THE ASTROPHYSICAL JOURNAL, 229:L65–L68, 1979 April 15

THE 4 TO 8 MICRON SPECTRUM OF THE GALACTIC CENTER

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Received 1978 November 20; accepted 1979 January 16

ABSTRACT

Observations of the complex Sgr A W(N) with a 28″ beam and 1.5% spectral resolution are reported. Neither unidentified absorption features at 6.0 and 6.8 μm nor emission features at 6.2 and 7.7 μm were detected. The absence of the absorption features demonstrates that they are not characteristic of general interstellar extinction. The absence of emission features suggests that there is considerable distance between the ionized gas and the molecular clouds. The absence of 6.2 and 7.7 μm emission features also suggests that a feature previously seen at 3.3–3.4 μm is an absorption at 3.4 μm, and this absorption is apparently characteristic of interstellar extinction. The strength of the [Ar II] emission indicates an overabundance of argon. CO absorption seen at 4.67 μm indicates that saturation effects are not large, and there is evidently a large velocity dispersion in the line of sight to the infrared sources.
Subject headings: galaxies: Milky Way — galaxies: nuclei — infrared: spectra

I. INTRODUCTION

The galactic center contains a complex of infrared sources discussed most recently by Becklin *et al.* (1978*a*) and Rieke, Telesco, and Harper (1978). The sources are embedded in an H II region, as demonstrated by radio observations (see, e.g., Ekers *et al.* 1975). The infrared radiation from the sources can also act as a probe of interstellar extinction, because the total extinction to the various sources is essentially uniform, although there are probably variations at the 20% level (Becklin *et al.* 1978*b;* Rieke *et al.* 1978; Knacke and Capps 1977). The extinction to the galactic center is thought to be general interstellar extinction, rather than associated with particular molecular clouds (Soifer, Russell, and Merrill 1976; Becklin *et al.* 1978*b*).

The wavelength range of 4 to 8 μm contains many important spectral features: unidentified emission features at 6.2 and 7.7 μm that have usually been seen whenever dust, molecules, and ultraviolet radiation are present (Russell, Soifer, and Willner 1978, and references therein); the fundamental CO band at 4.7 μm; unidentified absorption features at 6.0 and 6.8 μm; and an [Ar II] fine-structure line at 6.99 μm. This *Letter* reports exploratory observations in this spectral range to see which features are present. The spatial resolution of 28″ is too low to permit observations of individual sources, but the general nature of the source complex and some properties of the extinction are discussed.

II. OBSERVATIONS

Observations were obtained aboard the Kuiper Airborne Observatory on a flight from Moffett Field to Honolulu (1978 May 16 UT) and on a flight based in Honolulu (May 18). The beam size was 28″, the reference beam was 1′ separated in azimuth, and the spectral resolution $\lambda/\Delta\lambda$ was ~65. The position of largest 6.5 μm surface brightness was observed, corresponding to the complex of sources called Sgr A W(N) (Rieke *et al.*). A standard was observed on each flight, but the on-board water-vapor measurements (Kuhn, Magaziner, and Stearns 1976) showed somewhat lower water vapor during most of the galactic center observations than during the standard observations. The data taken with lower water vapor were compared with observations of α Boo obtained on a subsequent flight from Honolulu (May 20). Every fourth point in the spectrum was measured consecutively, followed by a broad-band measurement and then a measurement of a different set of points. The results are presented in Figure 1, which shows that excellent agreement was obtained among the various passes through the spectrum. All of the data in Figure 1 from 5.6 to 8.0 μm were in fact obtained on the May 18 flight; the earlier data had a somewhat poorer signal-to-noise ratio. Clouds were encountered during parts of both flights. The presence of clouds could be determined by large values and rapid fluctuations of the indicated water vapor, by their visibility in the wide-field acquisition camera, or by visual observations by the aircraft pilots. All data that were in any way questionable have been omitted from Figure 1, although inclusion of the omitted data would not have changed the spectrum significantly.

