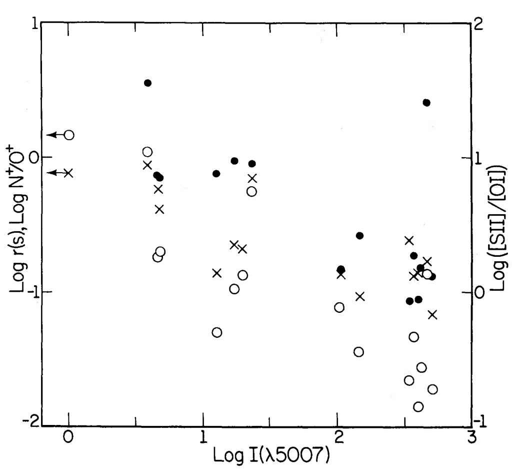

FIG. 5.—Log r(S) (*open circles*), log{I(λ6723)[S II]/I(λ6300)[O I]} (*filled circles*), and log N^+/O^+(X's) plotted against I(λ5007) for galactic planetary nebulae with log T_* < 4.65.

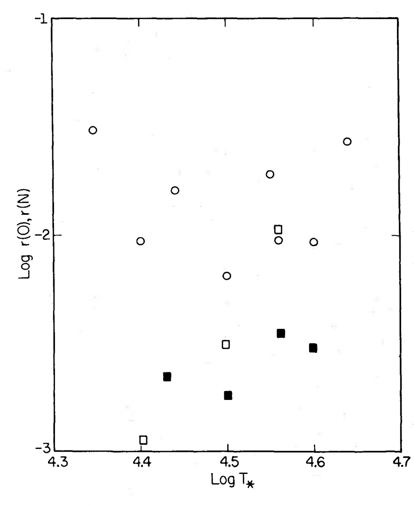

FIG. 6.— Log r(O) = log{I(λ6300)[O I]/I(λ3727)[O II]} (*circles*) and log r(N) = log{I(λ5199)[O I]/I(λ6548)[N II]} (*boxes*) plotted against log T_* for galactic planetary nebulae. The filled symbols show nebulae with log N_e > 3.8.

whereas r(O) seems to show no particular correlation at all. The variation in N^+/O^+ with T_* may be caused by changes in the ionization balance of nitrogen. Presumably, the T_*-variation in r(S) and in N^+/O^+ have similar causes. More [O I] and [N I] data are needed to confirm these oxygen and nitrogen ionization balances.

The [O I] lines are suppressed relative to [O II] for all of the low-T_* nebulae, with no correlation with T_* within the group. In the light of the new evidence above, it still seems that a likely explanation of this suppression is a lower incidence of condensations among the low-T_* objects (Kaler 1980*a*). The [N I] lines would certainly also be suppressed by this effect. Since the ionization potential of S^+ is less than that of the Lyman limit, some S^+ will exist in the same zones that contain neutral N and O, and the [S II] lines should be at least partly affected by the incidence of condensations. Note from Table 2 that the overall suppression of the [S II]/[O II] intensity ratio relative to the high T_* group is 2.1 ± 0.6, significantly less than it is for r(O) and r(N) from Kaler (1980*a*).

Thus, two different effects appear to play a role in controlling the strengths of the neutral and singly-ionized states of oxygen, nitrogen, and sulfur for the low-T_* group: the incidence of condensations, and an effect that causes N^+/O^+, r(S), and possibly r(N) to be a function of T_*. It is interesting that changes in ionization roughly all coincide with the onset of neutral helium at $\log T_* \approx 4.65$ (Kaler 1978*a*). Certainly the absorption of starlight by He° will cause a general lowering of the ionization level of the nebula, but its exact rate and the origin of the above correlations must be examined by the application of detailed models, which is beyond the scope of this paper.

c) *Sulfur Abundances*: *Ha* 4–1 *and the Vertical Galactic* S/O *Gradient*

From Figure 1 and Table 1 we see that for $\log T_* \geq 4.65$ the [S II] and [O II] lines strengths correlate linearly. From Figure 3, r(S) does not show a particular correlation with excitation, except that above Ex = 0.5, r(S) tends toward higher values. Therefore, r(S) should itself be a rough measure of relative S/O. The standard deviation of r(S) is about ±75% of the mean value, and a variation of S/O greater than a factor of 2 or 3 should be evident. Most of the scatter is intrinsic; see § III*a*. However, averages of groups of nebulae should produce lower errors for mean values of relative S/O.

