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NEAR-INFRARED SPECTROSCOPY OF PROTO–PLANETARY NEBULAE

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ABSTRACT

Sixteen proto-planetary nebulae were observed with low-resolution infrared spectroscopy in the *H* and *K* bands, and four were observed in the *L* band. In the *H* band, most of the objects show hydrogen Brackett lines (from $n = 10$–4 to $n = 20$–4) in absorption. In the *K* band, absorption bands ($\Delta v = 2$) of CO were observed to as high as $v = 6$–4, and in three cases the CO bands are in emission. The CO spectrum of 22272+5435 was found to change from emission to absorption over a 3 month interval. The CO emission most likely arises from collisional excitation resulting from recent episodes of mass loss. One new object which possibly shows weak 3.3 μm emission was found.

Subject headings: circumstellar matter — infrared: interstellar: lines — planetary nebulae: general

1. INTRODUCTION

Recent ground-based observations of cool *IRAS* sources have led to the discovery of a number of F and G supergiants with large infrared excesses. A defining characteristic of these stars is that they show a double-peaked energy distribution with approximately equal amounts of energy emitted in the photospheric and circumstellar components. Model fits to the energy distributions show that the infared excesses originate from an extended dust shell detached from the photosphere of the star (Hrivnak, Kwok, & Volk 1989). The dust is most likely in the circumstellar envelope created as a result of mass loss on the asymptotic giant branch (AGB). When the mass loss process deletes the hydrogen envelope of the AGB star, the star moves toward the blue side of H-R diagram. At the same time, mass loss terminates and the circumstellar envelope detaches from the stellar photosphere. By combining the results of radiative transfer models with the published expansion velocities of the molecular envelopes, it is possible to show that the envelopes of most of these objects detached several hundred years ago.

During this dynamical time of several hundred years, such stars evolve to an earlier spectral type of G or F. They are usually assigned as luminosity classes Ia or Ib from optical spectroscopic observations. Such luminosity classes are reflections of the low surface gravity of these objects, and are not necessarily indications of the high luminosities (or inferred high masses) of the stars.

These objects are particularly interesting because they represent a previously little-observed phase of stellar evolution—the "missing link" between AGB stars and planetary nebulae. They are referred to as proto–planetary nebulae (PPNs), or specifically defined as stars that have stopped their AGB mass loss but have not yet evolved to high enough temperatures to ionize the circumstellar material (Kwok 1987, 1993). Their circumstellar envelopes possess all the characteristics of late AGB stars (dust envelopes, molecular emissions, etc.), but are not yet ionized because of the low (5000–7000 K) temperatures of the central stars. A number of such stars have recently been identified (Parthasarathy & Pottasch 1986; Hrivnak et al. 1989; van der Veen, Habing, & Geballe 1989). We have been actively engaged in a program to identify and study PPNs. Candidates have been chosen on the basis of their *IRAS* colors to have dust temperatures between 150 and 300 K, which is the temperature region between planetary nebulae and late AGB stars. These *IRAS* sources have been followed up with ground-based visible and near-infrared photometry and visible spectroscopy. From photometry, their spectral energy distributions between 0.4 and 100 μm can be determined, which typically show "double-peaked" energy distributions. From optical spectroscopy, the spectral types and chemical abundances of the central stars can be found.

The atomic, molecular, and dust constitutents of the circumstellar envelopes can be best studied by infrared spectroscopy, and the spectra obtained can be compared with the spectra of AGB stars and planetary nebulae to determine the details of the transition process. While several of these objects show the 9.7 μm silicate emission feature indicating their descendance from oxygen-rich AGB stars, others have been found to display an unidentified emission feature at 21 μm and unusual 11–15 μm emission (Kwok, Volk, & Hrivnak 1989). The 21 μm feature has been suggested to be related to the polycyclic aromatic hydrocarbon (PAH) molecules commonly found in planetary nebulae (Buss et al. 1990). If this is the case, the 21 μm feature could be emitted by PAH molecules being excited under different physical conditions or by molecular species from which PAHs are made. Alternatively, the 21 μm feature could arise from a totally distinct molecule which is only excited in the neutral environment of these F-G supergiants.

In this paper, we report near-infrared spectroscopic observations in the *H*, *K*, and *L* bands of a number of these F and G supergiants which possess the properties of PPNs. For about half of these objects, we have previously discussed their PPN properties, based upon visible and near-infrared photometry

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and visible spectrometry in combination with *IRAS* data (Hrivnak et al. 1988, 1989; Hrivnak & Kwok 1991), and for the remainder a similar discussion is in preparation. The *L*-band spectra of two of these objects, which have unusual 3 μm emission features, are reported elsewhere (Geballe et al. 1992). While a few particular PPNs have been observed previously at these wavelengths (e.g., AFGL 618, Thronson 1981; AFGL 2688, Thronson 1982), this is the first paper to present spectra of a representative sample of these objects. Only two objects in this study have previously published near-infrared spectra (IRAS 07134 + 1005 = HD 56128, Kwok, Hrivnak, & Geballe 1990; AFGL 2688, Thronson 1982); most are objects which we have only recently identified as PPNs. The particular objects in this study were chosen because they are among the brightest PPNs observable from the Northern Hemisphere.