Figure 1 also displays 2 to 4 μm data obtained with a 17″ beam (Soifer, Russell, and Merrill 1976) and a smoothed version of 8 to 13 μm data obtained by Gillett

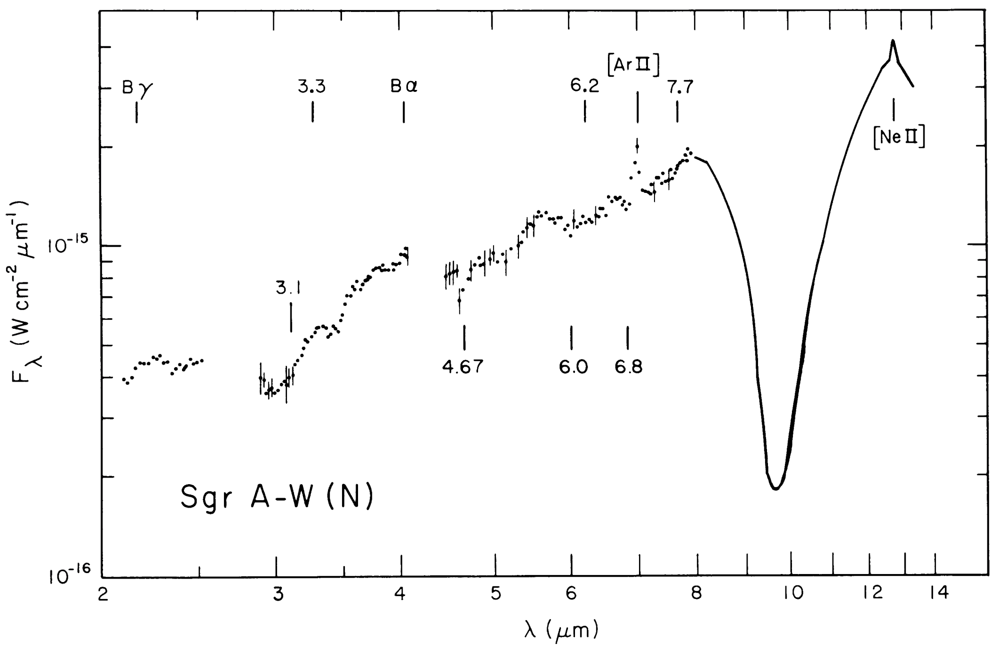

FIG. 1.—The 2–13 μm spectrum of the galactic center. The 2–4 μm portion is from Soifer, Russell, and Merrill (1976) and the 8–13 μm portion from Woolf (1973). Both were multiplied by 1.72 to normalize to the 4–8 μm data, and the 8–13 μm data were smoothed. Error bars are shown on the 2–8 μm data whenever the statistical uncertainty exceeds 5%.

and Woolf (Woolf 1973) with a 22″ beam. The latter data show a deeper 9.7 μm silicate absorption than the data of Becklin *et al.* (1978*a*) obtained with a 5″ beam. The ground-based data have been multiplied by 1.72 to normalize them to the airborne measurements. The factor of 1.72 for both the 2 to 4 and 8 to 13 μm. data was determined from the 16″ beam observations of Becklin and Neugebauer (1969) and from broad-band measurements with the KAO. Also marked in Figure 1 are the wavelengths or identifications of various spectral features. The only features plainly seen in the new data are an absorption at 4.7 μm, the wavelength of the fundamental band of CO, and the [Ar II] emission line at 6.99 μm.

The continuum shown in Figure 1 is much broader than a blackbody. Most of the emission beyond 3 μm is thought to be due to heated dust (Becklin and Neugebauer 1969), and the width implies that there is a distribution of dust temperatures. In this respect, the galactic center is similar to H II regions rather than to compact "protostellar" sources.

III. BROAD FEATURES

One of the most remarkable aspects of the spectrum in Figure 1 is the absence of any of the unidentified emission features seen in many planetary nebulae and H II regions. Two of the most prominent features should occur at 6.2 and 7.7 μm, but there is no evidence for them in the observed spectrum. These emission features generally are seen whenever heated dust, molecules, and ultraviolet radiation occur together. Although there may be a few instances where the features would be expected but are absent, such as the evolved object GL 618 (Russell *et al.*), the presence of the emission features seems to be independent of the spectrum of the ultraviolet source. The evidence for the association of heated dust and ultraviolet radiation in the galactic center is clear (Rieke, Telesco, and Harper 1978; Becklin *et al.* 1978*a;* Lacy *et al.* 1979). Molecules are also present, but their location relative to the heated dust and ionized gas is not well established (Oort 1977). Though no conclusion can be definite until the emission features are identified, we tentatively suggest that the interface between the ionized and molecular gas contains relatively little mass. In other words, the H II regions appear to be density-bounded and separated from the molecular clouds, and there is no prominent ionization front.

