THE ASTROPHYSICAL JOURNAL, **262**:153–163, 1982 November 1

ABUNDANCES IN FIVE NEARBY GALACTIC H II REGIONS FROM INFRARED FORBIDDEN LINES

T. HERTER,[1] H. L. HELFER, AND J. L. PIPHER[1]
Department of Physics and Astronomy, University of Rochester
D. A. BRIOTTA, JR., W. J. FORREST, AND J. R. HOUCK
Department of Astronomy, Cornell University
AND
R. J. RUDY AND S. P. WILLNER
Center for Astrophysics and Space Sciences, University of California at San Diego
Received 1982 March 1; accepted 1982 May 3

ABSTRACT

Airborne measurements of the [Ar II] (6.99 μm) and [S III] (18.71 μm) lines for five compact H II regions in the solar neighborhood are presented, as well as 2–4 μm and 8–13 μm spectroscopy where available. From these data and radio data we deduce lower limits to the elemental abundances of Ar, Ne, and S. Some of these H II regions suffer substantial nebular extinction, and some are extended. After correcting for beam size effects and extinction, we find that four of the objects are consistent with standard abundances, within the uncertainties of correcting for unobserved ionization states. A Perseus arm object, S156, is apparently overabundant in sulfur.

Subject headings: infrared: spectra — nebulae: abundances — nebulae: H II regions

I. INTRODUCTION

Observations of infrared fine-structure lines in H II regions provide a probe of nebular conditions (Lacy 1980). Optical observations, which are limited by interstellar extinction to H II regions within a few kiloparsecs of the Sun, have yielded information on atomic abundances, excitation, temperature, and density of the gas (e.g., Hawley, 1978). Radio observations, while not suffering extinction, offer abundance determinations only for He^+ and sometimes C^+. Although extinction corrections may be significant, infrared observations are not so severely limited by extinction as those at optical wavelengths (Herter *et al.* 1981, hereafter Paper I). The benefits of probing to large distances from the Sun, or deep within a local molecular cloud, and the lack of severe temperature dependence of the lines make infrared fine-structure lines well suited for abundance analyses in our Galaxy.

In this paper we report ground-based and airborne spectroscopic observations of fine-structure lines from 2 to 30 μm for the compact H II region complexes of S156, S88B, S106, NGC 2170 (Mon R2), and Orion. Since these regions are all relatively nearby (9–13 kpc from the galactic center), and since all have optical counterparts, we have the opportunity to compare available optically determined abundances with the infrared estimates presented here. These observations, in concert with those reported previously (Paper I), will be used to discuss potential abundance and/or excitation gradients in the Galaxy.

The fine-structure lines studied here include [Ar III] (8.99 μm) and [Ar II] (6.99 μm); [S III] (18.7 μm) and [S IV] (10.51 μm); and [Ne II] (12.81 μm). These argon and sulfur ionization states constitute the major ionization states for H II regions with exciting stars of temperature $T_* = 30{,}000$–$45{,}000$ K for sulfur, and $T_* = 25{,}000$–$40{,}000$ K for argon according to simple, dust-free ionization structure models (e.g., Lacasse *et al.* 1980; Lacy 1980). Thus, we can measure total atomic abundances.

To estimate the extinction to the emission line regions we measure the ratio of the Brα/Brγ hydrogen recombination line strengths, the ratio of the Brackett lines to the free-free radio flux, and the depth of the 9.7 μm silicate feature.

II. OBSERVATIONS

The data described here were obtained with a variety of infrared systems. The 2–4 μm and 8–13 μm data were primarily obtained either at Kitt Peak National Observatory (KPNO) or the University of California at San Diego-University of Minnesota Mount Lemmon Observatory using CVF spectrometers with resolutions $\Delta\lambda/\lambda \sim 0.013$–$0.02$. These data, both previously published and new results, are noted in Table 1. Sampling densities are typically one to two data points per resolution element.

The 4–8 μm data reported here consist of observations in the [Ar II] line and adjacent continuum using the UCSD filter wheel spectrometer (Russell,

[1] Visiting Astronomer at Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1

LINE FLUXES

Object	Line	$\bar{\tau}_{9.7}$	Measured Line Flux (10^{-18} W cm^{-2})	Aperture (arcsec)	Reference	Line Flux Corrected for Extinction (10^{-18} W cm^{-2})
S88B	Ar III	3.6 ± 1.0	0.4 ± 0.2	11	1	7 ± 7
	S IV		0.7 ± 0.2	11	1	15 ± 13
	Ne II		7.0 ± 0.9	11	1	26 ± 11
	S III		9.0 ± 1.6	30	2	80 ± 50
	Ar II		12.0 ± 1.0	27	2	37 ± 12
S156	Ar III	0	1.5 ± 0.2	11	2	1.5 ± 0.2
	S IV		...	11	2	...
	Ne II		7.8 ± 0.9	11	2	7.8 ± 0.9
	S III		21 ± 4	30	2	21 ± 4
	Ar II		≤7.5	27	2	≤7.5
S106[a] Source 2	Ar III	1.5	<0.8	11	2	<3
	S IV		<2.0	11	2	<7
	Ne II		14.4 ± 1.9	11	2	25 ± 3
	S III		20.8 ± 3.0	30	2	52 ± 7
	Ar II		12.2 ± 1.2	27	2	19 ± 2
NGC 2170 IRS 1	Ar III	2.1 ± 0.3[b]	<2.0	7	2	<9
	S IV		<0.75	7	2	<4.5
	Ne II		23.0 ± 1.6	7	2	51.0 ± 6.0
	S III		14 ± 3	30	2	51 ± 15
	Ar II		14 ± 4	27	2	26 ± 8
M42 (20″ N θ^1C)	Ar III	0	3.4 ± 0.7	11	2	3.4 ± 0.7
	S IV		7.2 ± 1.0	11	2	7.2 ± 1.0
	Ne II		6.6 ± 0.5	11	2	6.6 ± 0.5
	S III		93 ± 12	30	2	93 ± 12
	Ar II		<12	27	2	<12

[a] S106 source 1, 15″ beam, almost identical line fluxes to S106 source 2.

[b] Adopted uncertainty.

REFERENCES.—(1) Pipher *et al.* 1977. (2) This paper.

Soifer, and Willner 1977; Puetter *et al.* 1979) on flights of the Kuiper Airborne Observatory (KAO) in 1979 June and December. For these observations a 27″ focal plane aperture was employed, and the chopped beam spacing and orientation were chosen to avoid beam cancellation.

The 16–30 μm data consist of spectra obtained with the Cornell University cooled grating spectrometer (McCarthy *et al.* 1979) on flights of the KAO in 1980 March and July. A focal plane aperture of 30″ and choice of beam throw similar to that used with the UCSD instrument were employed. The spectral resolution over the [S III] line is 0.2 μm, sampled at a density of approximately three points per resolution element. The complete spectra from 2–30 μm are presented in Figures 1–3 and 5–6. When different beam sizes were employed in different wavelength regions, we have *not* attempted to correct for beam size effects in plotting these spectra, since the ionization structure of the region prohibits simple scaling of the line intensities.

The observed line fluxes (uncorrected for extinction) are listed in Table 1 along with the beam sizes and references for the observations. The line fluxes for all but [Ar II] have been derived from a detailed line fit to the observations of the form $F_\lambda = a + b\lambda + c\{\exp -[(\lambda - \lambda_c)/\sigma_\lambda]^2\}$; that is, a linear continuum plus unresolved line emission at $\lambda = \lambda_c$, and $\sigma_\lambda \sim 0.6\Delta\lambda_{\rm FWHM}$, where $\Delta\lambda_{\rm FWHM}$ was determined from laboratory measurements. We vary a, b, and c to minimize $\chi^2 = \sum [(F_{\rm obs} - F_{\rm model})/\text{obs error}]^2$. For [Ar II] a single point in the line and one on either side in the adjacent continuum were used to determine the line flux. The spectral resolution determined in the laboratory was 0.10 μm.

