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SPECTROPHOTOMETRY OF COMPACT H II REGIONS FROM 4 TO 8 MICRONS

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ABSTRACT

Spectrophotometric observations from 4 to 8 μm of the compact H II regions W51–IRS 2 and K3-50 are reported. Two broad absorption features at ~6.0 μm and 6.8 μm are observed in the spectra of W51–IRS 2, and the 6.0 μm feature is seen in K3-50. These features may be due to absorption by silicate grains. A more speculative identification is absorption by hydrocarbon molecules. The continuum flux from 2 to 13 μm is broader than emission from a single-temperature blackbody; this suggests a distribution of dust temperatures within the H II regions. Failure to detect hydrogen Pfund α in W51–IRS 2 indicates significant 7.5 μm extinction. Upper limits are placed on the abundance of Ar^+.

Subject headings: infrared: sources — infrared: spectra — nebulae: general

I. INTRODUCTION

H II regions have long been known to be strong emitters of infrared radiation (see Wynn-Williams and Becklin 1974 for a review). Since the early observations, it has been accepted that the mechanism for producing the infrared emission is predominantly thermal emission by dust associated with the ionized gas. Among the brightest galactic infrared sources are the compact ratio H II regions that have no optical counterparts. Through 2–4 μm and 8–13 μm spectroscopy of these regions (Soifer, Russell, and Merrill 1976, hereafter SRM; Gillett *et al.* 1975, hereafter GFMCS), identifications of major constituents of the warm emitting dust and cold absorbing dust have been obtained. Furthermore, a quantitative estimate of the near-infrared extinction to these regions has been obtained from measurements of hydrogen recombination lines.

In an effort to expand our understanding of these H II regions, we report here 4–8 μm spectrophotometric observations of two compact H II regions, W51–IRS 2 and K3-50. W51 is a large complex of H II regions (Martin 1972) associated with a dense molecular cloud having a CO column density on the order of 10^{19} cm^{-2} (Scoville and Solomon 1973). Wynn-Williams, Becklin, and Neugebauer (1974) mapped the W51 region at 2 μm and 20 μm and found a bright compact infrared source, IRS 2, to be coincident with the radio source G49.5d (Martin 1972). Deep absorptions at 3 μm and 10 μm indicate the presence of ice and a large column density of cold silicate dust, respectively (SRM, GFMCS), in the line of sight to the infrared source. In addition, there is considerable extinction at near-infrared wavelengths. SRM suggest the flux at Bγ is down by a factor of about 10 from that expected on the basis of optically thin radio observations.

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K3-50 is also a bright infrared source associated with a compact thermal radio source (Neugebauer and Garmire 1970). This object shows 10 μm silicate absorption (GFMCS) and significant near-infrared extinction, but only marginal evidence for 3 μm ice absorption (SRM). Wynn-Williams *et al.* (1977) have shown that the previously assumed association of the infrared source with an optical H II region in K3-50 was, in fact, incorrect. The radio and infrared sources, however, are apparently coincident. A molecular cloud with CO column density $N_{CO} \approx 4 \times 10^{18}$ cm^{-2} is associated with K3-50 (Wilson *et al.* 1974).

II. OBSERVATIONS

K3-50 was observed on two flights and W51–IRS 2 on one flight aboard the Kuiper Airborne Observatory in 1977 July. The observations were obtained with a variable filter wheel spectrophotometer having a spectral resolution $\lambda/\Delta\lambda \approx 65$ and spanning the spectral range 4.1 to 8.0 μm. The chopping secondary of the telescope permitted standard infrared beam switching with a separation of approximately 45″. The instrument and observing procedure were as described by Russell, Soifer, and Willner (1977), except that the detector was a PbSnTe photovoltaic cell. The beam diameter was 28″ for both sources. The combined instrumental response and atmospheric transmission were determined by observing α Boo on each flight. The spectrum of α Boo was measured with respect to that of α Lyrae on one flight and is well fitted by a 4000 K blackbody with a 15% depression at ~4.5 to 5.2 μm due to CO absorption in the atmosphere of α Boo. The star α Lyr was assumed to have a blackbody spectrum of temperature 9700 K with an absolute flux density level of 4.07×10^{-14} W cm^{-2} μm^{-1} at 2.2 μm. The strength of the CO absorption in α Boo, as determined by comparison with ρ Lyr, is consistent with that measured by Forrest