One absorption feature is seen near 4.67 μm, the wavelength of the fundamental vibration-rotation band of CO. The CO toward the galactic center has a large velocity dispersion (Oort 1977) permitting efficient absorption to occur. To produce the observed equivalent width of 4.8 cm^{-1} (=0.010 μm), a minimum column density of CO molecules of 5×10^{17} cm^{-2} (Burch and Williams 1962) is required.[1] A larger column density would be needed if the lines in the band are saturated. The depth of the silicate absorption and the near-infrared extinction (Becklin *et al.* 1978*b*) compared with the visual extinction of ζ Oph imply a total

[1] The measurements of Burch and Williams refer to a temperature of 273 K. If the CO is colder, fewer rotational levels will be populated. The transition probability is proportional to the angular momentum J, and J^2 is approximately proportional to T (see, e.g., Kovacs 1969). Thus at a temperature near 70 K, the integrated band intensity will be halved, and the implied column density will be doubled. The temperature is uncertain but is likely to be less than 273 K, so the value for that temperature is used to give a lower limit on the column density.

hydrogen column density of about (0.3 to 3) $\times 10^{23}$ cm^{-2}. At least 2% of the cosmic abundance of carbon is thus in the form of CO, comparable to the value found for ζ Oph (Morton 1975). The usual estimate for this fraction in molecular clouds is 10%, but, as discussed by Oort (1977), that value may be too low for the galactic center. Nevertheless, the saturation of the CO band does not appear to be larger than an order of magnitude, and thus a wide velocity dispersion is probably required in the CO directly in front of the infrared sources in order to produce the observed absorption. The velocity dispersion seen in the radio is therefore likely to occur along the line of sight, rather than only in separate clouds included in the larger radio beam.

The absence of 6.2 and 7.7 μm emission features suggests that there should be no 3.3 μm emission, because the features normally occur together (Russell *et al.*). It therefore appears likely that the structure in the spectrum at 3.3–3.4 μm (Soifer, Russell, and Merrill 1976) is an absorption at 3.4 rather than emission at 3.3 μm. The feature appears with approximately the same strength in both 17″ and 8″.5 beams and in the difference spectrum, so it is more likely to be associated with interstellar absorption than with any particular source. No ice absorption was seen in any of the three spectra (Soifer, Russell, and Merrill 1976).

An absorption at 3.4 μm has also been seen in the spectrum of the heavily reddened star VI Cygni No. 12 (Merrill, private communication). Such a feature may also be present in the spectrum of the infrared source W33 A (Capps, Gillett, and Knacke 1978), but if so it is relatively weak compared with the extremely strong ice absorption seen in that source. The 3.4 μm feature is thus probably characteristic of interstellar absorption. In the galactic center, it has a peak optical depth of about 3% of the 9.7 μm silicate optical depth.

A molecular identification of the 3.4 μm absorption might be possible, because the existence of molecules along the line of sight is demonstrated by the CO absorption. The best candidates are probably the stretching vibrations of methyl and/or methylene groups, occurring between 3.35 and 3.50 μm. These bands are the strongest exhibited by these groups, so no other features would be expected to appear in the data. The integrated band intensities (Wexler 1967), together with the measured equivalent width of 0.014 μm, imply a minimum column density of functional groups of 9×10^{17} cm^{-2} (Puetter *et al.* 1979). Molecules in the required abundance are very unlikely to exist in the gas phase (Morton 1975), but observations do not rule out the inferred column density of molecules or radicals as mantles on grains. Acceptance of this identification must, however, be reserved until further observational evidence for the existence of molecular mantles is found.

Two other features which might be expected to appear in the galactic center spectrum are absorptions at 6.0 and 6.8 μm seen in compact H II regions (Puetter *et al.* 1979) and several "protostars" (Puetter *et al.* 1977), including most prominently W33 A (Soifer *et al.* 1979). Figure 1 shows neither absorption feature, although there is an inflection near 5.6 μm that could possibly be interpreted as due to a very broad, shallow absorption centered at 6.0 μm. The 6.0 and 6.8 μm absorptions were suggested to be due to silicates; as can be seen from Figure 1, the galactic center suffers as much silicate extinction near 10 μm as many of the sources in which 6.0 and 6.8 μm absorptions were seen. The only difference that we can ascribe to the galactic center is that the absorption toward the galactic center is not due to cold, high-density molecular cloud material, as evidenced by the absence of ice absorption at 3.1 μm (Soifer, Russell, and Merrill 1976) and by the uniform amount of absorption (Becklin *et al.* 1978*b*). Perhaps only silicates that have been hydrated or otherwise processed in molecular clouds are capable of absorbing selectively at 6.0 and 6.8 μm. Another possibility is the speculative identification of the absorption features as due to hydrocarbon molecules (Puetter *et al.* 1979), which would occur only within molecular clouds. This identification may be somewhat strengthened if the 3.4 μm feature is identified with CH_3 and CH_2. Depending upon the exact molecule, the 6.8 μm feature would be weaker than the one at 3.4 μm (Wexler 1967), consistent with the absence of a 6.8 μm absorption in the observed spectrum. If this identification of the 6.0 and 6.8 μm features is correct, the small absorption at 3.4 μm would arise from those hydrocarbons that are sufficiently stable to exist in relatively unshielded interstellar space.