A galactic gradient vertical to the plane is suggested by the work of Hawley and Miller (1978*c*) and Torres-Peimbert and Peimbert (1979) on the distant, extreme halo planetary Ha 4–1. They find that S appears to be deficient relative to O by factors of 2 to 3 and 10, respectively. This feature of Ha 4–1 is evident from Figures 1 and 2 where the nebula is indicated by a cross. If r(S) and $I(\lambda6723)/I(\lambda6300)$ for Ha 4–1 are compared with the respective averages for high-T_* nebulae, a reduction in S/O by a factor of 16 is indicated. The above authors have suggested that this fact (and an apparent reduction in Ne/O) reflects an age-related vertical abundance gradient in the Galaxy, and that oxygen was subject to a rapid early increase with sulfur and other heavy elements lagging behind.

However, notice from Figure 3 that Ha 4–1, at Ex = 0.08, is consistent with the downward extension of the correlation between r(S) and $\log T_*$, and is not far below the other extreme points. The same behavior is seen for the [S II]–[O I] relation in Figure 4. It seems possible then that Ha 4–1 may represent the extreme end of the r(S)–$\log T_*$ correlation, and that the apparent deficiency of S/O in this object is the result of an ionization effect. The problem can be resolved only with the observation of the 10.51 μm[S IV] line, or with the clear understanding of the origin of the r(S)–$\log T_*$ correlation. At present, however, the empirical evidence casts doubt on the reported low S/O ratio in this nebula.

The existence of a vertical gradient can also be examined by computing the mean r(S) for the age groups defined by Kaler (1980*b*). Such a grouping shows that $\overline{O/H}$ increases steadily as the age of the group is decreased. The mean r(S) are presented in Table 3 for Kaler's (1980*b*) groups 2 through 5, excluding nebulae with Ex > 0.5. The numbers in parentheses

TABLE 3

$\overline{r(S)}$ FOR AGE GROUPS, Ex < 0.5

Group (1)	$\overline{r(S)}$ (2)	$\overline{r(S)}$ [a] corrected (3)
2. Intermediate halo (15) ...	0.205 ± 0.050	0.158 ± 0.022
3. Old disk (6)	0.120 ± 0.023	0.125 ± 0.020
4. Intermediate disk (17) ...	0.120 ± 0.019	0.118 ± 0.013
5a, b. Young disk (16)	0.160 ± 0.019	0.152 ± 0.014
Mean of all groups	0.155 ± 0.017	0.140 ± 0.009
SMC planetaries	0.134 ± 0.035	

[a] The two highest and lowest points removed from groups 2, 4, and 5; the single highest and lowest from group 3.

in column (1) give the number of nebulae in the group. Column (2) shows the averages for all nebulae in the group and column (3) the averages with the high and low points removed, as indicated by the footnote. No consistent trend can be seen to indicate a monotonic galactic S/O gradient. The mean r(S) first drops from group 2 to groups 3 and 4, which is contrary to the trend first indicated by Ha 4–1, and then increases to group 5.

The fifth row of Table 3 gives the mean r(S) of the nebulae used in all the groups. From column (3), we see that the maximum deviation from the mean for any group is less than 20%, and the maximum variation from any one group to any other is less than 35%. At this point there seems to be no convincing evidence for a vertical galactic S/O gradient at least to within ±35%. Since O/H exhibits a strong vertical gradient (Kaler 1980*b*), so must S/H, in contradiction to Barker's (1978*c*) conclusion.

