1990ApJ...365L..23B

THE ASTROPHYSICAL JOURNAL, 365:L23–L26, 1990 December 10
© 1990. The American Astronomical Society. All rights reserved. Printed in U.S.A.

HYDROCARBON EMISSION FEATURES IN THE INFRARED SPECTRA OF WARM SUPERGIANTS

R. H. BUSS, JR.,[1] M. COHEN, A. G. G. M. TIELENS, M. W. WERNER, J. D. BREGMAN,
F. C. WITTEBORN, D. RANK, AND S. A. SANDFORD
NASA/Ames Research Center
Received 1990 August 2; accepted 1990 September 20

ABSTRACT

Spectra at 3–13 μm of two carbon-rich transition stars with an unidentified 21 μm feature in their *IRAS* LRS spectra show weak 3.3 and 6.2 μm emission bands, strong 6.9 and 12 μm emission bands, and a strong, broad 6–9 μm emission plateau. We attribute the 3.3 and 6.2 μm bands to circumstellar PAH molecules and the 6–9 μm plateau and the 12 and 6.9 μm bands to larger aromatic hydrocarbon clusters. The 21 μm feature probably also originates from a carbonaceous carrier.

These are the coolest stars known with the IR emission bands. The low stellar UV flux suggests that visible photons pump the PAH bands in at least one source, implying relatively large PAH carriers (> 100 C atoms). Visual photons must power the much stronger 6–9 μm plateau and 12 and 21 μm features. Thus, the increased ratio of visual stellar photons over UV photons is likely to cause the spectral contrast between these transition stars (weak PAH bands, strong 6–9, 12, and 21 μm features) and hotter objects such as PNs (strong PAH bands, weak or absent 6–9, 12, and 21 μm features). The 6–9 and 12 μm features (and possibly the 21 μm feature) may contribute substantially to the 12 μm (and possibly 25 μm) emission from interstellar cirrus and reflection nebulae observed by *IRAS*.

Subject headings: infrared: general — infrared: spectra — interstellar: grains — interstellar: molecules — nebulae: planetary — stars: supergiants

I. INTRODUCTION

In the last several years, it has become apparent that intermediate-mass stars in transition from the asymptotic giant branch (AGB) to the planetary nebula (PN) phase can sometimes be seen prominently in both the visual and infrared (van der Veen, Habing, and Geballe 1989, hereafter VHG). These "transition branch" (TB) stars are often enshrouded by a dust shell that seems to have formed during a previous phase of strong stellar wind (Woodsworth, Kwok, and Chan 1989). The cool dust shell, heated by a luminous central F–K star, radiates strongly in the mid-IR (Odenwald 1986; Volk and Kwok 1989; Pottasch and Parthasarathy 1988).

A small subset of the F–K transition branch stars observed with the *IRAS* Low Resolution Spectrometer (LRS) display a broad 21 μm emission band (Kwok, Volk, and Hrivnak 1989, hereafter KVH). This unidentified band appears only in spectra of C-rich TB stars with C_3 photospheric absorption (Hrivnak and Kwok 1991), not in LRS spectra of oxygen-rich stars. The 21 μm TB objects might therefore possess a C-rich dust shell remaining from a previous C-rich AGB stage. Indeed, two hot, non–21 μm TB objects (HR 4049 and Roberts 22) show the aromatic hyrocarbon emission bands at 3.28, 6.2, 7.7, 8.6, and 11.3 μm, as do C-rich PNs (Geballe *et al.* 1989; Cohen *et al.* 1989).

Thus, since the shells of cool TB stars with 21 μm emission could be the precursors of C-rich PNs, they might also display the IR emission features. In fact, a recent 3 μm spectrum of one of the 21 μm objects, IRAS 07134+1005 (Kwok, Hrivnak, and Geballe 1990, hereafter KHG), exhibits a 3.28 μm emission band. In this *Letter*, we report our 3–13 μm observations of two of the 21 μm objects (IRAS 22272+5435 = BD +54°2787 = SAO 34504 [hereafter IRAS 22272]; and IRAS 07134+1005 = HD 56126 = SAO 96709 [hereafter IRAS 07134]) that were conducted to search for circumstellar aromatic hydrocarbon emission bands.

[1] NAS/NRC Associate.