III. DISCUSSION

a) *Estimating Extinction*

In Paper I we discussed extensively the nature of the extinction correction, and here we will only briefly review the correction techniques, the general philosophy of extinction correction, and the uncertainties involved. First, there is no guarantee that the extinction law is the same from region to region. Second, although we can accurately compute the extinction at 2.17 and 4.05 μm by (1) comparing observed and predicted Brackett fluxes with the free-free radio flux (assuming constant extinction over a beam size), or (2) by comparing the observed and predicted ratio of the Brackett fluxes, and assuming the form of the extinction law from 2 to 4 μm, we cannot easily extrapolate to the longer wavelengths at which the fine-structure lines appear. The 9.7 μm silicate extinction (Gillett *et al.* 1975*a*) has been determined by fitting the absorption spectrum of the 8–13 μm continuum radiation with an opacity law τ_λ which describes optically thin emission from hot dust in the Trapezium region from 8–13 μm. The underlying emission is assumed to be a gray body (model I) or a Trapezium emission spectrum (model II). Radiative transfer effects may be important (Kwan and Scoville 1976) but are not included. This method of extinction determination is quite uncertain. However, if $\tau_{8\,\mu m}$ derived by this method is approximately $0.5\tau_{4\,\mu m}$, where $\tau_{4\,\mu m}$ is determined from the Brackett line flux and also assuming a λ^{-1} extinction law to join these wavelengths,[2] then we can "choose" a model I or model II fit. Usually model II better fits the observations (minimizes the χ^2), and it is generally correlated with the measured value of $\tau_{4\,\mu m}$ (see also Lester and Rank 1980). As developed by Aitken *et al.* (1979*a*) and Jones *et al.* (1980), one can perform a multicomponent fit to the 8–13 μm spectrum including contributions from the unidentified 8.6 and 11.3 μm features as well as the 9.7 μm silicate feature. Where these features dominate the spectrum, we use this method to provide a better estimate of $\tau_{9.7}$. From observations of circumstellar shells, Forrest, McCarthy, and Houck (1979) conclude $\tau_{18.7\,\mu m} \sim 0.6\tau_{9.7\,\mu m}$, a relationship which also holds for galactic H II regions (McCarthy, Forrest, and Houck 1982).

In Paper I we have listed the adopted extinction law $\tau_\lambda/\tau_{9.7}$ used throughout. Mean values of $\bar{\tau}_{9.7\,\mu m}$ are computed for each region from all extinction techniques available, and $\tau_\lambda/\tau_{9.7}$ is then employed to deduce $\bar{\tau}_\lambda$, for the line fluxes listed in Table 1. All line fluxes, and the abundances calculated from them, reflect the estimated uncertainty in the adopted $\bar{\tau}_{9.7\,\mu m}$.

b) *Estimating Abundances*

Ionic abundances are estimated by comparison of the observed line fluxes with radio fluxes at frequencies where the nebulae are optically thin, using equation (3) of Paper I. In all the H II regions considered here, at 9–13 kpc from the galactic center, an electron temperature of 7500 K is appropriate (Wilson, Bieging, and Wilson 1979). The ratio of electrons to protons is assumed to be 1.15.

The prescription for computing total atomic abundances for argon and sulfur from the [Ar II], [Ar III], [S III], and [S IV] observations was discussed in Paper I. The abundances thus computed are strictly lower limits to the total abundance because (1) other ionization states may be present; (2) clumping may cause us to underestimate ionic abundances; (3) sources extended with respect to measurement beam sizes lead to exclusion of certain ionic contributions, as discussed in Paper I.

Since only one ionization state of neon is observed (Ne II), it is more difficult to comment on the total neon abundance. We will report in a separate paper theoretical predictions of the ratio of [Ne II/Ne] with [S III/S IV]. In most of the cases reported here, Ne II is expected to be the dominant ionization state, because all of the H II regions except M42 are low excitation objects. In the case of M42, optical estimates of [Ne III/H] are available. In this paper, we adopt a standard neon abundance [Ne/H] of 1×10^{-4} rather than 1.5×10^{-4} assumed in Paper I. This new value is deduced by Aller (1978) and Beck *et al.* (1981) from observations of planetary nebulae.

c) *Individual Sources*

S88B = G61.5+0.1.—The Hα knot, S88B, near the diffuse H II region S88 and the Hα knot S88A, has been studied previously by a number of investigators. Infrared maps by Zeilik (1977) and Pipher *et al.* (1977) revealed extended structure at 2.2 μm and 12.6 μm that encompassed the radio compact structure (Felli, Tofani, and D'Addario 1974; Felli and Harten 1981) as well as the more diffuse Hα knot. Maps of S88B at 1.6 μm, 2.2 μm, 3.4 μm, 50 μm, and 100 μm by Evans *et al.* (1981) confirm the extent of the IR source, and the 5 GHz maps of Felli and Harten delineate radio emission in the dark cloud to the east of the Hα knot. The latter authors resolve two components to S88B, namely a high electron density ($\geq 1.9 \times 10^4$ cm^{-3}), high emission measure ($\geq 1.8 \times 10^7$ pc cm^{-6}), unresolved source S88B-2, and a normal compact region source S88B-1 which contributes most of the radio flux. Molecular maps of the region close to S88B by Evans *et al.* extend all the way to S88A where an exciting star has been identified; the distance to this star places S88A at 2 kpc from the Sun. We adopt that distance in what follows.

The radio maps of Felli and Harten correspond to a completely obscured region at the peak position of S88B-1. Since the eastern edge of the Hα knot is very sharp, and since radio emission extends across this edge, there must be differential extinction. This is consistent with the assumption that the compact H II region is embedded in dark cloud material, and the Hα knot is a "blister" model artifact. The infrared maps of Pipher *et al.* (1977) and Evans *et al.* (1981) peak at different spatial positions than the radio peak, in the sense that longer wavelength maps peak closer to the radio center. This might also be interpreted as evidence for differential extinction, but the possibility of additional near-infrared heating sources cannot be discounted.

We have obtained new data centered on S88B-1 at wavelengths in and near the [Ar II] and [S III] lines, and these data as well as previously published data discussed below are plotted in Figure 1.

Extinctions have been estimated at several positions by different techniques. First, 2–4 μm spectroscopy on S88B at the peak 2.2 μm position was reported by Pipher *et al.* (1977). The Brα and Brγ line fluxes quoted by them incorporate an error in the assumed spectral resolution of the spectrometer. New line fits to the data lead to observed fluxes of $4.0 \pm 0.7 \times 10^{-19}$ W cm^{-2} in the 17″ beam at 2.17 μm (Brγ) and $3.1 \pm 0.6 \times 10^{-18}$ W cm^{-2} at 4.05 μm (Brα). The ratio of observed line fluxes compared to the predicted ratio $F(\mathrm{Br}\alpha)/F(\mathrm{Br}\gamma) = 2.84$ (case B, $N_e \sim 10^4$ cm^{-3}, $T_e = 7500$ K), using the extinction law from Paper I, yields an extinction of $\tau_{2.17\,\mu m} = 2.2 \pm 0.8$. This value corresponds to $A_v = 26 \pm 9$ mag and $\tau_{9.7\,\mu m} = 2.3 \pm 0.8$. The extinction to the

[2] Independent observations of obscured stars (Hackwell and Gehrz 1974 and Gillett *et al.* 1975*b*) suggest an extinction law of this form.

