THE ASTROPHYSICAL JOURNAL, 395:L111–L113, 1992 August 20

THE 8–13 MICRON SPECTRUM OF THE YOUNG STELLAR OBJECT WL 16

M. S. HANNER
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109

A. T. TOKUNAGA
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822

AND

T. R. GEBALLE
Joint Astronomy Centre, 665 Komohana Street, Hilo, HI 96720
Received 1992 March 20; accepted 1992 June 8

ABSTRACT

Spectroscopy of WL 16 in the 8–13 μm region reveals a spectrum dominated by the hydrocarbon emission features at 7.7, 8.6, 11.25, and 12.7 μm. The emission plateau between the latter two features is detected, the first such detection in a young stellar object. The expected silicate feature is badly masked by the strong emission bands. Combining our spectra with the infrared spectral energy distribution indicates that silicate absorption is probably present.

Subject headings: circumstellar matter — infrared: interstellar: lines — infrared: stars — stars: individual (WL 16) — stars: pre–main-sequence

1. INTRODUCTION

WL 16 is a low-luminosity young stellar object identified by Wilking & Lada (1983) in their 2 μm survey of the central core of the ρ Ophiuchi dark cloud. Lada & Wilking (1984) obtained narrow-band 10 μm photometry of WL 16 and described it as an embedded source with deep silicate absorption. Subsequent spectroscopy of WL 16 in the 2–4 μm region has revealed a wealth of spectral features, including hydrogen recombination emission lines, CO band head emission, ice band absorption, and the 3.3 μm hydrocarbon emission feature (Thompson 1985; Thompson & Januzzi 1989; Dent & Geballe 1991; Tanaka et al. 1990; Tokunaga et al. 1991). These measurements, especially the large observed CO velocities, demonstrate that WL 16 is in a stage of high activity. The presence of an ice absorption band and a strong 3.3 μm emission feature (Tanaka et al. 1990; Tokunaga et al. 1991) suggests that the 10 μm spectrum should contain silicate absorption and emission from the hydrocarbon emission features at 7.7, 8.6, and 11.3 μm (which invariably are present wherever the 3.3 μm feature is seen).

We report here low- and moderate-resolution spectra of WL 16 at 10 μm. These reveal strong emission from the family of infrared hydrocarbon features.

2. OBSERVATIONS

The observations were made at the United Kingdom Infrared Telescope (UKIRT), using CGS3, the new common user 10–20 μm spectrometer. CGS3 is a liquid helium–cooled grating spectrometer which employs a linear array of 32 Si:As photoconductive detectors. Two gratings provide resolving powers of roughly 55 and 200 in the 10 μm atmospheric window; a third grating (not used in the present observations) covers the 20 μm window at a resolution of 75. Standard chopping (5 Hz) and nodding (30″ EW) techniques were employed to measure WL 16 and nearby bright calibration stars in a 5″ (FWHM) aperture. The wavelength calibration was determined by observations of a krypton lamp through a *K* filter at fourth, fifth, and sixth orders and emission lines in the planetary nebula NGC 6572. We estimate the uncertainty in wavelength to be ± 0.06 μm at low resolution and ± 0.03 μm for the high-resolution grating.

The low-resolution spectra were taken on 1991 May 29 (UT) at two grating positions approximately one-half a resolution element apart. Absolute calibration was with respect to α Boo, assumed to be a 4200 K blackbody with flux of 2.17×10^{-11} W m^{-2} μm^{-1} at 10.1 μm. Repeated spectra of β Oph were used to define the extinction at each wavelength. The total integration time on WL 16 was 8 minutes. The 1 σ uncertainty of the individual points is $\sim 10^{-14}$ W m^{-2} μm^{-1}.