From Table 3, the best estimate of mean galactic r(S) is 0.140. From Dinerstein's (1980*a*, *b*) S/H ratios and Kaler's (1980*b*) O/H ratios, S/O≈0.36r(S). If solar S/O is adopted from Lambert (1978) and Lambert and Luck (1978) (see § 1), S/O (planetaries)≈0.14r(S).

d) *The* [S II]/[O II] *Ratio as an Indicator of* T_*

Kaler (1978*b*) showed that the $I(\lambda5007)$[O III]/$I(\mathrm{H}\beta)$ ratio can be used as an indicator of central star temperature for $\log T_* \lesssim 4.83$. However, this ratio does not work accurately when $\log T_* \lesssim 4.5$. The scatter in the correlation between the ratio and $\log T_*$ is too large, and for some nebulae (e.g., M1–67), the λ5007 line is absent. Figure 3 shows that the value of r(S) provides a good measure of T_* for $\log T_* < 4.65$, and it is especially useful for nebulae with weak or absent λ5007. The filled circles in Figure 3 represent the best determinations of $\log T_*$ and include only full evaluations by the revised Stoy method for quality classes A and B [see Kaler (1976*b*, 1978*b*)]. IC 2149 is also eliminated because of its anomalous position in both Figures 3 and 4. A least-squares fit, where each variable is assumed to have equal errors, yields

$$\log T_* = 4.325 - 14.7\, r(\mathrm{S}). \quad (1)$$

TABLE 4

T_* FROM r(S) FOR SELECTED NEBULAE

Nebula	$10^{-3}T_*$
Cn 3–1 . . .	29
He 1–2 . . .	23
Hb 12	36
M1–5	37
M1–65 . . .	28
M1–67 . . .	20
M2–9	31

Only nebulae without He II lines can be so evaluated. The λ5007 line only should be used for $\log T_* > 4.65$, and equation (1) should be used only when the He II strengths and λ5007 indicate the $\log T_* < 4.65$. The method assumes the constancy of S/O, demonstrated in this and later sections, and should be used only for planetaries or related low-mass objects. Values of $\log T_*$ for selected low-excitation nebulae, calculated from equation (1), are presented in Table 4. The lowest values, for M1–67 and He 1–2, are somewhat below the canonical limit for spectral class B1 for H II regions, as implied from Allen (1973), which may indicate a systematic error in the method. Nevertheless, these two objects have extraordinarily cool exciting stars.

IV. [S II] IN DIFFUSE NEBULAE AND SUPERNOVA REMNANTS

a) *Diffuse Nebulae*

Data on [S II] in diffuse nebulae are shown from observations made of five galaxies: our own, the Large and Small Magellanic Clouds, M101, and M33; see Table 1. The logs of the mean [S II] and [O II] line strengths are plotted for the individual nebulae in Figure 7. Note first that the distributions of nebulae in the different galaxies overlap one another, which anticipates the demonstration below that S/O is similar in all of them. Next, a comparison of Figure 7 with Figure 1 shows that the distribution of points for diffuse nebulae is the same as that for the planetaries. The diffuse nebulae show a limited range, because the range of temperatures of the exciting stars is less than it is for planetaries. Nevertheless the correlation between the strengths of [S II] and [O II] is still evident.

Figure 8 shows log r(S) plotted against $\log T_*$ for the diffuse nebulae, where $\log T_*$ is in all cases determined

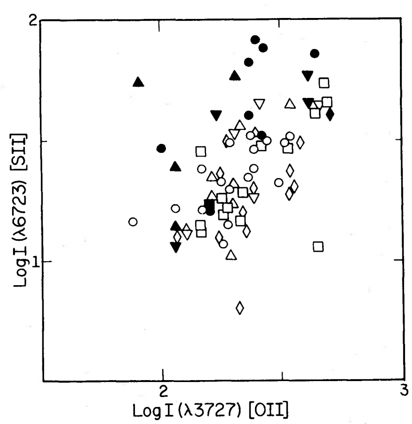

FIG. 7.—Log $I(\lambda6723)$[S II] plotted against log $I(\lambda3727)$[O II] for diffuse nebulae. *Circles*, the Galaxy; *boxes*, LMC; *diamonds*, SMC; *upward triangles*, M101; *downward triangles*, M33. Filled symbols show nebulae with $\log T_* \leq 4.45$ or ≥ 4.65.