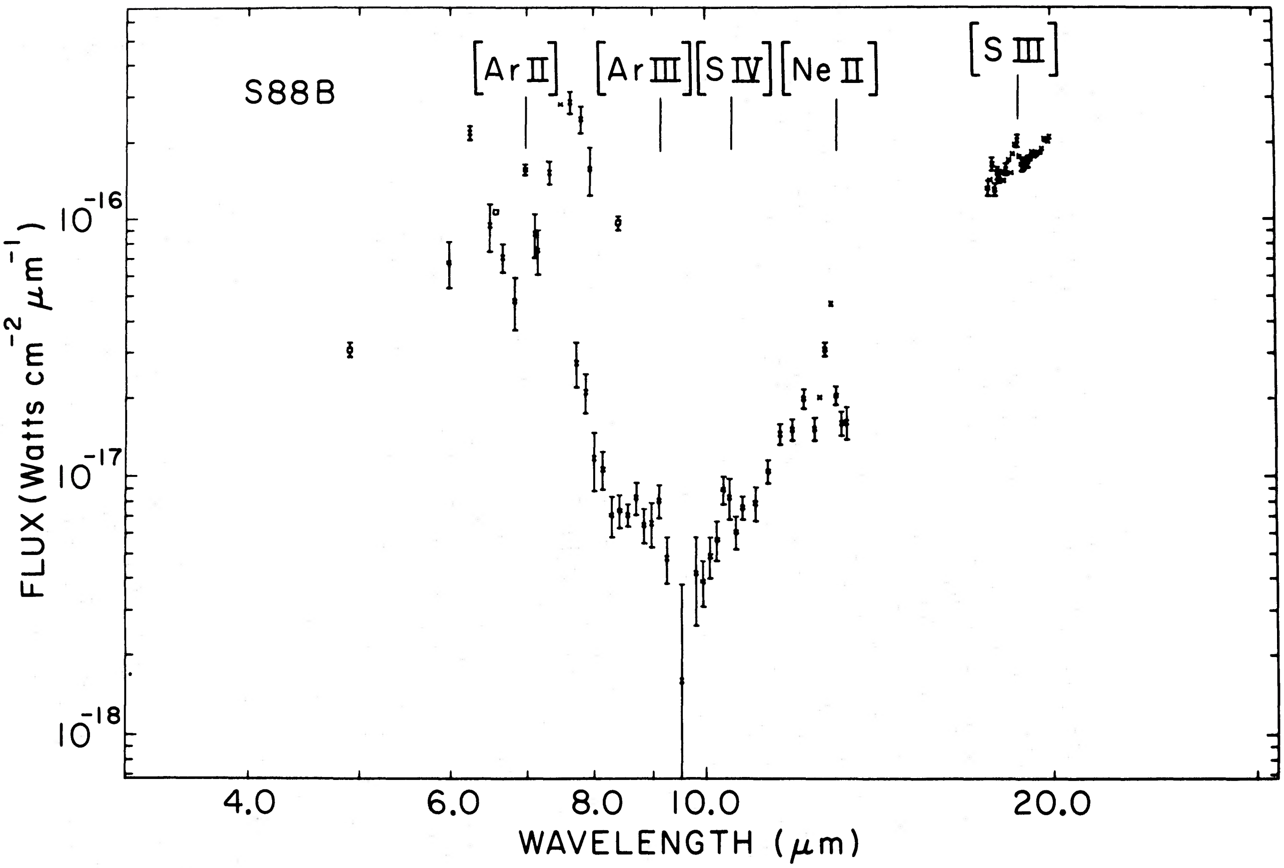

FIG. 1.—The 4–30 μm spectrum of S88B. Squares denote broad-band observations with a 27″ beam. The beam sizes were 27″ from 4 to 8 μm, 30″ from 16 to 30 μm, and 11″ from 8 to 13 μm. Error bars are shown for points where statistical uncertainties exceed 5%.

Hα knot of ~4 mag suggests the Hα knot is in the foreground.

Another extinction estimate, at the peak 12.6 μm position, is derived from the 8–13 μm continuum data (Pipher *et al.* 1977). A model II fit to the 9.7 μm silicate absorption feature leads to $T_{\rm dust} = 290$ K and $\tau_{9.7\,\mu{\rm m}} = 3.6$. The mean extinction is substantially larger than that found at the peak 2.2 μm position. Since the 12.6 μm peak position is closer to the visual eastern "edge" of the Hα knot and to the radio center than the 2.2 μm peak position, a gradient in the extinction is suggested. We assume that the discrepancy in $\tau_{9.7}$ between the two positions is real, and adopt $\tau_{9.7} = 3.6$ for the ionic line fluxes of [Ar III], [Ne II], and [S IV] observed from 8–13 μm. The line fluxes observed with the larger beams used at 16–30 μm and 4–8 μm ([S III] and [Ar II]) probably include both obscuring regions as well as an even more heavily obscured region centered on the radio peak; we adopt $\tau_{9.7} = 3.6$ in interpreting those data. Estimating the uncertainty in $\tau_{9.7}$ is more difficult, but we adopt a value of 1.0.

Line fluxes of [Ar II], [Ar III], [Ne II], [S III], and [S IV] are listed in Table 1, both measured and corrected for extinction. Uncertainties quoted reflect uncertainty in the extinction correction as well as in the line measurement. The radio data of Felli and Harten show that the compact H II region with a half power diameter of 21″ provides the bulk of the total flux of 6.1 Jy at 5 GHz. The radio interferometer results of Pipher *et al.* (1977) gave 4.3 Jy at 2.7 GHz in a 15″ diameter region, and Felli and Harten show that the object is optically thin at these frequencies. At 2 kpc, a single 35,000 K ZAMS star could supply the ionizing radiation and would give reasonably low excitation. We assume a radio flux of 6.1 Jy for the [Ar II] and [S III] measurements and we adopt 2.3 Jy for the [Ar III], [Ne II], and [S IV] measurements. Using equation (3) of Paper I, we compute the ionic abundances, which are listed in Table 2, relative to standard atomic abundance. The argon and sulfur ionic abundances taken at face value are consistent with S88B having standard atomic abundance. Because S88B is a relatively low excitation region, we expect that roughly 50% of the neon is in the form of Ne II. Within the uncertainty of correcting for other ionization states, we conclude that the neon abundance may be consistent with standard abundance or may be underabundant in S88B ($\geq 0.5 \times$ standard).

S156 = G110.1+0.0.—This compact H II region has been studied optically by Deharveng (1974), Glushkov and Karyagina (1972), and Heydari-Malayeri *et al.*

TABLE 2

IONIC ABUNDANCES RELATIVE TO STANDARD ABUNDANCES[a]

$\frac{\langle N_x{}^i/N_H \rangle}{(N_x/N_H)}$ standard

Object	Ar III	S IV	Ne II	S III	Ar II
S88B	<0.5	<0.2	0.3 ± 0.1	0.7 ± 0.5	1.5 ± 0.5
S156	0.26 ± 0.03	...	0.48 ± 0.04	1.7 ± 0.3	<3
S106	<0.2	<0.1	0.62 ± 0.05	1.0 ± 0.2	1.5 ± 0.2
NGC 2170 IRS 1	<0.3	<0.03	0.50 ± 0.04	0.4 ± 0.1	0.8 ± 0.3
M42 (20″ N θ_1C)	0.6 ± 0.1	0.27 ± 0.04	0.41 ± 0.02	1.0 ± 0.1	<0.8

[a] Assumed standard abundances: S/H = 1.6×10^{-5}; Ar/H = 4.7×10^{-6}; Ne/H = 1.0×10^{-4}.

(1980), and at radio wavelengths by Israel, Habing, and de Jong (1973), Israel (1977), and Birkinshaw (1978). Its optical diameter is ~30″, and the strong compact radio source corresponds to the northern optical condensation. The central star is visible, and the O7 V spectral classification is consistent with the observed optical ionization structure.