IV. EMISSION LINES

The most prominent feature in the 4 to 8 μm spectrum is the emission feature at 6.99 μm identified as a fine-structure line of [Ar II]. A number of other emission lines have been seen from approximately the same region, and these are listed in Table 1. The interpretation of the emission lines and their identification with individual sources within the galactic center complex is complicated, because the lines are broad and consist of many velocity components (Lacy *et al.* 1979). Nevertheless, large beams probably take similar sums over the emitting regions for all lines, and it is reasonable to compare the results. Comparison with radio observations is more difficult. Ekers *et al.* (1975) find 26 Jy at 5 GHz in a 0′.6 $\times$ 1′ beam, implying a brightness temperature of 800 K. Their map, on the other hand, shows a peak brightness temperature of 660 K. In order to predict the fluxes of infrared lines, we adopt the larger brightness temperature. Table 1 shows the predicted fluxes in various emission lines, based on the extinction curve adopted by Becklin *et al.* (1978*b*) and a constant radio surface brightness. The predicted fine-structure line fluxes are based on the assumption that each ionic abundance equals the cosmic abundance of the element (Allen 1973). Also shown in Table 1 are the measured line fluxes through various beam sizes; in each case, the beam size of the observation was used to calculate the predicted flux. Collision strengths and transition probabilities were taken from Osterbrock (1974), and a temperature of 10^4 K and electron density of 10^4 cm^{-3} were assumed.

Comparison of the predicted and measured fluxes in Table 1 suggests a factor of 2 overabundance of argon

TABLE 1

LINE FLUXES

Line	λ (μm)	Extinction (magnitudes)	Predicted Flux* (10^{-14} W m^{-2})	Measured Flux (10^{-14} W m^{-2})	Beam Size (arcsec)	Reference
Bγ	2.17	2.70	0.90	1.1±0.1	32	[1]
[Ar II]	6.99	0.70	31	64±12	28	[2]
[Ar III]	8.99	2.96	0.5	0.3	7	[3]
[Ne II]	12.81	1.14	62	78±7	25	[4]

* Including effect of extinction.

REFERENCES.—[1] Becklin *et al.* 1978*c;* [2] this *Letter;* [3] Lacy *et al.* 1979; [4] Aitken *et al.* 1976.

and a slight overabundance of neon. If the correct radio flux density is found to be lower, these overabundances will increase. Such large abundances of singly ionized species suggest that the H II regions in the galactic center are ionized by relatively cool stars, as also suggested by Aitken *et al.* (1976) and Lacy *et al.* (1979).

V. CONCLUSIONS

The absence of strong 6.0 and 6.8 μm absorption features in the spectrum of the galactic center implies that they are not characteristic of normal interstellar extinction, but rather that only material in molecular clouds produces these absorptions. Whether they come from hydration or other processing of silicate grains or from the formation of molecular mantles is not known. At 3.4 μm, there is absorption that is apparently characteristic of normal interstellar material, and which may be due to CH_2 and/or CH_3 groups.

The 6.2 and 7.7 μm unidentified emission features are not seen. The lack of detection of these bands, probably characteristic of interface regions between molecular clouds and H II regions, suggests that the galactic center H II regions may be density-bounded.

The large absorption found in the fundamental vibration-rotation band of CO requires substantial velocity dispersion in the material in a column in front of the infrared sources.

The observed [Ar II] flux implies that argon is overabundant in the galactic center compared with the vicinity of the Sun. A relatively low excitation level is also probable.

We thank the entire crew of the Kuiper Airborne Observatory for their efforts under the difficult conditions of operation away from base. We particularly thank J. W. Kroupa and P. M. Kuhn for obtaining the latest weather reports and modifying the flight plan to avoid most of the clouds. We also thank F. C. Gillett of Kitt Peak National Observatory for the loan of the PbSnTe detector. Airborne astronomy at UCSD is supported by NASA grant NGR 05-005-055 and at the University of Arizona by grant NGR 03-002-390. B. T. S. is also partially supported by NSF grant AST 77-20516 to the California Institute of Technology.

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