High-resolution spectra, covering 10.3–11.9 μm and 11.7–13.3 μm, were obtained on 1991 June 4, sampling approximately every one-third resolution element. Total integration times were 24 minutes at 10.3–11.9 μm and 12 minutes at 11.7–13.3 μm. The 1 σ errrors are typically (1.5–2.) $\times 10^{-14}$ W m^{-2} μm^{-1}. The spectra were ratioed by a spectrum of BS 5794 and normalized to the absolute flux-calibrated low-resolution spectrum at 11.7–12.1 μm.

3. DISCUSSION

3.1. *Spectroscopy: The Hydrocarbon Features*

The spectra are displayed in Figures 1 and 2. The hydrocarbon features at 7.7, 8.6, 11.25, and 12.7 μm are prominent in the low-resolution spectrum (Fig. 1). Although there is extended emission in the 12 μm *IRAS* band throughout this region (Ryter, Puget, & Perault 1987), the sky subtraction removes this background to first order. Eiroa & Hodapp (1990) detected no extended emission from WL 16 at 2.2 μm. Young, Lada, & Wilking (1986) find that the 10 μm emission within an 8″ beam is ~ 0.39 that of the *IRAS* 12 μm flux (0′.76 × 1′.18 beam). If the emitting material were uniformly distributed, the flux should scale by the projected areas of the beams and the flux ratio would be ~ 0.015. Therefore, the emission bands arise in the vicinity of WL 16.

Since WL 16 has the 3.1 μm ice band, one could expect silicate absorption to be present (e.g., Willner et al. 1982). The wavelengths, strengths, and breadths of the strong emission

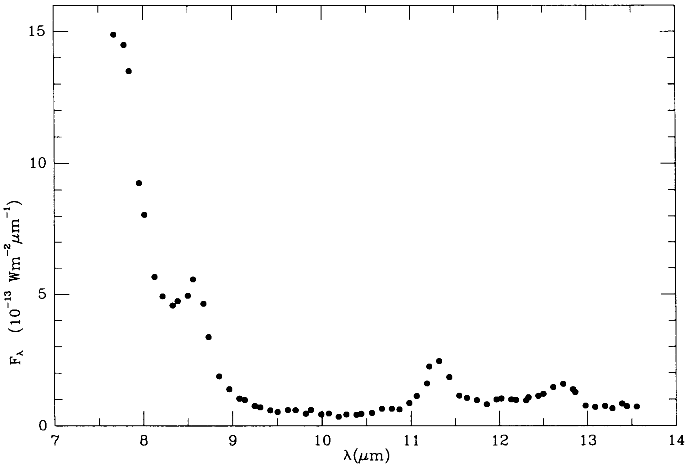

FIG. 1.—Low-resolution ($R \sim 55$) CGS3 spectrum of WL 16 on 1991 May 29, sampled at $\frac{1}{2}$ resolution element. One sigma uncertainty is $\sim 10^{-14}$ W m^{-2} μm^{-1}.

features make the presence of a silicate band difficult to determine in these spectra. We discuss this point further in the next section.

At high resolution (Fig. 2), the 11.25 μm and 12.7 μm features are clearly resolved and a prominent satellite peak at 11.04 μm is evident, as well as an emission plateau between the 11.25 and 12.7 μm features. This emission plateau was first seen in *IRAS* LRS spectra of a variety of objects (Cohen, Tielens, & Allamandola 1985). WL 16 is the first young stellar object in which the plateau has been detected.

The asymmetric profile of the 11.25 μm feature (excluding the 11.04 μm peak) is identical to that in NGC 7027 (Witteborn et al. 1989, Fig. 4) within the errors, when normalized in a similar fashion. The 12.7 μm feature resembles that in the Orion Bar (Roche, Aitken, & Smith 1991) and the average of 20 *IRAS* sources compiled by Cohen et al. (1985). The ratio of fluxes in the 8.6 and 11.25 μm features, 1.25 ± 0.15, is relatively high. Hence WL 16 does not follow the trend noted by Roche et al. that the 8.6/11.25 μm flux ratio is lower in sources with pronounced plateau emission.