Spectrophotometric data from 2 to 4 μm obtained at Mount Lemmon in 1979 November and from 8 to 13 μm at the KPNO 2.1 m telescope in the same month around the [Ar III] and [Ne II] lines, are shown in Figure 2. We present the averaged data from several nights. Radio observations, at 5 GHz (Israel 1977), indicate a dominant 0.59 Jy source, 5″ × 12″ in size with two weaker components positioned ~15″ south of the main source of flux density 0.04 Jy each. For computation of all ionic abundances, 0.59 Jy will be used for comparison with the measured line fluxes.

The extinction to S156 appears to be fairly uniform over the whole nebula and has an average value of $A_v \approx 3.6$ mag with some positions in the central bright part having $A_v = 5$ mag (Israel 1977 and references

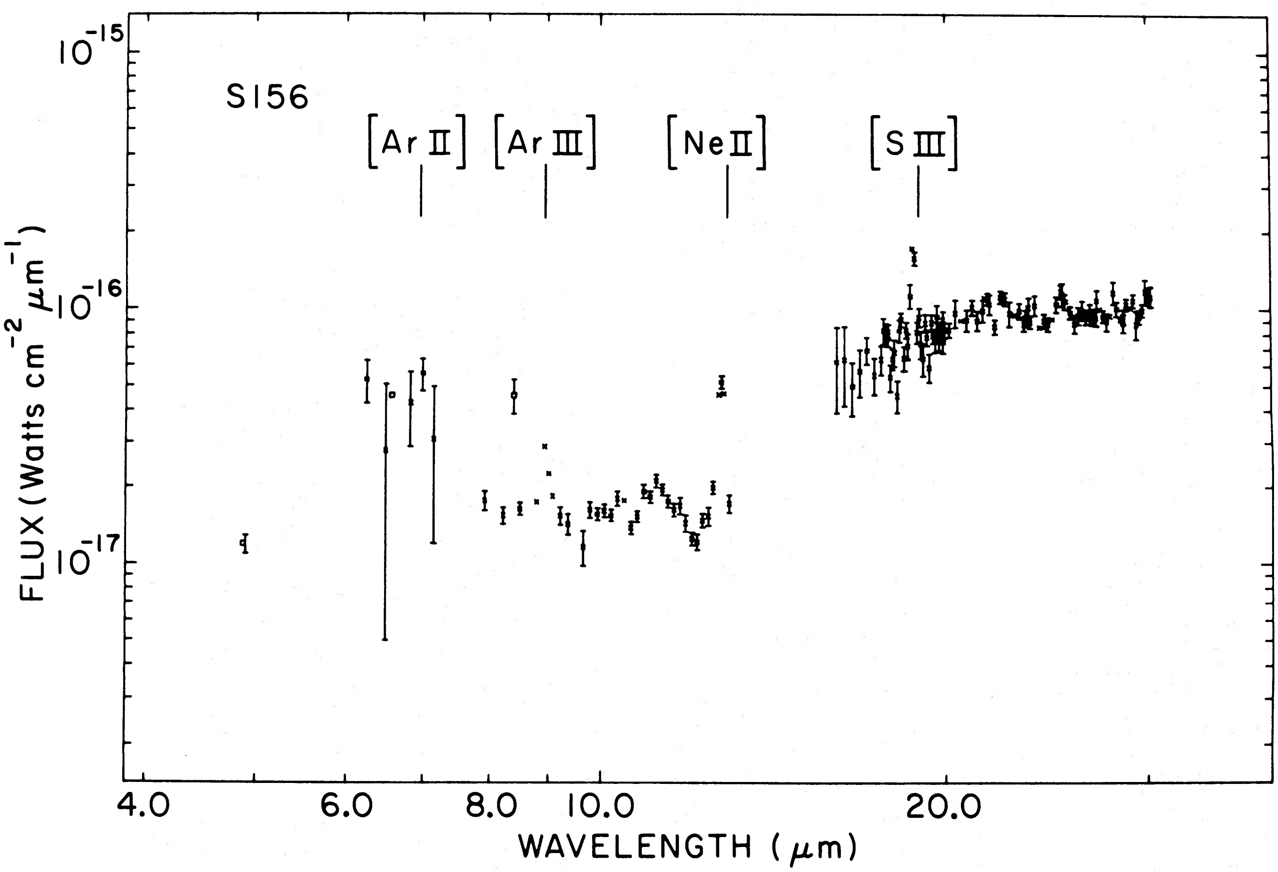

FIG. 2.—The 4–30 μm spectrum of S156

therein). Since this represents $\tau_{9.7} \leq 0.40$ and *at most* a 30% correction to the observed line fluxes, a conservative value of zero will be adopted for $\tau_{9.7}$. This is consistent with the extinction deduced from a ratio of the Brackett fluxes and from the shape of the 8–13 μm spectrum.

The computed ionic abundances relative to the standard elemental abundances are given in Table 2. Ar II was not detected, and S IV was not reliably measured; hence, we cannot combine ionic abundances or estimate the [Ar III/Ar II] or [S IV/S III] ratios; however, [S III] alone is 1.7 times greater than standard. In addition we note that for our calculated emissivities for S156 we adopted an rms value of $N_e^{\rm rms} = 5200\ \rm cm^{-3}$ as found by Israel, but as Israel points out, [S II] measurements by Glushkov and Karyagina and Deharveng yield electron densities as high as $N_e = 19{,}000\ \rm cm^{-3}$, indicating massive clumping in the nebula with $\phi \leq 0.1$ (ϕ = filling factor). This high density, if adopted, will have little effect on the ionic abundances of Ne II and Ar III but will increase the estimate above the S III abundance by 60% due to a decrease in the calculated emissivity at the higher density.

In conclusion, S156 exhibits ionic abundances for Ne II and [Ar III] which are consistent with the adopted standard atomic abundances of Ne and Ar, while S III has an ionic abundance approximately two times higher than standard.

Although S156 has not been included in an optical abundance program to our knowledge, Talent and Dufour (1979) conclude certain radial abundance gradients in a given spiral arm (including the Perseus arm) are larger than the average over the same range in galactocentric distance. Perhaps the enhanced sulfur abundance observed in S156 might be a result of such an effect. A greater sample of regions in the Perseus arm will be needed to confirm Talent and Dufour's conclusion.

S106 = G76.4 − 0.6.—Radio and infrared observations of the S106 complex (Pipher *et al.* 1976; Israel and Felli 1978; Tokunaga and Thompson 1979; Lucas *et al.* 1978) have revealed a bipolar nebula with an infrared point source (source 3 in the notation of Pipher *et al.* 1976) surrounded by three to four compact H II regions. The centroid of the cluster is somewhat displaced to the east from the diffuse Hα nebulosity. Eiroa, Elsässer, and Lahulla (1979) obtained a series of photographs in the *I* and *R* passbands and found nebulous knots close to the compact H II region centers 1, 2, and 4 in the notation of Pipher *et al.* (1976) and A, C, and B in the notation of Israel and Felli. These compact H II regions contribute only 20%–25% of the total synthesized radio flux (Israel and Felli 1978). A highly absorbing disk of dust seen edge-on crosses in front of the point source 3, which has been proposed as the single source of excitation for the complex. The distance to S106 is quite uncertain, and distance estimates range from 500 pc to 3.6 kpc. Eiroa, Elsässer, and Lahulla (1979) discuss these distance estimates and reconcile the spectrum and luminosity of source 3 with a single B0 V star (attenuated by $A_v = 22$ mag) as sole exciting source of the complex at a distance of 500 pc.

