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NEUTRAL GAS CONTRIBUTIONS TO [S II] EMISSION

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ABSTRACT

Emission in the forbidden lines of ionized sulfur arises in both predominantly ionized and predominantly neutral regions. The separation of [S II] emission from supernova remnants into nearly orthogonal dependences on [O I] and a power of [N II]/Hα is discussed. [S II] may be excited via photoionization into forbidden-line–emitting states in regions devoid of electronic excitation of [O I]. Emission along "background" lines of sight in the Milky Way and in extragalactic "froth" is considered in terms of contributions of neutral gas.

Subject headings: atomic processes — ISM: abundances — supernova remnants

1. INTRODUCTION

The interpretation of emission intensities in the forbidden lines of ionized sulfur relative to those of other species remains problematic. Hester (1991) has summarized the unsatisfactory status of H II region models, in particular, in this regard. Outside H II regions, ratios of [S II] λλ6716 + 6731/Hα that are higher than those typical of H II regions are used to identify both Galactic and extragalactic supernova remnants (SNRs) (see, e.g., Fesen, Blair, & Kirshner 1985). Elevated [S II]/Hα ratios are also observed in the diffuse background of our Galaxy (Reynolds 1985, 1988) and in gas observed on a large scale in other galaxies (Lehnert & Heckman 1994). (Sometimes [S II] λ6716/Hα is used to minimize the effect of the density-sensitive λ6716/λ6731 ratio, but the result is the same for present purposes.) In their study of a sample of Magellanic irregular galaxies, Hunter & Gallagher (1990) characterized regions of enhanced [S II]/Hα as ionized froth. For the ratio [S II] λλ6716 + 6731/Hα, they derived a median value of ∼0.4 in frothy regions, compared with ∼0.25 in identified H II regions. Similarly, in a catalog of 967 nebulae within the Andromeda galaxy (M31), Walterbos & Braun (1992) found many fields containing an enhanced [S II]/Hα ratio, while, in their analysis of the emission-line data in 90 nearby galaxies of Kennicutt (1992a, b), Lehnert & Heckman (1994) found that the integrated spectra of normal galaxies have [S II]/Hα enhanced, typically by a factor of 1.5, over what is expected for H II regions.

Because of its low ionization potential (10.36 eV), ionized sulfur may exist in gas that is predominantly neutral, with photoionization in equilibrium with recombination, as discussed below. By contrast, sulfur in classical H II regions or planetary nebulae can have a substantial fraction in the form of S III. Thus the [S II] line are weak, as evident in the sample observed by Meatheringham & Dopita (1991) in the Magellanic Clouds.

In SNRs, strong [S II] emission may arise due to the abundance of $\sim 10^4$ K electrons in shock regions. The electrons are sufficiently energetic to provide 1.85 eV excitation of the optical transitions at 6716 and 6731 Å (Dopita et al. 1984). Excitation is similar to that of [O I] in the same, predominantly neutral, regions. In § 2 we show that the [S II] flux can be expressed as a linear combination, in comparable parts, of emission from ionized regions of Hα (and [N II]) emission, and emission from predominantly neutral [O I] regions.

In § 3 a mechanism of photoionization into excited states is discussed whereby [S II] emission may arise, even in the absence of electronic excitation, when far-ultraviolet (FUV) radiation penetrates thin layers of denser neutral medium. Thus, a new avenue is opened to understanding [S II] emission in Galactic lines of sight where upper limits can be placed on [O I] emission and in regions of ionized froth.

2. [S II] IN REGIONS OF [O I] λ6300 EMISSION

The $^1D_2$ state of neutral oxygen, from which the forbidden lines at 6300 and 6363 Å arise, lies 2.0 eV above the ^3P ground state and is excited by collision with electrons created by shocks (in SNRs or starburst nuclei) or X-rays (from Seyfert nuclei in active galactic nuclei). Another mechanism invoked to explain an enhancement of low-ionization lines in active galactic nuclei is collisional ionization by relativistic electrons and heating of the gas through Coulomb interactions (Ferland & Mushotzky 1984). The excitation of [S II] emission can be expected to occur under all of these circumstances.

The radiative shock models of Dopita et al. (1984) predict intensities of optical forbidden lines in SNRs. The authors conclude, for example, that the correlation of [S II]/Hα with [N II]/Hα is due solely to metallicity effects. Thus, data on SNR emission-line intensities, both in the Milky Way and in external galaxies, bear on the question of abundances and nucleosynthetic origins of the elements.