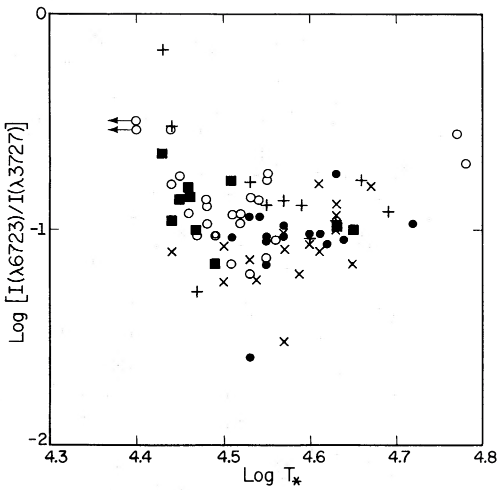

FIG. 8.—Log r(S) plotted against log T_* for diffuse nebulae. *Open circles*, the Galaxy, *filled circles*, LMC; X's, SMC; *crosses*, M101; *filled boxes*, M33.

from $I(\lambda5007)$[O III] according to Kaler's (1976*b*) equation. A negative correlation similar to the one discussed for planetaries (cf. Fig. 3) is present, below log $T_* = 4.5$. Above log $T_* = 4.5$, the values of r(S) tend to flatten out with increasing log T_* and are higher than are found for planetaries. Then above log $T_* = 4.75$, r(S) tends to become higher, again reminiscent of Figure 3. The correlation is also seen in Figure 7 where nebulae with $4.45 < \log T_* < 4.65$ only are denoted by open symbols.

Mean values of r(S) and data pertaining to least-squares fits to the points in Figure 7 are given in Table 2 for each of the galaxies studied. Row 4 of the table gives this information for the full collection of diffuse nebulae. But because of the correlation between r(S) and log T_*, it is more meaningful to restrict the nebulae to $4.45 < \log T_* < 4.65$ (the latter figure for consistency with the planetaries) where the correlation is not readily apparent. The next five rows thus provide data on averages and fits for the open symbols of Figure 7.

The diffuse nebulae do not show a correlation between the strengths of [O II] and [O I] as the planetaries do; consequently, [S II] shows no relation to [O I] for these objects. The reason for the absence of a correlation is not understood.

If we assume that the errors are uniformly distributed between the [S II] and [O II] line strengths, then the mean slope for the Galaxy, LMC, and SMC for $4.45 < \log T_* < 4.65$, weighted by the number of nebulae, is 0.99 which provides additional evidence for the linear relationship between $I(\lambda6723)$[S II] and $I(\lambda3727)$ [O II].

b) The Radial Galactic S/O *Gradient*

Peimbert, Torres-Peimbert, and Rayo (1978, hereafter PTR), Hawley (1978*a*), and Talent and Dufour (1979) have determined composition gradients in the Galaxy from studies of diffuse nebulae. They find both the negative O/H and N/O gradients that are observed in other galaxies by, for example, Searle (1971), Smith (1975), and Shields and Searle (1978).

The linear I[S II]/I[O II] ratio provides a good means of examining the radial S/O gradient, just as planetaries were used to study the vertical gradient. In the following analysis, the sample of nebulae observed by PTR, Hawley (1978*b*), and Talent and Dufour (1979) is utilized, as are their published values of galactocentric distance, R.

In the case of the planetaries we could make use of the high-T_* nebulae, which show no correlation with excitation. However, all the diffuse nebulae are in the regime in which I[S II]/I[O II] depends on T_*. Thus in order to derive correct relative S/O ratios, a correction for the slope of I[S II]/I[O II] against log T_* must be made. However, we must consider the following problem. It is well known that the excitation of diffuse nebulae increases with distance from the galactic center (see, for example, Smith 1975; Churchwell *et al.* 1978). The nebulae considered here show a similar general trend. The two nebulae with by far the highest excitation are at $R = 13.9$ kpc. The scatter of points is too large and the number of nebulae is too small for a definitive analysis, but if these two objects are dropped and log $T_* = 4.40$ is assumed for Hawley's (1978*a*) two nebulae without λ5007, $dT/dR \approx 500$ K kpc^{-1} at the Sun, roughly consistent with that found by Churchwell *et al.* (1978). Is the correlation pointed out in the last subsection between log r(S) and log T_* (for log $T_* < 4.65$) in Figure 8: (1) a true physical effect; (2) does it reflect only oppositely directed galactic gradients; or (3) is it in fact similar to the planetary log T_*–log r(S) relation but moderated by similarly directed galactic gradients?