Hefele and Hölzle (1980) present 8–13 μm spectroscopy at $\Delta\lambda/\lambda = 0.019$, with a 24″ aperture and a 45″ beam separation in right ascension for sources 1, 2, and 3. Unfortunately, their beam sizes were large enough to include not only the compact H II regions 1 and 2 (diameters 8″ × 8″ and 18″ × 12″, respectively; Israel and Felli 1978) but also the regions beyond the ionization edges where radiation in the 11.3 μm emission feature is strongest (Aitken *et al.* 1979*b*). This complicates interpretation of their deduction of the 9.7 μm absorption optical depth, as discussed in detail by Aitken *et al.* (1979*b*). We present in Figure 3 new 8–13 μm spectra on sources 1 and 2, obtained with an 11″ beam, and an EW beam separation of 50″. As can be seen, a small 11.3 μm feature as well as an 8.6 μm feature are present, but they do not dominate the 8–13 μm spectrum as in the observations of Hefele and Hölzle (1980). The model II silicate absorption depth (model II fit) is $\tau_{9.7} = 2.6$ for both regions when the 8.6 and 11.3 μm features are not allowed for. A multicomponent fit, also incorporating the 8.6 and 11.3 μm features, leads to $\tau_{9.7} = 1.5$ for both sources 1 and 2. This estimate exceeds the Calvet and Cohen (1978) estimate of $A_v = 8$ mag to optical knot 8 and the Eiroa, Elsässer, and Lahulla (1979) estimate of $A_v = 5$ mag and 11 mag to optical-infrared knots *close* to the positions of sources 1 and 2 (corresponding to $\tau_{9.7} = 0.4$ and 0.9, respectively). Our multicomponent fit excludes $\tau_{9.7} < 1$, which leads to the conclusion that the compact H II regions are not identifiable with the optical nebulosity.

By reference to the complete radio synthesis map of S106 by Israel and Felli, we ascertain that our observing aperture contained the 8″ × 8″ compact structure of source 1 plus some diffuse emission and most of the 8″ × 18″ compact structure of source 2, respectively. Israel and Felli measure 5 GHz radio fluxes of 0.8 and 1.3 Jy for sources 1 and 2; we estimate 1.5 Jy radio flux in our beam size for each compact H II region.

The 4–8 μm and 16–30 μm observations, obtained on KAO as described in § II, used 27″ and 30″ beams, respectively, centered on the infrared point source 3, which has no radio counterpart. In Figure 4 we depict the KAO beam position on a 2.7 GHz radio map obtained by Pipher *et al.* (1976), which is of lower resolution than Israel and Felli's map but which is otherwise comparable. We estimate a radio flux of ~3 Jy within the KAO beam sizes.

These observations are presented in Figure 3, and the line fluxes measured are listed in Table 1. Corrected fluxes were obtained for an extinction of $\tau_{9.7} = 1.5$. With this value of $\tau_{9.7}$, the total sulfur abundance and argon abundance are found to be approximately standard, and the ionized neon fraction is approximately 0.6 standard. This region is a low excitation H II region, so we take the total neon abundance to be consistent with standard abundance.

NGC 2170 = Mon R2.—Beckwith *et al.* (1976) discovered a cluster of infrared sources associated with the

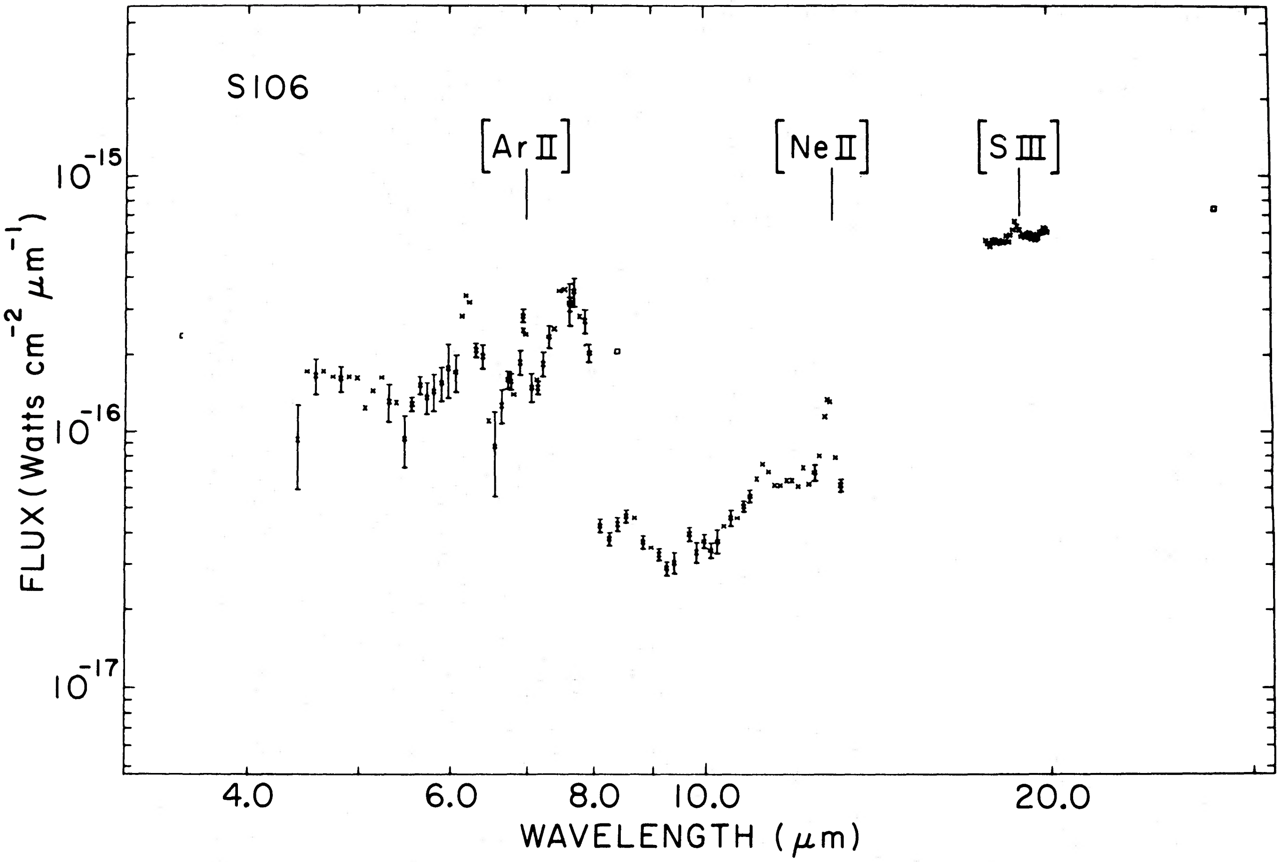

FIG. 3.—The 4–30 μm spectrum of S106

peak of the molecular cloud in Mon R2, which is an association of reflection nebulae. These sources are coincident with a region containing compact H II region(s), a type I OH maser and an H_2O maser (Downes *et al.* 1975; Brown, Knapp, and Kuiper 1976). A high resolution radio continuum map at 5 GHz obtained by Simon, Righini-Cohen, and Fischer (1981) with the VLA reveals a compact H II region approximately 20″ in diameter with the peak radio flux at IRS 1. Little continuum emission appears around the nearby source IRS 2. Since the extinction to IRS 2 at 9.7 μm is about a factor of 2 greater than that to IRS 1 (Beckwith *et al.* 1976; Pipher 1981), IRS 2 may be a background object. For these reasons IRS 1 is taken to be the dominant source of infrared forbidden line emission.

Spectroscopic data from 8–13 μm obtained with a 7″ aperture at KPNO are shown in Figure 5. The extinction was computed using the method of Gillett *et al.* (1975*a*) to obtain the model II value of $\tau_{9.7}$. In addition, 4–8 μm and 16–30 μm measurements were obtained on KAO, and the 27″ and 30″ beam sizes probably encompass the entire H II region. Unfortunately we do not have 2–4 μm data on this source. Only the [Ne II] line was detected from 8–13 μm, and scans across IRS 1 show that [Ne II] fills the H II region. Because [Ar II] and [S III] were the only ions of argon and sulfur detected, we can say that NGC 2170 is a low excitation H II region, and that [Ne II] is the primary ionization state of neon. The line fluxes, both corrected and observed, are listed in Table 1.