Prior studies have plotted log ([S II]/Hα) versus log ([N II]/Hα) for SNRs in the Milky Way and external galaxies (e.g., Daltabuit, D'Odorico, & Sabbadin 1976; Dopita et al. 1984; Russell & Dopita 1990). Binette et al. (1982) compared a plot of SNR emission-line data for several galaxies with theoretical predictions based on the production of nitrogen as a primary nucleosynthetic element, produced by H burning on carbon formed within a star, or as a secondary nucleosynthetic element, where the carbon was originally present in the star. They concluded that the best overall fit to the data corresponds to secondary enrichment of nitrogen, although the best fit to the ensemble of M33 data, taken alone, shows nitrogen enriched as a primary element in that galaxy. The nucleosynthetic status of nitrogen must still be said to be uncertain (Matteucci 1986). The variation of the inferred abundance ratio of N II/S II with galacto-

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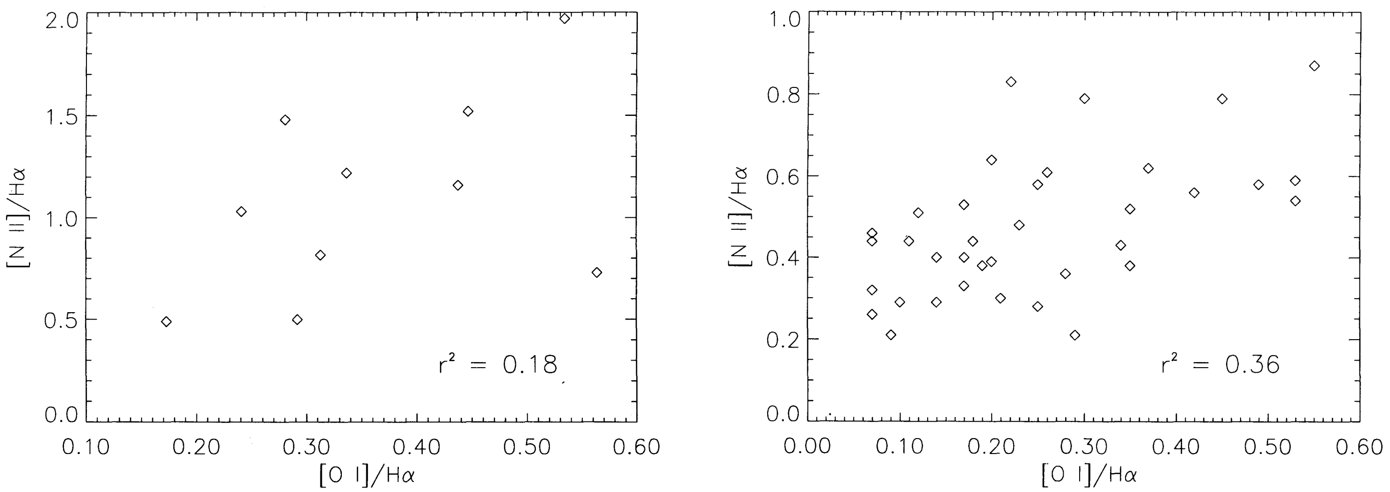

FIG. 1*a*

FIG. 1*b*

FIG. 1.—Correlation of [N II]/Hα with [O I]/Hα in SNRs in (*a*) M31 (Blair et al. 1981) and (*b*) M33 (Smith et al. 1993)

centric radius in M101 and M33 was remarked upon by Comte (1975) and has been studied in the Milky Way and other galaxies (e.g., Wilson & Matteucci 1992; Smith et al. 1993).

Recognizing that ionized nitrogen cannot exist in neutral regions because of its ionization potential (14.6 eV) in excess of that of hydrogen and its rapid charge exchange with hydrogen (Steigman, Werner, & Geldon 1971), we have explored the effect of separating distinct ionized and neutral gas terms as contributors to [S II] emission. The nearly orthogonal character of the ionized ([N II]) and neutral ([O I]) line emission is evident in the poor correlation between the corresponding line intensities in extragalactic SNRs shown in Figure 1.