The first case given above seems the most likely. First, the five nebulae of Figure 8 with the highest log r(S) are distributed from 10 to 14 kpc and do not fit the trend of a gradient. Second, the analysis of planetaries shows that r(S) can in fact be related to T_*. Finally, data from the other galaxies fit with that from galactic nebulae and indicate that the physical relation between r(S) and T_* is in fact less pronounced than that seen in the planetaries.

The r(S), or relative S/O, gradient is calculated for case (1) above, where values of r(S) are first reduced to log $T_* = 4.6$, via the equation

$$\log r(\mathrm{S}) = 8.81\times10^{-2} - 1.034\times10^{-3}\log T_*, \quad (2)$$

which is derived from the galactic diffuse nebulae of Figure 8 with $4.40 < \log T_* < 4.65$. Put in terms of $I(\lambda5007)$ directly,

$$\log r(\mathrm{S}) = -0.348 - 0.268\log I(\lambda5007), \quad (3)$$

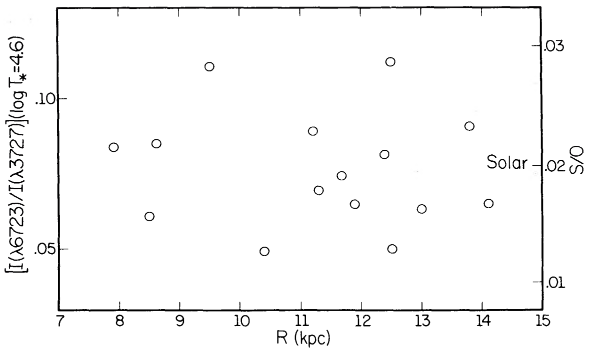

FIG. 9.—Log r(S) for galactic diffuse nebulae reduced to $\log T_* = 4.6$, for nebulae with $4.45 < \log T_* < 4.65$, plotted against distance from the galactic center, R(kpc). The right-hand axis shows S/O scaled to solar S/O at 10 kpc.

where $I(H\beta) = 100$. Only nebulae with $4.45 < \log T_* < 4.65$ $[50 < I(\lambda 5007) < 560]$ are used in the analysis in order to eliminate any residual effect caused by the T_* correlation. The results are presented in Figure 9, where the left-hand axis shows r(S) and the right-hand shows S/O, based upon solar S/O (see § I) at $R = 10$ kpc. No significant gradient is seen. A least-squares fit yields $d\log(S/O)/dR = -0.006(+.013, -0.027)$. This result is similar to that found by comparing $d(\log N/O)/dr$ and $d(\log N^+/S^+)/dr$ from PTR and Hawley (1978*a*), from the latter's Table 9, but with improved error limits. The problem of a T_* gradient introduces a problem that cannot be entirely clarified, especially as regards selection effects, but from the above analysis there is no evidence of a radial S/O gradient in the galaxy, just as there is no evidence for a vertical one.

c) *Relative* S/O *among Galaxies*

In order to examine the variation in mean S/O among different galaxies from studies of diffuse nebulae, we must again correct for the T_* correlation. Note in Figure 8 that observed nebulae in other galaxies tend toward higher T_* than do those in our own. The values of r(S) are first reduced to $\log T_* = 4.6$ by equation (2), and only nebulae with $4.45 < \log T_* < 4.65$ are used.

The comparison between the four other galaxies and our own is summarized in Table 5. Column (2) gives the average $\log T_*$, and column (3) gives the relative correction required to reduce each galaxy to the Milky Way through the $\log T_*$ relation. The mean r(S) or S/O ratios relative to that of our Galaxy are shown in column (4), after each nebula is individually corrected to $\log T_* = 4.6$. The fact that the ratios are slightly above unity can be explained as a residual effect of T_*. The error given is the mean error of the mean, which does not reflect the error inherent in the $\log T_*$ correction. The type of nebula used is given in column (5); the results from supernova remnants are discussed in the next subsection.