The abundances are computed assuming a radio flux of 3.8 Jy for the 7″ aperture measurements and 7.5 Jy for the KAO data. Although the argon abundance is approximately standard, the sulfur abundance (S III + S IV) is somewhat low compared to the other H II regions that have been sampled. A probable explanation for this latter result is the low temperature of the exciting star (see below) which would result in most sulfur being in the [S II] ionization state. For an assumed distance of 0.95 kpc (Beckwith *et al.* 1976), the observed 7.5 Jy radio continuum flux at 5 GHz (Simon *et al.* 1981) implies only a 31,000 K exciting star, although this probably is a lower limit to the stellar temperature due to possibility of absorption of Lyman-continuum photons by dust within the H II region. The ionized neon abundance is ~0.5 standard abundance. Since NGC 2170 IRS 1 is of *very* low excitation, it is possible that neon is somewhat underabundant in this region.

M42: The Orion Nebula.—M42, containing the closest compact H II region to us, is, of course, the best studied. For example, it was because silicate dust in Orion was

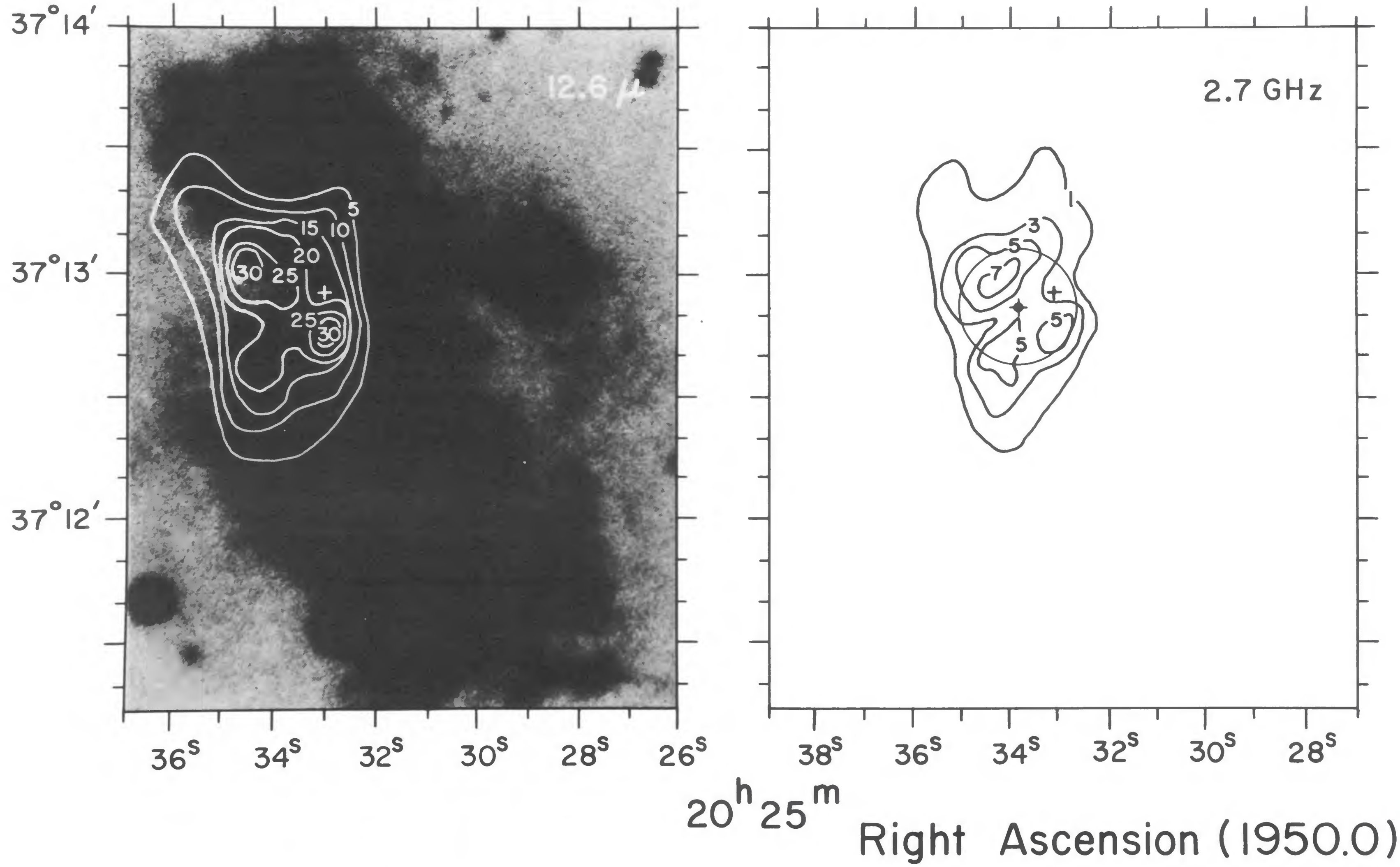

FIG. 4.—(*left*) An infrared map of S106 superposed on a Palomar E plate, showing the location of the infrared sources. (*right*) The 2.7 GHz map of S106 by Pipher *et al.* with the KAO beam location marked by a circle centered on source 3.

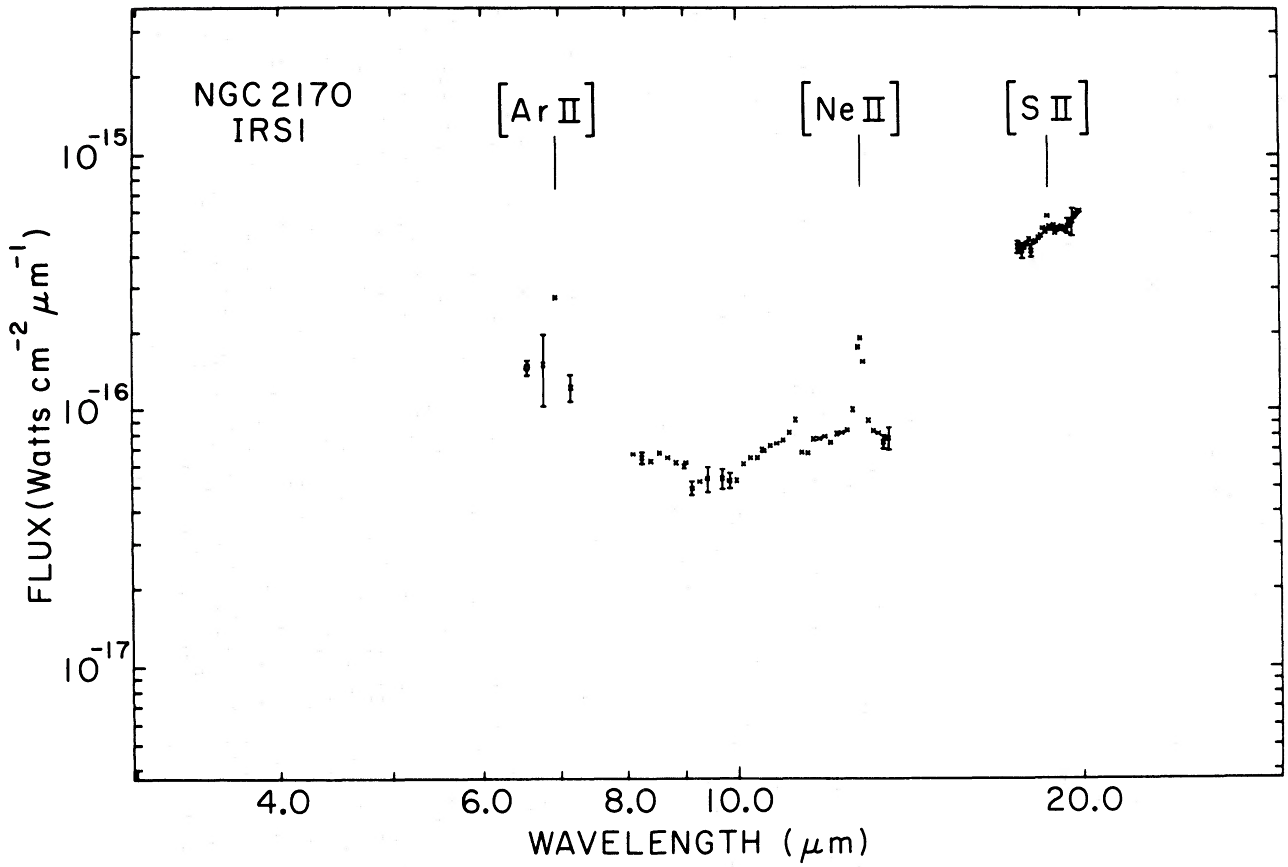

FIG. 5.—The 4–30 μm spectrum of NGC 2170 IRS 1. The 8–13 μm data are multiplied by a factor of 10. The beam sizes employed and chopper throws are discussed in the text, for all sources.