Ionized nitrogen and sulfur emission-line data, corresponding to samples of 10 SNRs in M31 (Blair, Kirshner, & Chevalier 1981) and 36 SNRs in M33 (Smith et al. 1993) for which [O I] λλ6300, 6363 intensities have been reported, are fitted, for comparison, using a simple power-law relation between [N II] and [S II]. Only [O I] λ6300 is included in the case of M31 because of typically highly uncertain measurements of [O I] λ6363. Reddening-corrected fluxes supplied by the respective authors are used in all cases. The resulting fits are shown in Figure 2. Fitting the intensity of [S II], instead as

$$I([\mathrm{S\ II}]) = a_{\mathrm{ion}} I([\mathrm{N\ II}]/\mathrm{H}\alpha)^m I(\mathrm{H}\alpha) + a_{\mathrm{neut}} I([\mathrm{O\ I}]) \quad (1)$$

produces the relations shown in Figure 3. The fit parameters and χ^2 are presented in Table 1.

The improvements in χ^2 per degree of freedom by factors of 2 or 3 justify the decomposition into ionized and neutral components contributing, in nearly equal parts, to the intensity of [S II] emission. The factor preceding the term proportional to Hα, and thus corresponding to the ionized component, contains the power-law dependence that reflects different dependences of N and S abundance on overall metallicity. The neutral term appears to be free of abundance effects, as is to be expected, since studies have shown O/S to be invariant within a galaxy (Dopita et al. 1984).

TABLE 1

FITS TO SNR DATA

Parameter	M31 SNRs[a]	M33 SNRs[b]
$\frac{d \log [\mathrm{S\ II}]/\mathrm{H}\alpha}{d \log [\mathrm{N\ II}]/\mathrm{H}\alpha}$	0.44	0.67
Reduced χ^2 of [S II] versus [N II]^m......	0.37	1.11
m	0.43	0.67
a_{ion}..	0.78	0.99
a_{neut}	0.85	1.17
Reduced χ^2 of decomposition fit.........	0.18	0.39

[a] Blair et al. 1981.

[b] Smith et al. 1993.

A fit to the emission-line data of McCarthy, Heckman, & van Breugel (1987) at 13 points along the minor axis of the starburst galaxy M82, shown in Figure 4, illustrates that, while [S II] emission is uncorrelated with [N II]/Hα, it is well fitted as proportional to [O I], with a residual ionized contribution equal to 0.086Hα. This suggests a significant neutral contribution to the [S II] emission associated with large-scale galactic emission.

3. PHOTOIONIZATION INTO EXCITED STATES

Having addressed the case where the neutral component of [S II] is made manifest because the excitation of [O I] by electronic collision gives rise to emission by neutral gas, we turn to the case where [O I] emission is absent but where [S II] emission may arise in neutral gas nonetheless.

A partial energy-level diagram of neutral and singly ionized sulfur is shown in Figure 5. The mechanism whereby [S II] emission arises in neutral gases in the absence of collisional excitation involves the photoionization of sulfur by a FUV photon, creating S II ions, with approximately one-third excited to the ^2D level. Thus, 6716 and 6731 Å emission ensues, even in regions which are nearly fully neutral. We suggest that implications for interpretation of [S II] in the faint Galactic background follow from this picture.

The photoionization spectrum of sulfur has been measured from threshold at 1196.7 Å to above the Lyman continuum, at 912 Å, by Joshi et al. (1987). Tayal (1988) and Altun (1992) treated the partial cross sections for photoionization to the various product states and found the spectra dominated by overlapping autoionizing resonances. We have gone back to earlier results of Chapman & Henry (1971), which, while not incorporating resonance effects, qualitatively reflect the relative weights of the photoionization products as a function of