II. OBSERVATIONS

We observed IRAS 22272 from 2.88 to 13.5 μm and combined our data with IRAS LRS spectra. The 2.88–3.72 μm spectrum (Fig. 1) was acquired through an 11″ aperture at Mount Lemmon with the SIRAS, a linear, 32-channel In:Sb array, and flux-calibrated with α Lac. A cross-calibration check of α Lac showed no telluric CH_4 absorption near 3.3 μm; the 3.28 μm band is real (Fig. 1). A 7.8–13.5 μm spectrum (Fig. 2) of IRAS 22272 was acquired at Mount Lemmon with the FOGS (Witteborn and Bregman 1984), a linear, 29-element Si:Bi photoconductor array, and flux-calibrated with β Peg. IRAS LRS scans (7.7–23 μm) were co-added, dewarped (cf. Volk and Cohen 1989), and normalized to the *IRAS* 12 μm in band flux by bandpass convolution. The 5.0–8.3 μm spectra of IRAS 22272 and IRAS 07134 (Figs. 2 and 3) were taken through 14″ and 21″ apertures with the FOGS on the Kuiper Airborne Observatory (KAO) at an altitude of 12 km and flux calibrated with α Boo. A spectral cross-comparison of α Her with α Boo showed no spurious features. The KAO data have been matched to the LRS spectra, and the merged spectra are shown in Figure 3.

III. ANALYSIS

Stellar blackbodies ($3200 < T_* < 4500$ K), normalized at 3.0 μm, fit within the uncertainties both the 2.88–3.72 μm spectrum (Fig. 1) and IRAS 22272 *KLM* photometry from the literature (Manchado *et al.* 1989; VHG). A spline continuum through 5.2, 9.7, 18, and 22.7 μm appears to fit well the mid-IR data of the 21 μm stars (Fig. 3). For comparison, data on NGC 7027 (Table 1), a PN with strong mid-IR emission bands, are also

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990ApJ...365L..23B

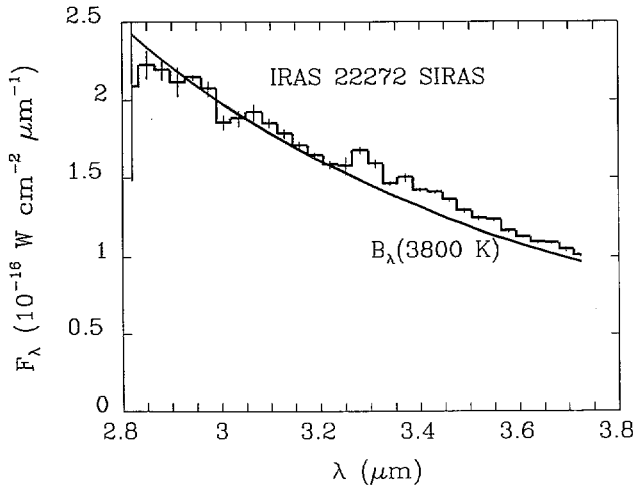

FIG. 1.—The SIRAS spectrum of IRAS 22272 exhibits a weak 3.28 μm aromatic hydrocarbon band above a $T_* \simeq 3800$ K stellar photosphere continuum. An emission plateau longward of 3 μm is also present for $3200 \leq T_* \leq 4500$ K.

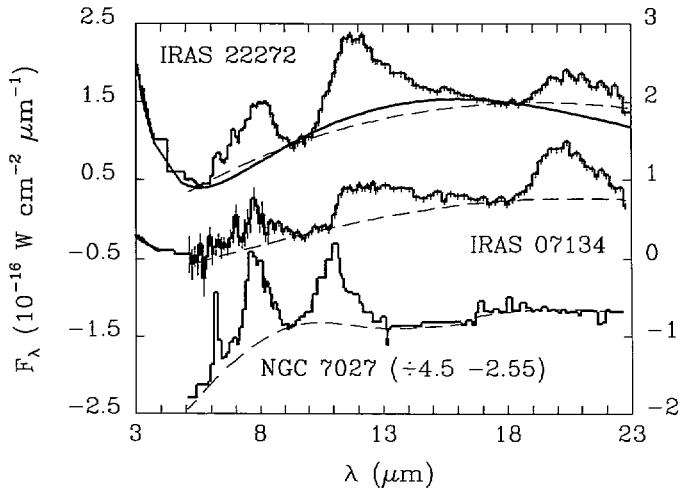

FIG. 3.—The merged 3–23 μm spectra of the TB objects, IRAS 22272 and IRAS 07134, and the PN, NGC 7027 (scaled by the indicated factors). Splined continua (*dashed*) provide an estimate of the underlying emission from grains. A model for the IRAS 22272 continuum, combining a 3810, a 240, and a λ^{-2} modified 105 K blackbody (*smooth solid*), fits equally well and illustrates uncertainties (cf. VHG). In addition to the 21 and 12 μm bands, both transition stars exhibit aromatic hydrocarbon emission bands and plateaus from 6 to 9 μm, which are in different proportions in NGC 7027.