observed in emission at 9.7 μm that the model II fit of Gillett *et al.* (1975*a*) is typically quoted in assessing the extinction, $\tau_{9.7}$. Thus, it is natural to obtain observations of the fine-structure lines at various locations in the compact H II region. Unfortunately, however, the angular extent of the nebula is sufficiently large that we cannot beamswitch off the region, so that there is always some reduction in signal level.

We have obtained observations at several positions in Orion, but report here only observations 20″N of θ^1C, which are shown in Figure 6. The 8–13 μm observations were obtained at KPNO, with an 11″ beam and a 48″ N-S beam throw. The 4–8 μm and 16–30 μm data were obtained on KAO with ~30″ beams, and beam throws of 2′.5 E-W, and 2′.0 N-S, respectively. Radio fluxes were estimated from the 5 GHz maps of Martin and Gull (1975) and are assumed to be 0.6 Jy in the beam corresponding to the 8–13 μm observations, and 4.4 and 3.6 Jy in the 16–30 μm and 4–8 μm observation beam sizes, respectively. Extinction to this part of Orion is negligibly small. The line fluxes are listed in Table 1 and ionic abundances relative to hydrogen are reported in Table 2.

For the case of sulfur, where more than one ionic state was detected, the ionic abundances can be combined. (See Paper I for the formalism.) If the S IV does not extend beyond the 11″ beam, then the total sulfur abundance is approximately 1.0 ± 0.1 times standard, whereas if the S IV extends to at least the limits of the 30″ beam, then the sulfur abundance would be 1.3 ± 0.2 times standard. The ionic abundances of Ar III and Ne II are 0.6 ± 0.1 and 0.41 ± 0.03 times standard, respectively. These latter ionic abundances will be significant underestimates of the total elemental abundances of Ar and Ne for two reasons. As mentioned previously, due to the extended nature of the source, the 53″ N-S chop employed in the observations is inadequate to prevent cancellation effects which decrease the observed fluxes. Lester, Dinerstein, and Rank (1979), who obtained measurements on the radio continuum peak 1″ W and 10″ S of θ^1C with a 10″ beam and a 26″ N-S chop, find correction factors of 4.8 for their [Ar III] and [Ne II] measurements, and 1.3 for their [S IV] measurements from multiple beam switching techniques (to extend the chop to 100″) and drift scans in Hα. Second, for an O6 exciting star, higher ionization states such as A IV and Ne III can be expected to contribute significantly to abundance estimates. Lester,

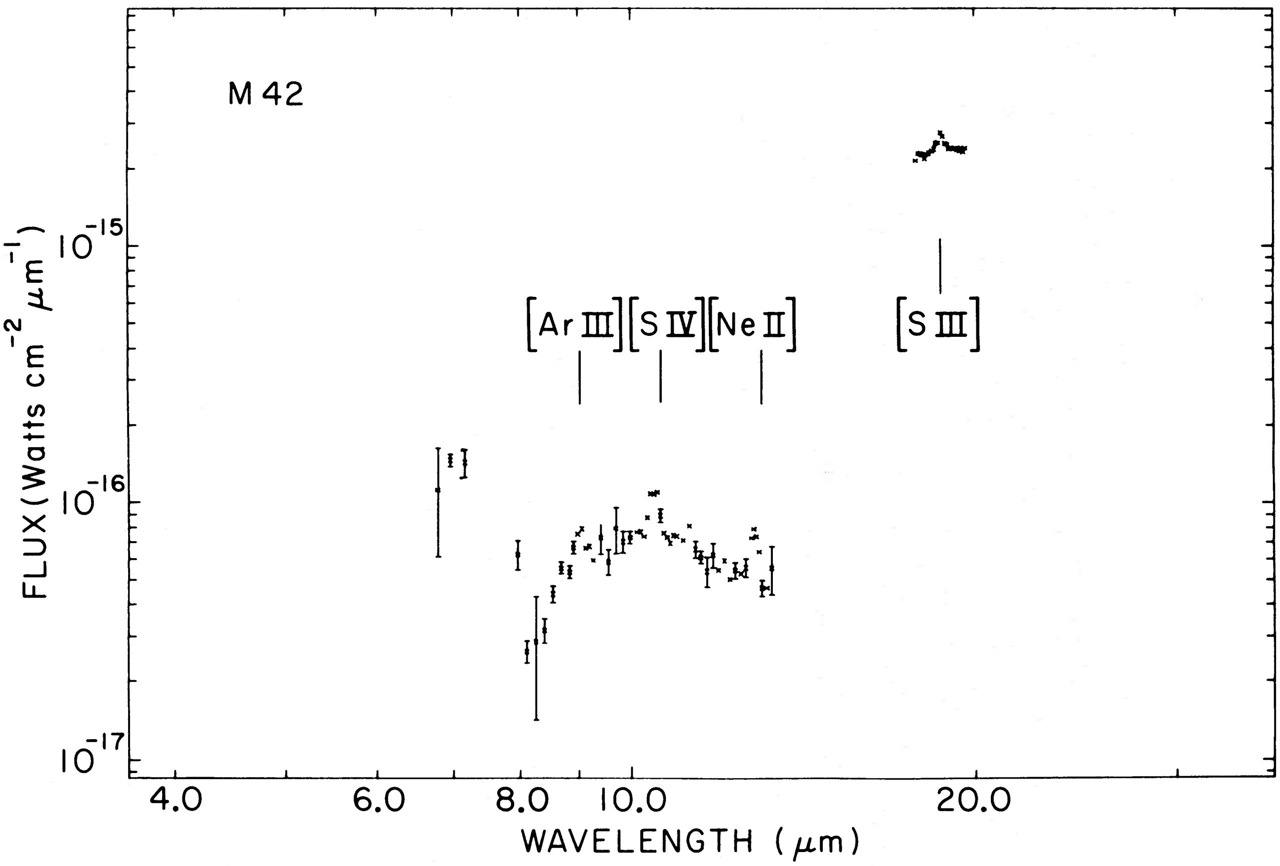

FIG. 6.—The 4–30 μm spectrum of M42, at a position 20″ N of θ^1C

Dinerstein, and Rank (1979) measured [Ne III] optically with a beam size similar to their infrared measurements and find 70% of the neon to be Ne III in the region they sampled. They found ionic abundances of 0.75, 0.60, and 0.26 relative to our adopted standard abundances for S III, S IV, and Ne II, respectively, with S II being negligible. Upon comparison with the results reported here, we find that the spatial position sampled by Lester, Dinerstein, and Rank (1979) appears to be of considerably higher excitation than the position we sampled. The total sulfur abundance deduced by both groups is in agreement.