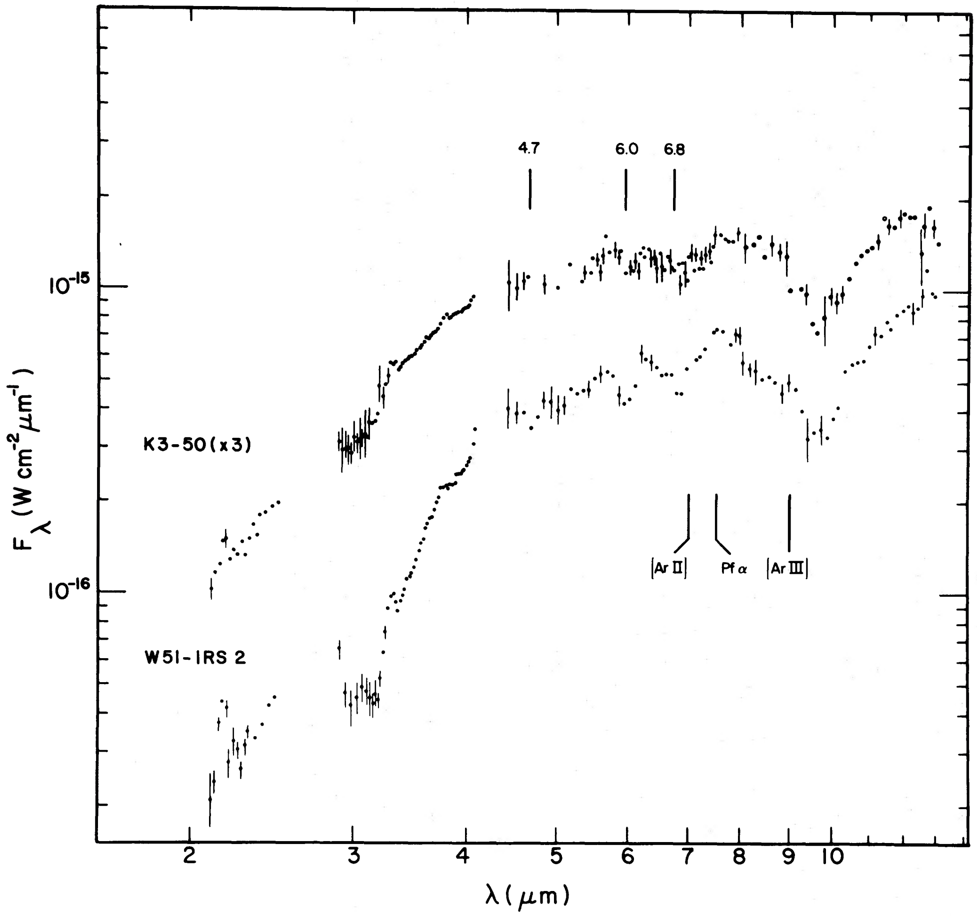

FIG. 1.—The 2 to 13 μm spectra of W51–IRS 2 and K3-50. The 4–8 μm spectra are from the present work. The 2–4 μm data are from SRM, and the 8–14 μm data are from GFMCS. The spectral resolution for all the data is $\lambda/\Delta\lambda \sim 65$, and error bars are shown for points whose statistical uncertainties are greater than 5%. For K3-50 from 5.45 to 7.41 μm, alternate points were obtained on different flights in most cases.