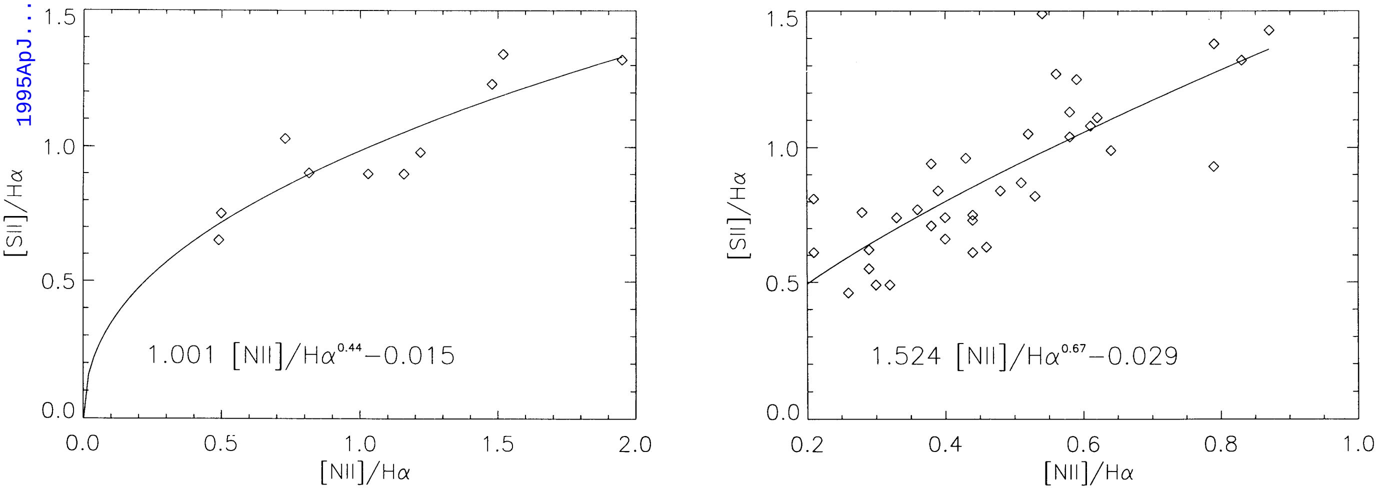

FIG. 2*a* **FIG. 2*b***

FIG. 2.—Fits to [S II]/Hα vs. ([N II]/Hα)^m + constant for SNRs in (*a*) M31 (Blair et al. 1981) and (*b*) M33 (Smith et al. 1993)

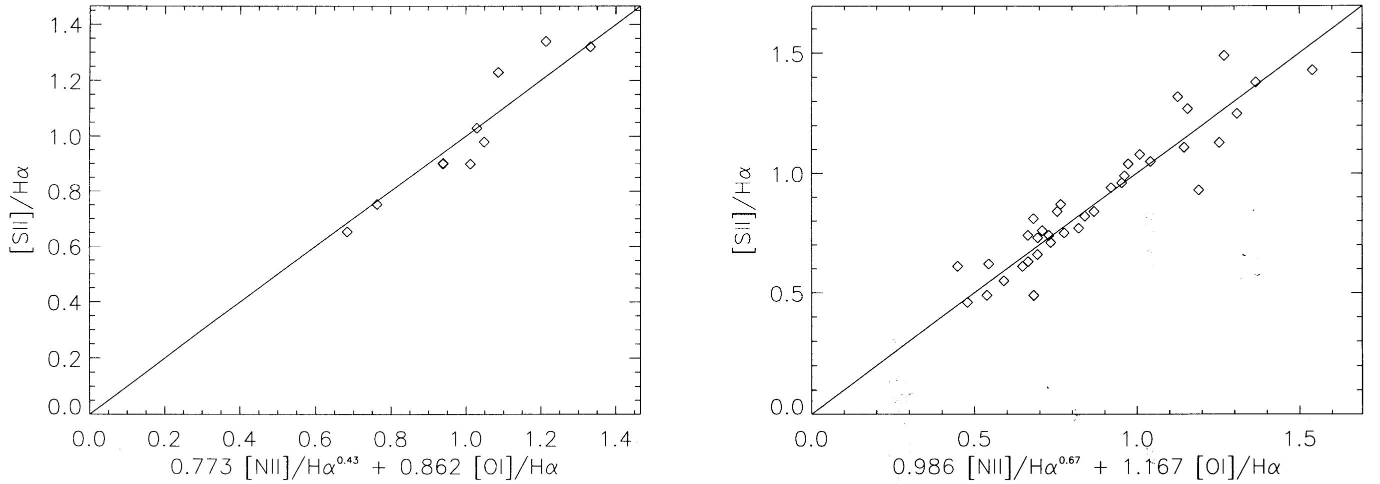

FIG. 3*a* **FIG. 3*b***

FIG. 3.—Fits to [S II]/Hα vs. $a_{\rm ion}$([N II]/Hα)^m + $a_{\rm neut}$[O I]/Hα for SNRs in (*a*) M31 (Blair et al. 1981) and (*b*) M33 (Smith et al. 1993)