With the marginal exception of M101, all the ratios are within the error of being unity. The Magellanic Clouds, for which a substantial number of nebulae are observed, have the same S/O as the Galaxy to within about ±10%. This conclusion is supported by the planetaries. Table 3 (see also Table 2, row 2) shows the mean r(S) observed for SMC planetaries. Compared to the last entry for galactic planetaries in column (3) of that table, S/O in the galaxy is within 5%±28% of that in the SMC. These are the tightest restrictions yet placed on S/O variations among galaxies. There is no significant evidence that S/O shows any variation either among galaxies or within a given galaxy.

d) *Supernova Remnants*

There are sufficient observations of SNR in both the Galaxy and M33 to enable the study of their relative S/O ratios (see Table 1). Mathewson and Clarke (1973) pointed out that the [S II] lines are strong in SNR and can be used as a test to discriminate SNR from diffuse nebulae. This high strength is seen in the average values of r(S), given in the last two rows of Table 2*b*, which are 2.5 times larger than $\overline{r(S)}$ for the diffuse nebulae. The use of r(S) as a test is not unambiguous,

TABLE 5
RELATIVE S/O RATIOS

Object (1)	$\langle \log T_* \rangle$ (2)	Corr. to Galaxy (3)	(S/O) / (S/O) Galaxy (4)	Type (5)
Galaxy ...	4.512			
LMC.....	4.575	1.25	1.12±0.11	Diffuse
SMC.....	4.576	1.25	1.02±0.11	Diffuse
M101	4.563	1.20	1.23±0.17[a]	Diffuse
M33	4.503	0.97	1.06±0.16	Diffuse
			1.03±0.14	SNR

[a] 1.36±0.11 excluding one low point near center.

however. Three SNR (2–16 in M33, and N86 and N206 in the LMC) have r(S) similar to the majority of diffuse nebulae, and the diffuse nebulae with the lowest T_* (Fig. 8) have r(S) appropriate to the SNR. The test does seem to pick out the SNR if they have both high r(S) and $50 < I(\lambda 5007) < 560$.

The high values of $\overline{r(S)}$ for supernova remnants reflect only the very different conditions under which the lines were formed. The actual calculation of sulfur and oxygen abundances for SNR in M33 (as well as in the Galaxy, M31, and the LMC) by Dopita, D'Odorico, and Benvenuti (1980) show a mean S/O which is close to solar, consistent with the fact that diffuse nebulae in the various galaxies considered show similar S/O. (However, note that S/O calculated for planetaries, Orion, and the Sun are not generally consistent; see § I). The $\overline{r(S)}$ for M33 and the Galaxy are remarkably similar. The ratio of $\overline{S/O}$ between M33 and the Galaxy is shown in the last row of Table 5 where it clearly confirms the results found from the diffuse nebulae, that $\overline{S/O}$ does not vary generally among the nearby galaxies studied.

V. SULFUR AND THE NITROGEN ABUNDANCE

Nitrogen abundances have generally been calculated under the assumption that $N/O = N^+/O^+$ (Peimbert 1968) because of the coincidence of ionization potentials. However, this relation has been subject to some uncertainty since for some objects as little as 1% of the nitrogen can be in the N^+ state. It is clear, of course, that the [N II] and [O II] lines are correlated in strength, but the relation is confused by the fact that N/O shows strong intrinsic variations in nebulae (see, e.g., Torres-Peimbert and Peimbert 1977; Barker 1978*b*; Kaler 1979; PTR; Hawley 1978*b*; Talent and Dufour 1979).

Kaler (1979) provides support for the above relation in planetaries since the N/O so derived correlates with He/H as expected, for $\log T_* \geq 4.65$, and for $He^{2+}/He < 0.5$. The linear relation between the [S II] and [O II] line strengths provide additional support. Since S^+ and O^+ are apparently linearly related over a range of a factor of 100, we would expect N^+ and O^+ to be so related since the ionization potentials of N and O are more similar to one another than are those of S and O. The relation between r(S) and $\log T_*$ for $\log T_* < 4.65$ confirms the fact that $N/O \neq N^+/O^+$ for planetary nebulae with central stars in this temperature range.