Only a few pre–main-sequence stars and other young stellar objects exhibit the suite of hydrocarbon features at 3–13 μm. In the sample of 31 sources in Ophiuchus observed by Tanaka et al. (1990), for example, WL 16 is the only one to show the 3.3 μm emission feature. A survey of young stars by Brooke & Tokunaga (1992) shows that the hydrocarbon features, if seen at all, are found in Herbig Ae/Be stars, but in only 16% of those surveyed to date. The conditions which give rise to the hydrocarbon features are as yet not identified. However their presence in H II regions and reflection nebulae in star-forming regions is well known (Soifer, Russell, & Merrill 1976; Sellgren 1981; Sellgren, Werner, & Dinerstein 1983). The pre–main-sequence sources with hydrocarbon features differ in important details. The pre–main-sequence Ae star TY CrA has a prominent 11.04 μm peak, similar to WL 16, but, unlike WL 16, it also shows an unusually strong 8.6 μm feature relative to the usually considerably more intense 7.7 μm feature (Roche et al. 1991). The Ae star HD 97048 shows only a hint of the 11.04 μm peak. Neither TY CrA nor HD 97048 appears to have the 12 μm emission plateau (Roche et al.). Elias 1 is unique in having both silicate emission and at least some of the hydrocarbon features (Schutte et al. 1990). It and HD 97048 also have the unusual 3.53 μm and 3.43 μm features (Whittet et al. 1983), whereas TY CrA and WL 16 do not (D. C. B. Whittet & T. R. Geballe, private communication; Tokunaga et al. 1991).

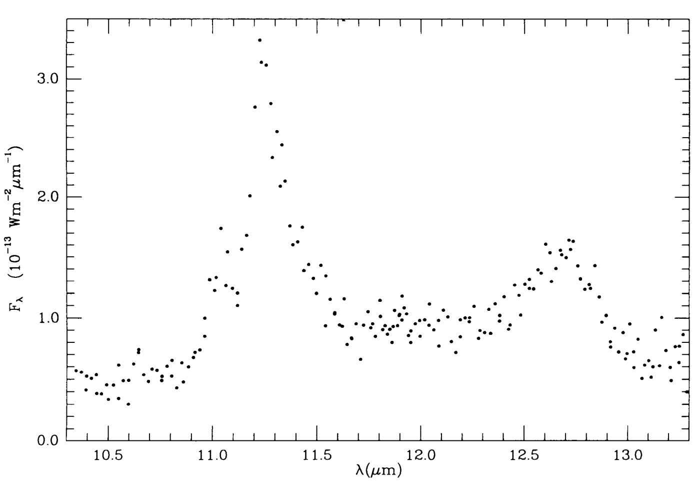

FIG. 2.—High-resolution ($R \sim 200$) CGS3 spectrum of WL 16 on 1991 June 4, sampled at $\sim 1/3$ resolution element. One sigma uncertainty is $\sim(1.5\text{–}2.) \times 10^{-14}$ W m^{-2} μm^{-1}.

The observations of hydrocarbon features in WL 16 do not simplify the understanding of these features. Rather, they add to the diversity in the relative strengths of the hydrocarbon features in the few young stellar objects in which they have been detected. The hydrocarbon emission features are believed to be UV-excited vibrational stretching and bending modes in hydrocarbons such as polycyclic aromatic hydrocarbons, either in free molecules or in amorphous carbonaceous materials (Sellgren 1990). The chemistry in the circumstellar matter of active young stellar objects (which is oxygen-rich but obviously is capable of producing hydrocarbons under some conditions) may be more variable than in evolved carbon-rich objects such as planetary and proto–planetary nebulae in which the hydrocarbon features are common. This may make patterns and correlations difficult to discern in young stellar objects.