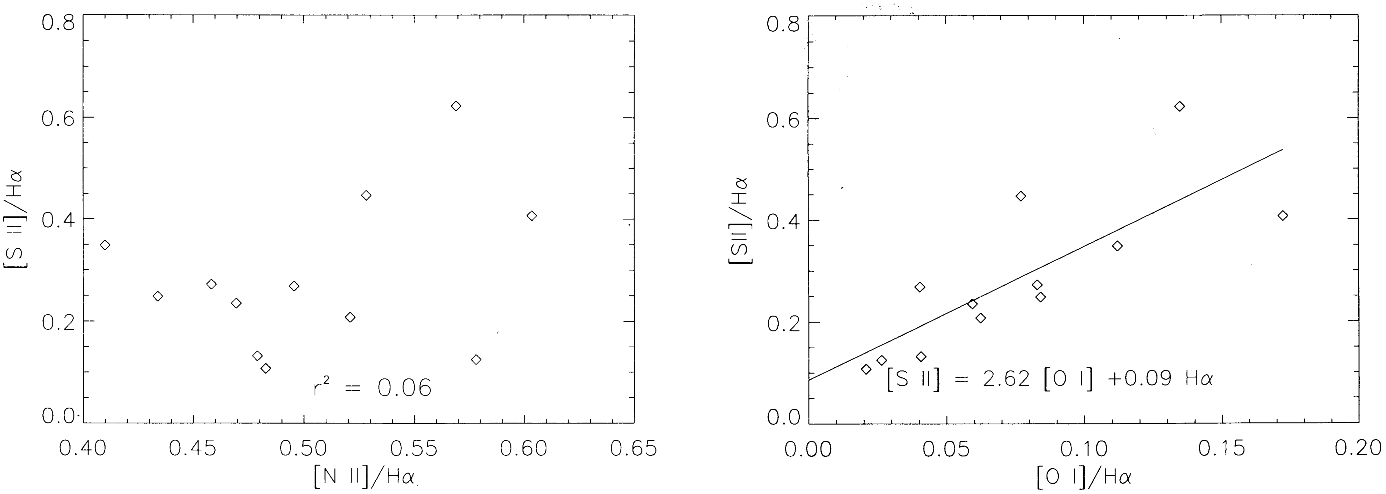

FIG. 4*a* **FIG. 4*b***

FIG. 4.—Correlation of large-scale galactic [S II]/Hα in M82 (McCarthy et al. 1987) with [N II]/Hα; (*b*) fit of the same data to $a_{\rm neut}$[O I]/Hα + constant

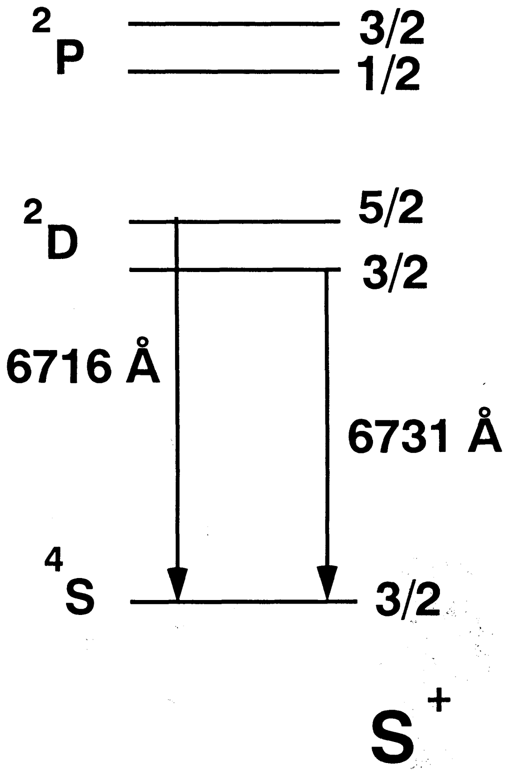

FIG. 5.—Partial energy-level diagram of S II showing levels responsible for the emission of forbidden lines.

photon energy and were fitted to a readily applicable functional form.