The diffuse nebulae generally fall into the low-T_* regime, but r(S) is not nearly so strong a function of T_* for these as it is for planetaries. Consequently, N^+/O^+ probably reflects N/O reasonably well. In fact, a plot of $\log N^+/O^+$ against $\log I(\lambda 5007)$ from Peimbert and Torres-Peimbert (1977), PTR, Hawley (1978*a*), and Talent and Dufour (1979) shows a possible correlation similar to that found for r(S), but clearly weaker. It would seem that N^+/S^+ is a good approximation to N/S. Since S/O is apparently constant, N^+/S^+ will represent N/O very well, and r(S), with appropriate limits and corrections as defined above, will indicate relative N/O.

VI. [S II] AND [S III]

As a secondary study, the mutual behavior of the line strengths of [S II] and [S III] have also been examined. In Figure 10, the log of the intensity of λ6723 [SII] is plotted against that of λ6712 [S III] both for nebulae with $\log T_* \geq 4.65$ (*open symbols*) and with $\log T_* < 4.65$ (*closed symbols*). Ha 4–1 is again indicated by a cross. A steep linear correlation is evident for the high-T_* group , which shows that $I[\text{S II}] \sim I[\text{S III}]^n$, where $n = 2$ if all the error is in [S II], and $n = 3$ if all the error is in [S III]. Since the [S III] lines are much weaker than those of [S II], the latter exponent is probably closer to being correct. Figure 11 shows that the diffuse nebulae fit into the correlation exhibited by the planetaries, although they do not themselves show a clear correlation because of the restricted range. The result implies that the amount of S^+ is strongly dependent upon that of S^{2+}, or rather that S^{2+} is only weakly dependent on the amount of S^+. This correlation is presented because of its possible use in the development of ionization models. It has no direct relation to the relative ionization balance between sulfur and oxygen, since for a proper comparison S^{3+} must also be included.

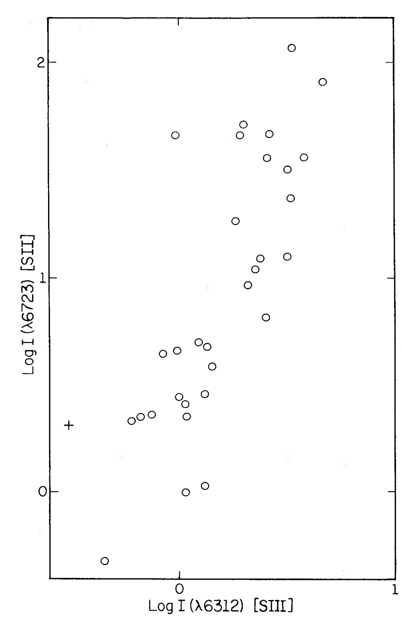

FIG. 10.—Log $I(\lambda 6723)$[S II] plotted against log $I(\lambda 3712)$[S III] for planetary nebulae. The filled circles indicate nebulae with $\log T_* < 4.65$, and the cross indicates Ha 4–1.

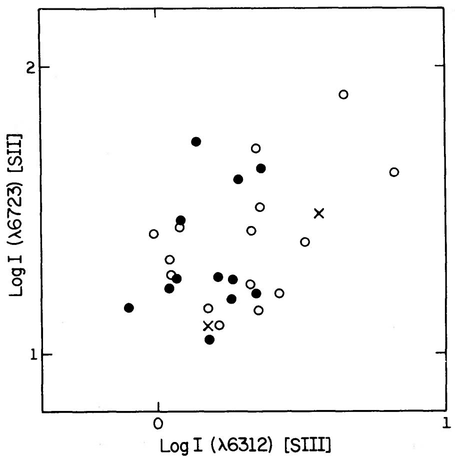

FIG. 11.—Log $I(\lambda 6723)$[S II] plotted against log $I(\lambda 3712)$[S III] for diffuse nebulae. *Open circles*, the Galaxy; *closed circles*, LMC; X's, SMC.