depicted with a spline continuum. We normalized at 13.2 and 16.5 μm and omitted strong ionic lines. In Table 1 the integrated band strengths of IRAS 22272, relative to the 6.2 μm band (see Cohen *et al.* 1989 for details), are compared to those of related objects.

Our mid-IR spectra (Figs. 2 and 3) show that, in addition to the 21 μm band, IRAS 22272 and IRAS 07134 have prominent emission features near 8 and 12 μm, as tentatively suggested by KVH. The IRAS 22272 spectra clearly also exhibit both 6.2 and 6.9 μm emission bands (Figs. 2 and 3). Likewise, IRAS 07134 has a 6.9 μm emission (Fig. 3), but data around 6.2 μm are too noisy for clear detection of a 6.2 μm band. Further, there is good evidence for the 3.28 μm band and for a longer wavelength plateau in IRAS 22272 (Fig. 1) and IRAS 07134 (KHG). The positions of the 3.28, 6.2, and 8 μm features of IRAS 22272 as well as the 3.3 to 6.2 μm band ratio (Table 1), closely resemble those of the well-known IR emission bands that are present in many H II regions, RN, and PN, such as NGC 7027 (Fig. 3).

However, there are some striking differences in the spectra of IRAS 22272 and IRAS 07134 with previously observed IR emission bands of PNs, particularly at longer wavelengths. The peak of the 8 μm feature in IRAS 22272 lies at 7.7–8.0 μm, similar to the peak in PN and in another TB star, HR 4049 (Cohen *et al.* 1989; Bregman 1989). The 8 μm band in IRAS 22272, however, is broader and seems to be dominated by the 6–9 μm plateau that often underlies the 7.7 μm feature in many other sources. While the 7.7 μm feature is normally much stronger than the plateau, the 6–9 μm plateau of IRAS 22272 is so strong [$F(6\text{–}9) = 1 \times 10^{-16}$ W cm^{-2}] that it dwarfs the 7.7 μm band flux [$F(7.7 + 8.6) \approx 1.6 \times 10^{-17}$ W cm^{-2}] predicted from the 7.7/6.2 μm ratio in PN (Cohen *et al.* 1989). When scaled to the 6–9 μm plateau in NGC 7027 at 8.6–9 μm, the IRAS 22272 plateau has a very similar shape, suggesting that the two plateaus have a similar carrier. Thus, based on the mid-IR spectral similarities, we conclude that IRAS 22272 *is the coolest object yet found that exhibits the hydrocarbon IR emission bands and plateaus.*

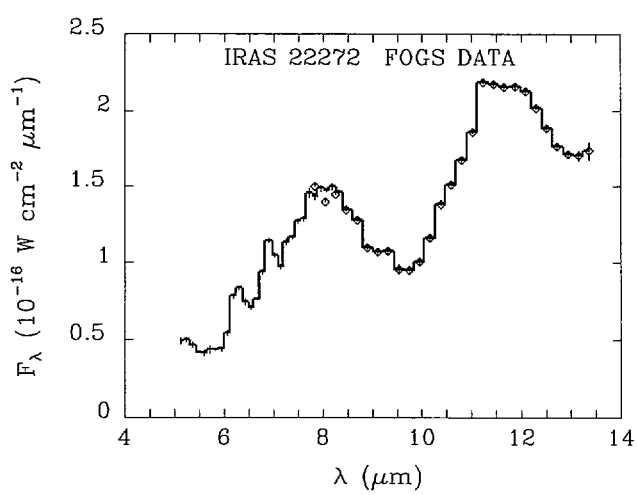

FIG. 2.—The KAO FOGS 5–8 μm spectrum of IRAS 22272, combined with the Mount Lemmon FOGS spectrum (*diamonds*), shows 8 and 12 μm features, as well as the narrow 6.2 and 6.9 μm bands seen in PNs.