(1974) from ground-based photometry in the 5 μm atmospheric window. In addition to narrow-band spectrophotometric observations, broad-band photometry at 8.4 μm was obtained to allow direct comparison with ground-based observations. The data are summarized in Figure 1, which displays the 2–13 μm spectra. The 2–4 μm data are from SRM, while the 8–13 μm spectra are from GFMCS.

III. DISCUSSION

a) The Absorption Features

The spectra of W51–IRS 2 and K3-50 show a relatively flat continuum between 4 and 8 μm with several apparent absorption features. The 6.0 μm feature occurs in both objects, while the 6.8 μm feature is apparent in W51–IRS 2 and is possibly present in K3-50. Both features are seen in the spectra of several protostellar objects (Puetter *et al.* 1978). These absorptions might be attributed to silicate features, although this identification cannot be made definitive at this time. Some protosilicates produced in the laboratory show two absorptions between 5.8 and 7.0 μm (Duley and McCullough 1977). Although no single sample correctly reproduces both observed features, this class of material must be regarded as a relatively likely identification for these bands due to the close wavelength agreements of these bands and the associated strong featureless 10 μm absorption known to be present in the materials.

The 6.0 μm feature could be attributed to water of hydration in silicate grains. It is well known that hydrated silicates constitute a considerable fraction of the mass of some meteorites (Mason 1962); thus it might not be surprising to find hydrated grains in interstellar space. Hydrated minerals show a vibration band associated with the bound water at about 6.1 μm, with the exact wavelength being dependent on the host material.

One difficulty with the above identification is that hydrated silicates show an absorption at $\sim$2.9–3.0 μm typically stronger than that shown at 6.1 μm (Saksena 1961). The evidence for such an absorption in the 3 μm spectra of these objects is weak or inconclusive. The absorption feature at 3.08 μm in W51–IRS 2 appears to be strongest at a wavelength longer than that expected for bound water and has been identified with interstellar ice absorption (SRM). Furthermore, the relatively constant shape of this absorption (Merrill

Russell, and Soifer 1976) as seen in various objects would require a remarkably constant ratio of hydrated material to ice among these different clouds. This seems unlikely, since the ratio of ices to silicates appears to vary widely within these same clouds. We therefore regard this identification as quite tentative.

Carbonate minerals have a strong resonance band near 6.8 μm which might be identified with this absorption. We regard this identification as unlikely, because an expected carbonate band of comparable strength does not appear at $\lambda > 25\ \mu$m (McCarthy, Forrest, and Houck 1978). A weaker carbonate feature at 11.3 μm that might be expected to appear is not seen (GFMCS), but the presence of the silicate absorption makes the absence of this feature a weaker constraint. In addition, the presence of carbonates in interstellar material is doubtful, on the basis of infrared spectra where the 11.3 μm band had previously been seen in emission (Russell, Soifer, and Willner 1977).

Because none of the above identifications of the absorptions at 6.0 and 6.8 μm are completely satisfactory and because the H II regions are viewed through large column densities of cold molecular cloud material, more exotic identifications associated with this material might be considered. Both the 6.0 and 6.8 μm bands coincide with frequencies common to hydrocarbon bonds. The 6.0 μm absorption may be due to aliphatic carbonyl groups (C═O, not associated with ring structures) that arise from the oxidation of hydrocarbons, and the 6.8 μm band may be caused by the bending vibration of CH_2 or CH_3. The structural group C═C also has a feature at 6.0 μm, but the integrated band intensity is probably too small for this to be a correct identification. It has been shown that complicated hydrocarbons exist in molecular clouds (Zuckerman and Palmer 1974), so perhaps this wavelength coincidence is more than random chance. Hydrocarbons would also be expected to show a feature near 3.3–3.4 μm due to C—H stretching. In fact, the "ice" band at 3.1 μm has a longer-wavelength wing that cannot easily be attributed to H_2O absorption or scattering (Merrill *et al.*).