In the spectral region above the ^2D threshold, photoionization from the $3p^4\ ^3P$ ground state of S I favors population of the $3p^3\ ^2D$ ionized state. For a typical interstellar radiation field (ISRF) of nonionizing photons, approximately one-quarter of the sulfur ions created through photoionization of neutral sulfur are left in the metastable ^2D state. For concreteness, we consider the ISRF derived by Draine (1978) on the basis of a polynomial fit to independent theoretical estimates for spiral arm regions far from ionizing sources and the solar neighborhood and to local measurements. Convolving the Draine spectrum with the partial cross sections of Chapman & Henry (1971), we derive the fractional photopopulation of the ionized product states shown in Figure 6. In total, over the range from the ionization threshold of S I to 13.6 eV, 24.8% of the product sulfur ions are left in one of the ^2D states.

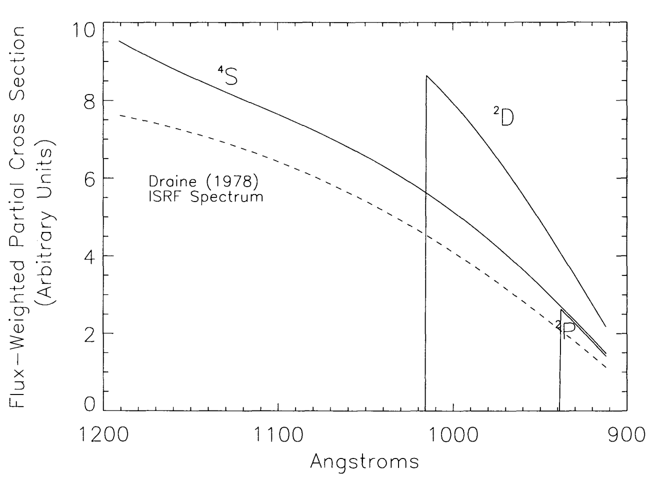

FIG. 6.—Partial cross sections of the lowest electronic states of S II (after Chapman & Henry 1971) weighted by the ISRF spectrum of Draine (1978).

The rate of spontaneous emission of 6716 Å photons ($A = 2.60 \pm 10^{-4}$ s^{-1}; Mendoza 1982) is comparable to the rate at which the metastable $^2D_{5/2}$ state is collisionally de-excited by neutrals under typical [n(H I) ~ 10^2–10^5 cm^{-3}] low-density conditions of a photodissociation region (PDR) (Hollenbach, Takahashi, & Tielens 1991). An electron collision strength of 7.19 at 100 K has been extrapolated, by means of a cubic fit, from the values calculated by Tayal, Henry, & Nakazaki (1987) for the temperature range 500–2000 K. This implies a collision rate

$$\gamma_{e\text{-coll}} = 6.2 \times 10^{-7}\left(\frac{100\ \mathrm{K}}{T}\right)^{1/2}\left(\frac{n_e}{1\ \mathrm{cm}^{-3}}\right)\ \mathrm{s}^{-1}\ ,$$

while for neutral collisions we assume the temperature-independent value of $\gamma_{\text{neu-coll}} = 2.2 \times 10^{-9}$ cm^{-3} s^{-1} (Spitzer 1978). Where the electron abundance is of the order of the carbon abundance, (Tielens & Hollenbach 1985), or 3.4×10^{-4} in the nebular abundance model of Rubin et al. (1991), the collisional de-excitation is dominated by neutral partners.

The rate of [S II] recombination, γ_{recomb}, over the temperature range of 10–1000 K is

$$\gamma_{\text{recomb}} = 1.05 \times 10^{-11}\left(\frac{T}{100\ \mathrm{K}}\right)^{-0.593}\left(\frac{n_e}{1\ \mathrm{cm}^{-3}}\right)\mathrm{s}^{-1}$$

(Péquignot & Aldrovandi 1986). The S I ionization cross section at threshold is typically on the order of 5×10^{-17} cm^{-2} (Joshi et al. 1987) while the average local interstellar FUV flux is 1.6×10^{-3} ergs cm^{-2} s^{-1}, or greater than 7×10^7 sulfur-ionizing photons cm^{-2} s^{-1}, based on the Draine (1978) ISRF spectrum. Under these conditions, every recombined sulfur atom which is not substantially shielded from the ISRF is immediately photoionized, and the [S II]$\lambda\lambda$6716, 6731 flux is thus governed, in equilibrium, by the recombination rate.