While the 11–15 μm spectra of all other objects with the IR emission features are dominated by the 11.3 μm band and an underlying 11–13 μm plateau (Cohen, Tielens, and Allamandola 1985), these two TB stars instead possess an exceedingly strong 12 μm band that extends to much longer wavelengths than the NGC 7027 features (Fig. 3). Conversely, the well-known 11.3 μm feature seems to be missing from the TB star spectra, though by scaling from the 11.3/6.2 μm ratio of PNs, the expected 11.3 μm band strength [$F(11.3) \approx 3.7 \times 10^{-18}$ W cm^{-2}] in IRAS 22272 would be dwarfed by the enormous 12 μm band (Table 1). A less apparent, but just as dramatic, difference is evinced by the 6.9 to 6.2 μm ratio of IRAS 22272, the largest yet observed (Table 1; Fig. 3). Thus, *the TB object IRAS 22272, which was selected by its 21 μm emission feature, shows not only (weak) 3.28 and 6.2 μm bands but also (strong) 12 and 6.9 μm bands and a (strong) 6–9 μm plateau.*

IV. DISCUSSION

The 3.28, 6.2, and 8 μm emission bands are generally attributed to C—H and C—C stretching and deformation of poly-

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990ApJ...365L..23B

TABLE 1

OBSERVED BAND STRENGTHS AND RATIOS[a]

Name	Class	$F(6.2)$[b]	3.3	6.9	6–9	11.3	12[c]	(11.3 or 12)/3.3	21/12
22272	K5 I	5.28	0.23	0.68	19	...	47	200	0.6
07134	F2 I	...	Y	Y	...	...	Y	480	1.6
NGC 7027	WD	120	0.26	0.10	3.2	1	~0.4	5.3	...
HR 4049	A0 I	18.	0.2	...	...	0.35	...	1.6	...

NOTE.—IR data: this *Letter*; KHG; McCarthy, Forrest, and Houck 1978; Russell, Soifer, and Willner 1977; Cohen *et al.* 1989; Geballe *et al.* 1989; Waters *et al.* 1989.

[a] All bands relative to 6.2 μm band. Y means band present but no 6.2 μm band flux available for ratio.

[b] 10^{-18} W cm^{-2}.

[c] For IRAS 22272 centroid at 12.0–12.2 μm integrated from 10–15 μm.

cyclic aromatic hydrocarbon molecules (PAHs: Allamandolla, Tielens, and Barker 1989, hereafter ATB). Based on energetics, Bregman *et al.* (1989) assign the 6–9 μm plateau in the Orion Bar to clusters of PAHs containing ~500 C atoms. However, on a microscopic level, hydrogenated amorphous carbon (HAC) grains structurally resemble PAH clusters and HAC emission can fit the 6–9 μm plateau equally well (Goebel 1987; Blanco, Bussoletti, and Colangeli 1988). Whatever the case, *the 21 μm TB objects, in accordance with their C-rich photospheres, have IR spectra that reveal the presence of circumstellar aromatic hydrocarbons.*

Since the TB stars are C-rich and have the spectral signatures of PAHs and PAH clusters/HAC, the 12 and 21 μm features probably also arise from a carbonaceous carrier. In contrast to small PAH molecules, it is likely that PAH clusters containing 500 C atoms possess a broad, extended 12 μm band (ATB). Clustering can also enhance the strength of bands in this wavelength region (Witteborn *et al.* 1989). Likewise, laboratory spectra of heated HAC show a strong 12 μm band that sometimes extends to 16 μm and a broad 6–9 μm plateau (Angus, Koidl, and Domitz 1986; Dischler, Bubenzer, and Koidl 1983; Morterra and Low 1983). It is currently undetermined whether HAC or PAH clusters emit a 21 μm band, though out-of-plane ring-bending modes of aromatic materials occur throughout the 20 μm region (ATB). The presence of just one strong band at 21 μm in the TB objects could therefore be due to the dominance of only a few structural units. In addition, the 6.9 μm band appears in HAC spectra (Dischler, Bubenzer, and Koidl 1983) and can be attributed to CH deformation modes in aliphatic (CH_3, CH_2) groups, which are abundant in HAC and cross-link the aromatic domains. Thus, the observed bands of IRAS 22272 could be interrelated, arising from similar carriers. The observational evidence suggests that the TB stars have prominent emission from aromatic hydrocarbon clusters and weak emission from molecular PAHs.