3.2. *Spectral Energy Distribution*

The infrared spectral energy distribution of WL 16 is presented in Figure 3. The data plotted include intermediate- and broad-band ground-based photometry (Wilking & Lada 1983; Lada & Wilking 1984), *IRAS* photometry (Young et al. 1986; Wilking, Lada, & Young 1989), and our spectrum from Figure 1. With only filter photometry, one can understand why WL 16 was misidentified as a source with deep silicate absorption. Our measured flux near 10 μm (i.e., between the hydrocarbon bands) lies on a 900 K blackbody continuum fitting the 1–5 μm data of Wilking & Lada (1983). However, the elevated flux at 13–13.5 μm and at 20 μm, where hydrocarbon features are weak or absent, suggests that there is emission from warm dust ($T \sim$ 200–300 K) within the beam. In that case, the 10 μm continuum level could be roughly double the level observed by CGS3, indicating that some silicate absorption is indeed present, as expected from the presence of the 3.1 μm ice band.

Quantitative estimates of the depth of the silicate band are made difficult by the differing aperture sizes used to obtain the plotted data, the wide range in dust temperatures, the possibility that the 10 μm emission is extended, and the possibility that extended silicate emission partially fills in the absorption feature. The *IRAS* measurements demonstrate that a large

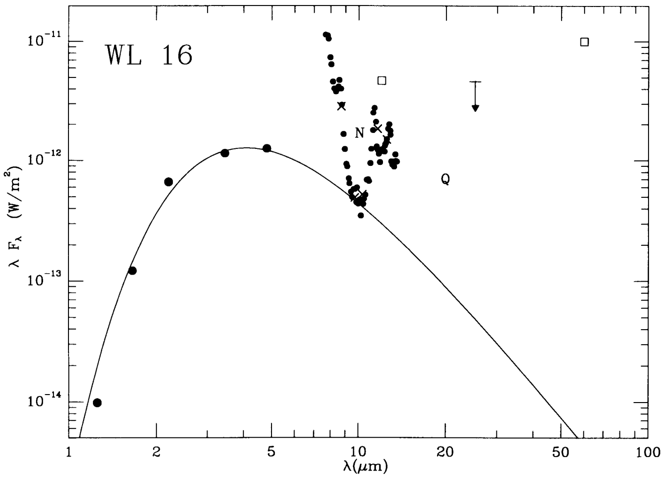

FIG. 3.—Spectral energy distribution of WL 16. A 900 K blackbody is shown. *Large filled circles:* filter photometry. 1.2–3.4 μm with ~7 beam (Lada & Wilking 1984), 4.8 μm with 12″ beam (Wilking & Lada 1983). *Small filled circles:* spectrum from Fig. 1 (5″ beam). N, Q: broad-band 10, 20 μm photometry with 7″ beam (Lada & Wilking 1984). X: intermediate bandpass photometry with 7″ beam (Lada & Wilking 1984). *Open square: IRAS* detections at 12, 60 μm, 0.′75 × 1.′18 beam (Young et al. 1986). The *IRAS* upper limit at 25 μm is shown (Young et al. 1986).

amount of cool dust is present. More than half of the emission detected by *IRAS* originates from an extended region >8″ diameter. Silicate absorption at 10 μm could arise from this extended region of cool dust, as well as from cold dust associated with the foreground molecular cloud.

We estimate that the total luminosity contributed by the 7.7–13 μm hydrocarbon bands is ~1 $L_\odot$ within a 5″ beam. By comparison, Wilking et al. (1989) derive a 1.2–60 μm luminosity of 14 $L_\odot$ and an estimated bolometric luminosity of 22 $L_\odot$.

Adams, Lada, & Shu (1987) have modeled WL 16 as a protostar and a disk embedded in an extensive envelope of infalling material. In these models the angular velocity of the surrounding material is used to determine the breadth of the spectral energy distribution and the depth of the 10 μm silicate feature. The presence of strong 10 μm emission features and weak or absent silicate absorption should lead to a much lower angular velocity in their models. By ascribing all of the 12 μm flux to the continuum, their model overestimates the mid-infrared flux. We also note that WL 16 has not been detected at 1.3 mm (André et al. 1990; Cabrit & André 1991) and is more than 100 times fainter at this wavelength than predicted by Adams et al. (1987). Indeed, WL 16 is a peculiar source that is not readily treated with a standard model.