If emission detected in the [S II]λ6716 line arises within a thickness of photodissociated gas of optical depth unity ($A_V = 2.5$), the corresponding column density of S II is 4.0×10^{16} cm^{-2}, where a fractional sulfur abundance of 8.5×10^{-6} (Rubin et al. 1991) and a gas column of 1.9×10^{21} N_{H}/A_V (Bohlin, Savage, & Drake 1978) have been assumed. If, on the basis of the above discussion, 25% of the sulfur ions are photoionized into the ^2D state, and thus, statistically, 15% into the $^2D_{5/2}$ state, radiating a λ6716 photon prior to either collisional de-excitation or recombination, the spectral line intensity corresponding to this column is

$$\begin{aligned} I[\mathrm{S\,II}] &= \frac{0.15\gamma_{\text{recomb}} N\,(\mathrm{S\,II})}{2\pi}\ \frac{A}{A + \gamma_{\text{coll}}} \\ &\approx 0.15\gamma_{\text{recomb}} N\,(\mathrm{S\,II})/2\pi \\ &\qquad \text{for } n\,(\mathrm{H\,I}) \ll 10^5\ \mathrm{cm}^{-3} \\ &= 1.0 \times 10^4\left(\frac{T}{100\ \mathrm{K}}\right)^{-0.593} n_e\ \text{photons cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ . \end{aligned} \tag{2}$$

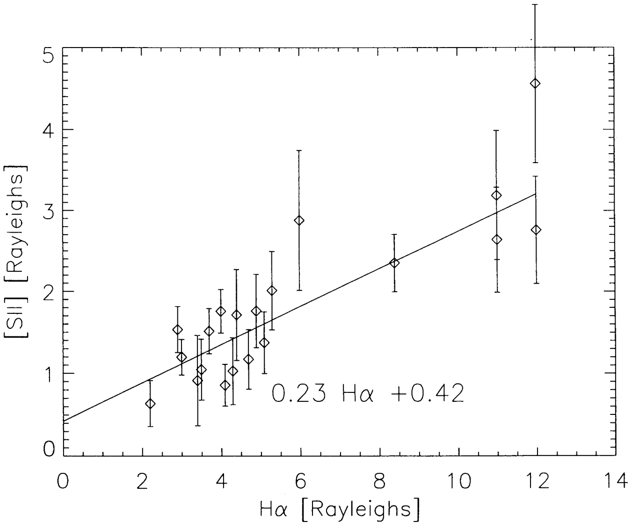

FIG. 7.—[S II]/S II data of Reynolds (1985) in Milky Way background fields, plotted against Hα.

Reynolds (1985) has observed [S II] in 20 of 21 Galactic "background" directions (with a 49′ field of view) devoid of identified H II regions, with fluxes plotted against Hα in Figure 7. Some of the scatter might be attributable to a small number of discrete interfaces per line of sight giving rise to the observed [S II] emission. If we assume a decomposition of the [S II] emission into a component arising in the ionized medium which scales as Hα, and an Hα-independent term, we obtain the fit shown in the figure. The linear dependence on Hα, attributed to the ionized component, corresponds, in the diffuse ionized limit, to a fractional abundance of sulfur in its singly ionized state of approximately $\frac{1}{2}$; however, this does not significantly constrain the conditions of the warm medium. The intercept of the fit suggests a contribution of (0.42 ± 0.19) rayleighs to the [S II] flux from neutral gas, while an F-test shows a zero intercept to be probable at a level no greater than 0.05.

As we have seen, the photoionization-excited emission mechanism is limited by the recombination rate, which in turn requires an electron density of 1–5 cm^{-3} to account for the Galactic background [S II] emission observed by Reynolds and attributed here to the neutral medium. Note that the absence of [O I] emission is consistent with a *cold* neutral medium. We have assumed a range of temperatures between 37 and 120 K, encompassing the lowest temperature consistent with the error limits derived by Allen, Snow, & Jenkins (1990) for the H I region along the line of sight toward σ Sco, and a typical PDR surface temperature of 120 K calculated for an average ISRF by Hollenbach et al. (1991).