One can better understand the relative strengths of these two components by examining their excitation. The measured emission flux (6.4×10^{-16} W cm^{-2}) of all the IRAS 22272 emission features (Table 1) is 20% of the total measured IR flux [$F(>5\ \mu\text{m}) \simeq 3.2 \times 10^{-15}$ W cm^{-2}]. However, the 3.28 and 6.2 μm bands alone, which are thought to be fluorescently excited by UV photons in the ISM, contribute ~0.15% of the IR flux. This corresponds to 0.1% of the total flux of the star and to almost all of its UV flux ($\lambda < 3000$ Å; Wu *et al.* 1983) even if it were a G5 supergiant. In contrast, the emission from the 3.28 and 6.2 μm bands in other objects (e.g., NGC 7027) comprise only ~1% of the UV flux. This difference strongly suggests that the PAHs in IRAS 22272 are not pumped just by UV photons but also by visible photons. Since typical interstellar molecular PAHs (~50 C atoms) do not absorb strongly throughout the visible, the IRAS 22272 molecules must be somewhat larger (>100 C atoms; Tielens and Allamandola 1987). Moreover, because the broad plateaus/bands at 6–9, 12, and 21 μm are stronger than the available UV flux, *the broad features absolutely require pumping by visible photons, consistent with our assignment of the broad features to large PAH clusters/HAC grains.*

Thus, the predominance of visual radiation from the cool star in IRAS 22272 could strengthen the 6–9, 12, and 21 μm features relative to the narrow PAH bands because PAH clusters/HACs efficiently absorb visible photons, whereas molecular PAHs absorb weakly in the visible. Conversely, because a molecular–PAH UV cross section is larger than its visual cross section, the weakness of the broad features and the strength of the narrow bands in PNs (cf. NGC 7027, Fig. 3) could be caused by the predominance of UV radiation in PNs. Indeed, the 1000-fold increase in the ratio of visual/UV radiation energy between cool supergiants and PN stars can easily account for a six-fold increase of the IRAS 22272 plateau strength relative to that in NGC 7027 (Table 1). The visually pumped carriers of the 6–9 μm plateau and the 12 μm feature, if present in the ISM, could also be responsible for the *IRAS* 12 μm band emission of reflection nebulae that are illuminated by warm stars ($T_* \simeq 5000$ K; Sellgren, Luan, and Werner 1990). Likewise, because of the large flux of visible light in the diffuse interstellar medium, the visually pumped 6–9, 12, and 21 μm features might contribute substantially to the widespread *IRAS* 12 and 25 μm emission from interstellar cirrus clouds.

Alternately, the strength of the circumstellar bands might reflect the higher dust temperatures. A blackbody at the inferred dust temperature (240 K) of *IRAS* 22272 peaks at 12 μm, whereas in NGC 7027, the thermal grains are cooler (90 K; McCarthy, Forrest, and Houck 1978) and, consequently, have less emission from 6 to 12 μm. This temperature difference, however, would not explain the strong 21 μm feature in IRAS 22272 and its absence in PNs. Finally, one cannot exclude a variation in the relative abundances of the carriers of the different emission components, with TB objects containing more HAC, relative to molecular PAHs, than PNs. For example, HAC grains might "graphitize" during the TB evolutionary phase, transforming the broad spectral features into a smoother continuum, leaving mainly emission from PAH molecules in the PN stage. Also, a fast stellar wind from the central stars during the TB phase (e.g., IRAS 07134; KHG) might shatter HAC grains into PAH molecules, possibly obliterating the carrier of the 21 μm band. Whatever the explanation, we have clearly detected both PAH–like and PAH cluster/HAC–like

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1990ApJ...365L..23B

emission around transition stars as cool as F–K type. The (likely carbonaceous) carrier of the 21 μm band still needs to be further identified.

We wish to thank K. Volk and S. Kwok for providing valuable preprints and their latest observations of IRAS 07134. We are grateful to L. Allamandola for insightful discussions and to D. Wooden and A. Graps for assistance with the data acquisition. We also appreciate the professional efforts of the Kuiper Airborne Observatory Staff in conducting the research flights. This work was performed under NASA program 352-02-03-02, the NAS National Research Council, and with the Strassbourg CDS SIMBAD data base.