4. SUMMARY

1. The 10 μm spectrum of WL 16 exhibits very strong hydrocarbon emission features at 7.7, 8.6, 11.25, and 12.7 μm. Combining the spectroscopy with previous broad-band filter photometry indicates that silicate absorption is probably also present near 10 μm.

2. Plateau emission between the 11.25 and 12.7 μm features is seen for the first time in a pre–main-sequence star. This is further evidence that the emitting material shares a common origin with that observed in other classes of objects, including planetary nebulae and other post–main-sequence stars.

3. WL 16 is a rare example of a pre–main-sequence object with the hydrocarbon emission features. The conditions which lead to the excitation or production of the hydrocarbon material around young stellar objects are not yet known.

We acknowledge the support of the staff of UKIRT and the Joint Astronomy Centre in making these observations possible. UKIRT is operated by the Royal Observatory Edinburgh on behalf of the U.K. Science and Engineering Research Council. We thank the referee for his helpful comments. A. Tokunaga acknowledges the support of NASA grant NAGW-2278. M. Hanner thanks the Institute for Astronomy, University of Hawaii, for support as a Visiting Professor. A portion of M. Hanner's research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 312, 788
André, P., Montmerle, T., Feigelson, E. D., & Steppe, H. 1990, A&A, 240, 321
Brooke, T. Y., & Tokunaga, A. T. 1992, in preparation
Cabrit, S., & André, P. 1991, ApJ, 379, L25
Cohen, M., Tielens, A. G. G. M., & Allamandola, L. J. 1985, ApJ, 299, L93
Dent, W. R. F., & Geballe, T. R. 1991, A&A, 252, 775
Eiroa, C., & Hodapp, K. W. 1990, A&A, 236, 217
Lada, C. J., & Wilking, B. A. 1984, ApJ, 287, 610
Roche, P. F., Aitken, D. K., & Smith, C. H. 1991, MNRAS, 252, 282
Ryter, C., Puget, J. L., & Perault, M. 1987, A&A, 186, 312
Schutte, W. A., Tielens, A. G. G. M., Allamandola, L. J., Cohen, M., & Wooden, D. H. 1990, ApJ, 360, 577
Sellgren, K. 1981, ApJ, 245, 138
———. 1990, in Dusty Objects in the Universe, ed. E. Bussoletti & A. A. Vittone (Dordrecht: Kluwer), 35
Sellgren, K., Werner, M. W., & Dinerstein, H. L. 1983, ApJ, 271, L13
Soifer, B. T., Russell, R. W., & Merrill, K. M. 1976, ApJ, 210, 334
Tanaka, M., Sato, S., Nagata, T., & Yamamoto, T. 1990, ApJ, 352, 724
Thompson, R. I. 1985, ApJ, 299, L41
Thompson, R. I., & Januzzi, B. T. 1989, ApJ, 344, 799
Tokunaga, A. T., Sellgren, K., Smith, R. G., Nagata, T., Sakata, A., & Nakada, Y. 1991, ApJ, 380, 452
Whittet, D. C. B., Williams, P. M., Bode, M. F., Davies, J. K., & Zealey, W. J. 1983, A&A, 123, 301
Wilking, B. A., & Lada, C. J. 1983, ApJ, 274, 698
Wilking, B. A., Lada, C. J., & Young, E. T. 1989, ApJ, 340, 823
Willner, S. P., et al. 1982, ApJ, 253, 174
Witteborn, F. C., Sandford, S. A., Bregman, J. D., Allamandola, L. J., Cohen, M., Wooden, D. H., & Graps, A. L. 1989, ApJ, 341, 270
Young, E. T., Lada, C. J., & Wilking, B. A. 1986, ApJ, 304, L45