If the electron density is no greater than the carbon density in this boundary layer, the inferred neutral hydrogen density lies in the range of $(8000 \pm 4000)\,(T/100\ \mathrm{K})^{0.593}\ \mathrm{cm}^{-3}$, within the 10^2–$10^5\ \mathrm{cm}^{-3}$ range typical of PDR interfaces of neutral clouds in the Galaxy (Hollenbach et al. 1991).

The total S II column density of $4 \times 10^{16}\ \mathrm{cm}^{-2}$ required within a neutral region to account for the background field excess of [S II] emission over that ascribable to the ionized medium is consistent with the S II column of $(3.4 \pm 1.4) \times 10^{16}\ \mathrm{cm}^{-2}$ observed by Allen et al. (1990) in one of the H I regions along the line of sight toward σ Sco and might be typical of extinction-limited lines of sight in the solar neighborhood.

4. SUMMARY

Background [S II] emission in the Milky Way and in the "froth" of external galaxies might be understood in the context of a significant contribution from FUV-illuminated neutral gas. Photoionization has been shown to account for excitation of emitting states in the absence of energetic electrons and [O I] emission. The [S II] emission due to a single optical depth of neutral gas may account for the observed excess in Galactic background directions over emission attributable to the ionized medium.

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REFERENCES

Allen, M. M., Snow, T. P., & Jenkins, E. B. 1990, ApJ, 355, 130
Altun, Z. 1992, J. Phys. B, 25, 2279
Binette, L., Dopita, M. A., D'Odorico, S., & Benvenuti, P. 1982, A&A, 115, 315
Blair, W. P., Kirshner, R. P., & Chevalier, R. A. 1981, ApJ, 247, 879
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Chapman, R. D., & Henry, R. J. 1971, ApJ, 168, 169
Comte, G. 1975, A&A, 39, 197
Daltabuit, E., D'Odorico, S., & Sabbadin, F. 1976, A&A, 52, 93
Dopita, M. A., Binette, L., D'Odorico, S., & Benvenuti, P. 1984, ApJ, 276, 653
Draine, B. T. 1978, ApJS, 36, 595
Ferland, G. J., & Mushotzky, R. F. 1984, ApJ, 286, 42
Fesen, R. A., Blair, W. P., & Kirshner, R. P. 1985, ApJ, 292, 29
Hester, J. J. 1991, PASP, 103, 853
Hollenbach, D. J., Takahashi, T., & Tielens, A. G. G. M. 1991, ApJ, 377, 192
Hunter, D. A., & Gallagher, J. S., III. 1990, ApJ, 362, 480
Joshi, Y. N., Mazzoni, M., Nencioni, A., Parkinson, W. H., & Cantu, A. 1987, J. Phys. B, 20, 1203
Kennicutt, R. C., Jr. 1992a, ApJ, 388, 310
———. 1992b, ApJS, 79, 255
Lehnert, M. D., & Heckman, T. M. 1994, ApJ, 426, L27
Matteucci, F. 1986, MNRAS, 221, 911
McCarthy, P. J., Heckman, T., & van Breugel, W. 1987, AJ, 92, 264
Meatheringham, S. J., & Dopita, M. A. 1991, ApJS, 75, 407
Mendoza, C. 1982, MNRAS, 198, 127
Péquignot, D., & Aldrovandi, S. M. V. 1986, A&A, 161, 169
Reynolds, R. J. 1985, ApJ, 294, 256
———. 1988, ApJ, 333, 341
Rubin, R. H., Simpson, J. P., Haas, M. R., & Erickson, E. F. 1991, ApJ, 374, 564
Russell, S. C., & Dopita, M. A. 1990, ApJS, 74, 93
Smith, R. C., Kirshner, R. P., Blair, W. P., Long, K. S., & Winkler, P. F. 1993, ApJ, 407, 564
Spitzer, L., Jr. 1978, Physical Processes in the Interstellar Medium (New York: Wiley)
Steigman, G., Werner, M. W., & Geldon, F. M. 1971, ApJ, 168, 373
Tayal, S. S. 1988, Phys. Rev. A, 38, 729
Tayal, S. S., Henry, R. J., & Nakazaki, S. 1987, ApJ, 313, 1987
Tielens, A. G. G. M., & Hollenbach, D. J. 1985, ApJ, 291, 722
Walterbos, R. A. M., & Braun, R. 1992, A&AS, 92, 625
Wilson, T., & Matteucci, F. 1992, Astron. & Astrophys. Rev., 4, 1