REFERENCES

Allamandola, L. J., Tielens, A. G. G. M., and Barker, J. R. 1989, *Ap. J. Suppl.*, **71**, 733 (ATB).
Angus, J. C., Koidl, P., and Domitz, S. 1986, in *Plasma Deposited Thin Films*, ed. J. Mort and F. Jansen (Boca Raton, FL: CRC Press), p. 89.
Blanco, A., Bussoletti, E., and Colangeli, L. 1988, *Ap. J.*, **334**, 875.
Bregman, J. D. 1989, in *IAU Symposium 135, Interstellar Dust*, ed. L. J. Allamandola and A. G. G. M. Tielens (Dordrecht: Kluwer), p. 109.
Bregman, J. D., Allamandola, L. J., Tielens, A. G. G. M., Geballe, T. R., and Witteborn, F. C. 1989, *Ap. J.*, **344**, 791.
Cohen, M., Tielens, A. G. G. M., and Allamandola, L. J. 1985, *Ap. J. (Letters)*, **299**, L93.
Cohen, M., Tielens, A. G. G. M., Bregman, J., Witteborn, F. C., Rank, D., Allamandola, L. J., Wooden, D. H., and de Muizon, M. 1989, *Ap. J.*, **341**, 246.
Dischler, B., Bubenzer, A., and Koidl, P. 1983, *Appl. Phys. Letters*, **42**, 636.
Geballe, T. R., Noll, K. S., Whittet, D. C. B., and Waters, L. B. F. M. 1989, *Ap. J. (Letters)*, **340**, L29.
Goebel, J. H. 1987, in *Polycyclic Aromatic Hydrocarbons and Astrophysics*, ed. A. Léger, L. B. d'Hendecourt, and N. Boccara (Dordrecht: Reidel), p. 329.
Hrivnak, B. J., and Kwok, S. 1991, in preparation.
Kwok, S., Hrivnak, B. J., and Geballe, T. R. 1990, *Ap. J. (Letters)*, **360**, L23 (KHG).
Kwok, S., Volk, K., and Hrivnak, B. J. 1989, *Ap. J. (Letters)*, **345**, L51 (KVH).
Manchado, A., Pottasch, S. R., Garcia-Lario, P., Esteban, C., and Mampaso, A. 1989, *Astr. Ap.*, **214**, 139.
McCarthy, J. F., Forrest, W. J., and Houck, J. R. 1978, *Ap. J.*, **224**, 109.
Morterra, C., and Low, M. J. D. 1983, *Carbon*, **21**, 283.
Odenwald, S. F. 1986, *Ap. J.*, **307**, 711.
Pottasch, S. R., and Parthasarathy, M. 1988, *Astr. Ap.*, **192**, 182.
Russell, R. W., Soifer, B. T., and Willner, S. P. 1977, *Ap. J. (Letters)*, **217**, L149.
Sellgren, K., Luan, L., and Werner, M. W. 1990, *Ap. J.*, **359**, 384.
Tielens, A. G. G. M., and Allamandola, L. J. 1987, in *Physical Processes in Interstellar Clouds*, ed. G. E. Morfill and M. Scholer (Dordrecht: Reidel), p. 333.
van der Veen, W. E. C. J., Habing, H. J., and Geballe, T. R. 1989, *Astr. Ap.*, **226**, 108 (VHG).
Volk, K., and Cohen, M. 1989, *A.J.*, **98**, 1918.
Volk, K., and Kwok, S. 1989, *Ap. J.*, **342**, 345.
Waters, L. B. F. M., *et al.* 1989, *Astr. Ap.*, **211**, 208.
Witteborn, F. C., and Bregman, J. D. 1984, *Proc. Soc. Photo.-Opt. Eng.*, **509**, 123.
Witteborn, F. C., Sandford, S. A., Bregman, J. D., Allamandola, L. J., Cohen, M., Wooden, D. H., and Graps, A. L. 1989, *Ap. J.*, **341**, 270.
Woodsworth, A. W., Kwok, S., and Chan, S. J. 1990, *Astr. Ap.*, **228**, 503.
Wu, C.-C., *et al.* 1983, *IUE NASA Newsletter*, No. 22.

J. Bregman, R. H. Buss, Jr., S. A. Sandford, A. G. G. M. Tielens, and F. C. Witteborn: NASA/Ames Research Center, MS 245-6, Moffett Field, CA 94035

M. Cohen: Radio Astronomy Laboratory, University of California, Berkeley, CA 94720

D. M. Rank: Lick Observatory, University of California, Santa Cruz, CA 95064

M. W. Werner: 171-267, JPL, Pasadena, CA 91109

© American Astronomical Society • Provided by the NASA Astrophysics Data System