Optical abundances have been measured for Orion by Peimbert and Torres-Peimbert (1977). They sample a position 45″ N of θ^1C and find ionic abundances of 0.8 standard neon abundance for Ne III, 0.03 standard sulfur abundance for S II, and 0.6 standard sulfur abundance for S III. They deduce, on the basis of their ionization state correction procedures, a total neon abundance of 0.93 standard, and a total sulfur abundance of 1.9 standard. Because of differing beam sizes, it is difficult to make quantitative comparisons. However, our Ne II abundance of 0.4 standard agrees qualitatively with Peimbert and Torres-Peimbert's conclusion that greater than 50% of the neon is Ne III.

IV. CONCLUSIONS

We have gathered infrared line fluxes for [Ar II], [Ar III], [Ne II], [S III], and [S IV] in five compact H II regions in the solar neighborhood. With the exception of M42, the regions are all low excitation objects with temperatures of the exciting stars <35,000 K. This result is consistent with radio excitation parameters for the objects. We have corrected the line fluxes of these objects for extinction and beam size effects using the techniques developed in Paper I. Since our sample includes one extended object with virtually no extinction and several small and extended objects embedded in molecular cloud material, as well as one small object with negligible extinction and since the abundances calculated are for the most part consistent with standard abundance for the solar neighborhood, we claim that the techniques used in these analyses are thus validated. Thus, when we combine the results of this paper, Paper I, and recently obtained results on a larger sample of objects close to the galactic center in a future paper, we can evaluate whether excitation and abundance gradients exist in the Galaxy. Gradients not only with galactocentric distance but also in a spiral arm will be assessed once a larger sample of H II regions has been observed. It is interesting to note an overabundance of S in the Perseus arm object

S156 in the present paper; we shall compare S156 with other Perseus arm objects in a future paper to assess whether abundance variations in H II regions at a given galactocentric radius are spiral arm dependent.

We wish to thank the staff of KAO and KPNO for their excellent support. In addition, we thank George Gull of Cornell University for his devoted assistance. Infrared Astronomy at Cornell University, University of Rochester, and University of California at San Diego is supported by grants from NASA.

REFERENCES

Aitken, B. K., Roche, P. F., Spenser, P. M., and Jones, B. 1979*a*, *Ap. J.*, **233**, 925.
———. 1979*b*, *Astr. Ap.*, **76**, 60.
Aller, L. H. 1978, in *IAU Symposium 76, Planetary Nebulae, Observations and Theory*, ed. Y. Terzian (Dordrecht: Reidel), p. 225.
Beck, S. C., Lacy, J. H., Townes, C. H., Aller, L. H., Geballe, T. R., and Bras, F. 1981, *Ap. J.*, **249**, 592.
Beckwith, S., Evans, N. J., II, Becklin, E. E., and Neugebauer, G. 1976, *Ap. J.*, **208**, 390.
Birkinshaw, M. 1978, *M.N.R.A.S.*, **182**, 401.
Brown, R. L., Knapp, G. R., and Kuiper, T. B. H. 1976, private communication referenced in Beckwith *et al.* (1976), above.
Calvet, N., and Cohen, M. 1978, *M.N.R.A.S.*, **182**, 687.
Deharveng, L. 1974, *Astr. Ap.*, **35**, 63.
Downes, D., Winnberg, A., Goss, W. M., and Johansson, L. E. B. 1975, *Astr. Ap.*, **44**, 243.
Eiroa, C., Elsässer, H., and Lahulla, J. F. 1979, *Astr. Ap.*, **74**, 89.
Evans, N. J., II, Blair, G. N., Harvey, P., Israel, F., Peters, W. L., III, Scholtes, M., de Graauw, T., and Van den Bout, P. 1981, preprint.
Felli, M., Tofani, G., and D'Addario, L. 1974, *Astr. Ap.*, **31**, 431.
Felli, M., and Harten, R. H. 1981, preprint.
Forrest, W. J., McCarthy, J. T., and Houck, J. R. 1979, *Ap. J.*, **233**, 611.
Gillett, F. C., Forrest, W. J., Merrill, K. M., Capps, R. W., and Soifer, B. T. 1975*a*, *Ap. J.*, **200**, 609.
Gillett, F. C., Jones, T. W., Merrill, K. M., and Stein, W. A. 1975*b*, *Astr. Ap.*, **45**, 77.
Glushkov, Y., and Karyagina, Z. V. 1972, *Astr. Circ. USSR*, **711**, 4.
Hackwell, J., and Gehrz, R. 1974, *Ap. J.*, **194**, 49.
Hawley, S. A. 1978, *Ap. J.*, **224**, 417.
Hefele, A., and Hölzle, E. 1980, *Astr. Ap.*, **88**, 145.
Herter, T. L., *et al.* 1981, *Ap. J.*, **250**, 186 (Paper I).
Heydari-Malayeri, M., Testor, G., and Lortet, M. C. 1980, *Astr. Ap.*, **84**, 154.
Israel, F. J. 1977, *Astr. Ap.*, **59**, 27.
Israel, F. J., and Felli, M. 1978, *Astr. Ap.*, **63**, 325.
Israel, F. P., Habing, H. J., and de Jong, T. 1973, *Astr. Ap.*, **27**, 143.
Jones, B., Merrill, R. M., Stein, W., and Willner, S. P. 1980, *Ap. J.*, **242**, 141.
Kwan, J., and Scoville, N. J. 1976, *Ap. J.*, **209**, 102.
Lacasse, M. L., Herter, T., Krassner, J., Helfer, H. L., and Pipher, J. L. 1980, *Astr. Ap.*, **86**, 231.
Lacy, J. H. 1980, in *IAU Symposium 96, Infrared Astronomy*, ed. C. G. Wynn-Williams and D. P. Cruikshank (Dordrecht: Reidel), p. 239.
Lester, D., Dinerstein, H. L., and Rank, D. 1979, *Ap. J.*, **232**, 139.
Lester, D., and Rank, D. 1980, preprint.
Lucas, A. M., Le Squeren, A. M., Kazes, I., and Encrenaz, P. J. 1978, *Astr. Ap.*, **66**, 155.
Martin, A. H. M., and Gull, T. 1976, *M.N.R.A.S.*, **175**, 235.
McCarthy, J. F., Forrest, W. J., and Houck, J. R. 1979, *Ap. J.*, **231**, 711.
———. 1982, *Ap. J.*, submitted.
Peimbert, M., and Torres-Peimbert, S. 1977, *M.N.R.A.S.*, **179**, 217.
Pipher, J. L. 1981, private communication.
Pipher, J. L., Sharpless, S., Savedoff, M. P., Kerridge, S. J., Krassner, J., Schurmann, S., Soifer, B. T., and Merrill, K. M. 1976, *Astr. Ap.*, **51**, 255.
Pipher, J. L., Sharpless, S., Savedoff, M. P., Krassner, J., Varlese, S., and Soifer, B. T. 1977, *Astr. Ap.*, **59**, 215.
Puetter, R. C., Russell, R. W., Soifer, B. T., and Willner, S. P. 1979, *Ap. J.*, **228**, 118.
Russell, R., Soifer, B. T., and Willner, S. P. 1977, *Ap. J.*, **213**, 66.
Simon, M., Righini-Cohen, G., and Fischer, J. 1981, private communication.
Talent, D. L., and Dufour, R. J. 1979, *Ap. J.*, **233**, 888.
Tokunaga, A., and Thompson, R. 1979, *Ap. J.*, **231**, 736.
Wilson, T. L., Bieging, J., and Wilson, W. E. 1979, *Astr. Ap.*, **71**, 205.
Zeilik, M. 1977, *Ap. J.*, **213**, 58.

D. A. BRIOTTA, JR., T. HERTER, and J. R. HOUCK: C. R. S. R., Space Sciences Building, Cornell University, Ithaca, NY 14853

W. J. FORREST, H. L. HELFER, and J. L. PIPHER: Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627

R. J. RUDY: University of Arizona, Steward Observatory, Tucson, AZ 85721

S. P. WILLNER: SAO, Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138