The column densities of functional groups required to explain the absorption features as hydrocarbons can be calculated from the observed equivalent widths. The integrated band intensities, A, of these functional groups are well known and are found to be essentially independent of the nature of the molecule in which they are contained (Wexler 1967). The column density

$$N = 2.62 \times 10^{20} W A^{-1} \lambda^{-2}\ \text{cm}^{-2}\,, \qquad (1)$$

where A is in units of 10^4 liters cm^{-2} mole^{-1} and W and λ are in microns.

For the aliphatic carbonyl group A is approximately 1 (Wexler 1967); thus the required column density of this group for both K3-50 and W51–IRS 2 is roughly 1/20 the observed radio CO column density. For CH_2 and CH_3, the value of A is roughly 0.07 for the absorption band at 6.8 μm. The inferred column density of CH_2 and/or CH_3 is ~one-half to ~one-quarter that of the observed radio CO. These column densities are most probably too high for the molecules to be in the gas phase, on the basis of molecular abundances inferred from radio observations (Allen and Robinson 1977, and references therein). Molecules adsorbed on dust grains, however, would not generally be detected by radio observations and might provide the necessary column densities to produce the observed infrared features. It must be emphasized that the presence of hydrocarbons in such large abundances has not been demonstrated. This possibility should be considered speculative, unless silicates can be shown to be incompatible with the observations or some other evidence for large quantities of hydrocarbons can be found.

There is an apparent absorption at 4.7 μm in the spectrum of W51–IRS 2. A similar feature appears in the spectra of two protostellar objects (Puetter *et al.* 1978) and possibly BN (Russell, Soifer, and Puetter 1977). If real, the most obvious identification of this feature is with absorption in the fundamental vibration-rotation band of CO. High-spectral-resolution observations (Hall *et al.* 1978) have revealed the presence of CO absorption at 4.7 μm in BN. The equivalent width of the absorption in W51–IRS 2 (0.01–0.03 μm) is comparable to that derived from the observations of Hall *et al.* for BN.

b) *The Continuum*

The overall continuum from 2 to 13 μm in W51–IRS 2 and K3-50, like that in many other H II regions, is quite flat, much broader than expected from any single-temperature blackbody. The emission from small dust grains at a single temperature and possessing a λ^{-n} emissivity dependence would be even narrower. Thus simple models incorporating only a single temperature for the emitting dust in the H II region (e.g., GFMCS) are not sufficient to explain all the observations. More detailed models of H II regions, such as those described by Panagia (1975) and Natta and Panagia (1976), predict that a relatively small fraction (less than 50%) of the dust heating within the H II region is produced by the trapped Lα emission. These models suggest substantial gradients in the dust temperature within the H II regions and would be consistent with our observations.

Another possible explanation of the observations is that several distinct objects dominate the observed flux at different wavelengths. If, for example, the Orion Nebula were observed from 10 times farther away (as in W51), the BN source, the KL nebula, and the Trapezium region would all be included in the observed spectrum, and the result would be very difficult to unravel.

Both of these possibilities are amenable to observational tests. Both predict a wavelength-dependent size of the infrared source, with the source size increasing as the wavelength increases. Indeed, just such a behavior has been found for W51–IRS 2 by Wynn-Williams, Becklin, and Neugebauer (1974). They found that the source diameter changes from

TABLE 1

EMISSION LINES

Parameter	W51–IRS 2	K3-50	Unit
Radio flux*................	14.7	5.2	Jy
Pfα 7.46 μm flux............	< 9	< 11.5	10^{-18} W cm^{-2}
[Ar II] 6.98 μm flux.........	< 14	5 ± 3	10^{-18} W cm^{-2}
$n(Ar^+)/n(Ar)$...............	< 0.3	0.3 ± 0.2	...
[Ar III] 8.99 μm flux†........	< 6.5	< 6.5	10^{-18} W cm^{-2}
$n(Ar^{++})/n(Ar)$.............	< 0.4	< 1.2	...