VII. SUMMARY

The strength of λ6723[S II] is linearly related to that of λ3727[O II] for planetaries with log T_* (central star temperature) ≥ 4.65, and for diffuse nebulae with restricted T_*. The [S II] lines are similarly related to [O I] for planetaries, and I[S II] is roughly proportional to $I[\text{S III}]^3$. The correlation with [O II] applies to a range in $I(\lambda 3727)$ of two orders of magnitude. The ratio $r(\text{S}) = I(\lambda 6723)/I(\lambda 3727)$ for planetaries is not related to nebular ionization for $\log T_* \geq 4.65$ and $0 < \text{He}^{2+}/\text{He} < 0.5$. These facts imply that for this set of objects S^+/O^+ is proportional to S/O. This correlation supports the contention that for this same set $N^+/O^+ = N/O$, since the ionization potentials of N are closer to those of O than are those of S.

The low-T_* planetaries (log: $T_* < 4.65$) exhibit a strong negative correlation between both r(S) and I[S II]/I[O I] and log T_*, which is similar to that between N^+/O^+ and log T_*. The [N I]/[N II] ratio is positively correlated with log T_*, whereas the [O I]/[O II] ratio is not, which indicates that the correlation is caused by changes in the nitrogen ionization balance. These sulfur and nitrogen correlations presumably have similar origins. The [O I] lines are weakened in these nebulae by their increased homogeneity, which must also weaken [N I], and to a lesser degree, should weaken [S II]. But the correlation of the ionization levels of N and S with T_* indicates the action of an additional effect which, like the apparent increase in homogeneity, is roughly coincident with the onset of neutral helium, and which must be explored quantitatively by the use of detailed models. The value of r(S) for $\log T_* < 4.65$ (as determined from the λ5007 and He II lines) provides a good empirical indicator of T_* for this set of nebulae.

The above correlations regarding planetaries allow an evaluation of relative S/O ratios and the vertical galactic S/O gradient. The extreme halo planetary Ha 4–1, for which S has appeared to be deficient relative to O by as much as a factor of 10, is consistent with the extrapolated correlation between r(S) and log T_* and $I(\lambda 6723)/I(\lambda 6300)$ and log T_*. This nebula may share in the ionization problem discussed above, which casts doubt on conclusions regarding its low S/O. The mean r(S) also fails to show any consistent relation to nebular age group, or rather to distance from the galactic plane, or to radial velocity. The difficulty of Ha 4–1 must however be resolved by detailed modeling, or by observation of [S IV].

The radial galactic gradient, and the relative S/O variations among galaxies, can be explored by the examination of diffuse nebulae. These fall generally in the range of T_* wherein r(S) varies strongly with log T_* for planetaries. A similar correlation is present for diffuse nebulae, but one which is clearly weaker than it is for the planetaries and which is somewhat confused by the existence of a positive radial gradient between T_* and galactocentric distance. An empirical correction factor, based on the assumption that the correlation between r(S) and T_* is physical and is not moderated or caused by the radial T_* gradient, is applied to reduce all the values of r(S) to $\log T_* = 4.6$. In order to avoid any residual errors, only nebulae with $4.45 < \log T_* < 4.65$ are chosen.

Consideration of the corrected r(S) shows no significant radial galactic gradient. A least-squares analysis shows $d(\log \text{S/O})/dR = 0.006(+0.012, -0.027)$ at the Sun, which is the most restrictive limit yet defined for this ratio. Comparison of relative S/O in the Magellanic Clouds, M101, M33, and the Galaxy shows no significant differences. The Magellanic Clouds and M33 have S/O ratios within about ±10% of those of our own Galaxy, again the most restrictive limits yet determined. Data from SNR also show that M33 and the Galaxy have the same S/O.

The analysis of this paper shows no significant unambiguous variations of the S/O ratio. The Galaxy exhibits no detectable radial or vertical gradients (although the matter of Ha 4–1 needs further study), and there are no differences with regard to other nearby galaxies. S/O seems to be constant.

Finally, for planetaries with $\log T_* > 4.65$, and for diffuse nebulae with $4.45 < \log T_* < 4.65$ [$60 < I(\lambda 5007)/I(\text{H}\beta) < 560$]$N^+/S^+$, and probably $I(\lambda 6584)/I(\lambda 6723)$, appears to be a good indicator of N/S. Since S/O is constant, this intensity ratio alone, excluding the low-T_* planetaries and with an appropriate correction factor for diffuse nebulae with respect to $I(\lambda 5007)$, is apparently an excellent indicator of relative N/O.

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