* 10.6 GHz radio flux density from Felli *et al.*

† 8.99 μm line flux upper limit from GFMCS.

less than 2″ at 4.8 μm to 5″ at 20 μm. However, the single H II region model would require the position of the center of the infrared source to remain the same, while this position might change as a function of wavelength if the multiple-source model is valid. Such observations have been made for K3-50 by Wynn-Williams *et al.* (1977). To within 1″, or 0.05 pc, the radio, 2 μm, and 10 μm positions agree.

As previously suggested (Natta and Panagia 1976, and references therein; Willner 1977, and references therein), if the infrared emission raises from dust interior to the H II region, this region may have a normal dust-to-gas ratio. Previous estimates of large dust depletion in H II regions (e.g., GFMCS; Soifer and Pipher 1975) refer only to the dust hot enough to emit substantially near 10 μm and thus neglect the larger mass of colder material that should exist within the H II region.

c) *Hydrogen Recombination Line Pfund* α

The hydrogen (6–5) recombination line at 7.46 μm (Pfund α) was not observed in either source. Three sigma upper limits are given in Table 1. The expected line flux was calculated on the basis of 10.6 GHz radio observations (Felli, Tofani, and D'Addario 1974) and unpublished $b(n, l)$ values calculated by Brocklehurst (1971). In W51–IRS 2 the expected flux is 30% greater than the upper limit, consistent with the 0.7 mag of extinction estimated by extrapolating the extinction at Bγ (SRM) to 7.46 μm with a λ^{-1} law. In K3-50, the upper limit is larger than the predicted flux and places no bound on the extinction. In the following section, 0.7 mag of extinction will be assumed to apply at 6.98 μm for both W51 and K3-50.

d) *The Argon Fine-Structure Lines*

Emission lines from fine-structure transitions in heavy elements have been predicted to be quite strong from regions such as W51–IRS 2 and K3-50 (Petrosian 1970; Simpson 1973). The strongest such line in the 4–8 μm region is the 6.98 μm line of [Ar II]. This line is only marginally present in K3-50 and is not seen in W51–IRS 2, as shown in Table 1. The ionic abundances were calculated from the collision strength of Krueger and Czyzak (1970) and the transition probability given by Wiese, Smith, and Miles (1969) for an assumed electron density of 10^4 cm^{-3} and temperature of 10^4 K. These abundances, corrected for extinction, are given relative to the cosmic abundance of argon (Allen 1973) in Table 1. Similar upper limits are given for the line flux and abundance of Ar^{++}, based on the data of GFMCS. In W51–IRS 2, argon either is underabundant or is in higher ionization states. In K3-50, the limits are weaker, but probably most of the argon is more than singly ionized. The nondetection of the [Ne II] 12.8 μm fine-structure line in the same regions (GFMCS) suggests that most of the argon should be at least triply ionized.

IV. SUMMARY

The present observations of the compact H II regions K3-50 and W51–IRS 2, combined with other infrared spectroscopic observations of these regions, lead us to the following conclusions:

1. Two broad absorption features at 6.0 μm and 6.8 μm are observed in W51–IRS 2, and the 6.0 μm feature is seen in K3-50. The most plausible explanation of these bands is absorptions by silicate minerals; however, a unique identification does not appear to exist at this time. Hydrocarbon absorptions could also explain both features, but must be regarded as a much more speculative identification.
2. There is evidence for absorption due to the fundamental band of CO in W51–IRS 2.
3. The continuum flux distribution in these sources is broader than a single-temperature blackbody and is consistent with a distribution of dust temperatures within the H II regions.
4. The absence of Pfund α in W51–IRS 2 implies a finite extinction at 7.46 μm. The amount of extinction is consistent with a λ^{-1} extrapolation from 2.17 μm.
5. Most of the argon is probably more than singly ionized in both sources and more than doubly ionized in W51–IRS 2.

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