2. OBSERVATIONS

The observations were carried out at the 3.8 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. Most of the measurements were made during 1990 September 25–27 (UT). Additional observations were made during 1990 June 26–27, and during Service observing on 1990 October 1 and 1991 November 4. All of the 1990 observations were obtained using CGS2, a seven-channel cooled grating spectrometer, with a 5″ aperture. The chopper throw and telescope nod were approximately 30″ EW. The spectral resolutions of these data are approximately 0.004, 0.003, and 0.008 μm in the centers of the *H*, *K*, and *L* bandpasses, respectively, for the observations of 1990 September and October (the majority of the spectra), and 0.004 and 0.007 μm in the *H* and *K* bandpasses for 1990 June. For the 1991 November 4 observations, the new grating and two-dimensional array spectrometer CGS4 was employed at a resolution of 0.007 μm in the *K* band. The slit width and pixel dimensions were both 3″.1. The observations were made in stare mode; to allow subtraction of the sky emission, "sky" frames were obtained by nodding the telescope along the (NS) slit so that the spectrum was shifted an integral number of rows on the detector array. In all cases spectra were sampled every 1/3 resolution element. A log of observations is given in Table 1, in chronological order.

A number of reference stars (also listed in Table 1) were observed close in time and air mass to the program stars, and were used for flux calibration and to cancel telluric absorption features by ratioing. The particular reference stars used were chosen for their lack of certain spectral features in the various bands, as will be discussed later. The flux calibrations involved ratioing by the reference stellar spectra scaled to the magnitudes of the reference stars, and then multiplying by blackbody functions assuming that the stellar continua are blackbodies at temperatures typical of their spectral types. For those reference stars without near-infrared photometry, magnitudes were inferred by comparison of their observed flux levels in the spectra with those of known standards. Flux calibration is thought to be accurate to 10%–15%, except for 1990 October 1, which was not photometric and for which the accuracy is estimated to be 20%–30%. The spectroscopic flux levels of the program objects are found to agree to within 10% of the observed photometric values for all sources except 19114 + 0002, 20004 + 2955, and 22272 + 5435, where the differences are somewhat higher. However, the latter two of the three objects are known to vary in visual brightness.

Wavelength calibrations were derived from observations of an argon lamp and checked with emission lines in planetary nebulae. A number of the flux-calibrated spectra have been smoothed using a Gaussian of FWHM 1.5 data points. This removed much of a residual systematic ripple in the spectra, while slightly reducing the resolution (by 12%) from the values given above.

3. *H*-BAND SPECTRA

The *H*-band spectra range from 1.48 to 1.79 μm, an interval containing most of the lines of the Brackett series of hydrogen. Sixteen program objects were observed in 1990 September; two of the same objects had been observed in 1990 June at lower signal-to-noise. Reference stars of G–K spectral type, primarily G8 giants, were observed, and the program spectra are divided by these reference spectra. The G stars were chosen based upon their lack of H I lines. However, numerous atomic absorption lines are present in the *H*-band spectra of G stars (e.g., Livingston & Wallace 1991). A few of these, at 1.504, 1.570–1.595, 1.62, and 1.71 μm, are prominent at the resolution of the present measurements. We removed the stronger absorption features at 1.504 and 1.570–1.595 μm from the reference stars by interpolation across these features in the spectrum. The neglect of these would result in spurious emission features appearing in the spectra of program objects.[2] Some effect from the feature at 1.711 μm is apparent as a slight peak in some of the spectra. There may also be an unidentified intrinsic feature at 1.776 μm, as a peak appears at that wavelength in most of the ratioed spectra of the F and early G supergiants, although it is probably more likely that this represents the continuum level surrounded by absorption features.

Most of the *H*-band spectra of the PPNs are dominated by absorption lines from the Brackett series of H I. The detected transitions range from $n = 4$–10 to as high as $n = 4$–20, with possibly weaker lines present due to $n = 4$–21 and $n = 4$–22 transitions. These spectra are displayed in Figure 1. These H I lines are clearly stronger in the objects of F spectral type than in the later spectral types, as expected based upon temperature. The transitions in the middle of the range—$n = 13$, 14, 15, 17—appear to have consistently stronger absorption features. However, it is unclear exactly where the continua lie in these spectra at the longer wavelengths. The strength of the feature attributed to H ($n = 4$–14) at 1.5885 μm may possibly be due in part to blending with a nearby Si absorption line at 1.5892 μm; the $n = 4$–14 line is particularly strong in the cool objects, consistent with this suggestion. For comparison, we have also obtained *H*-band spectra for the normal yellow supergiants BS 382 (F0 Ia), BS 1865 (F0 Ib), and BS 1017 (F5 Ia), and their spectra are also shown in Figure 1. The Brackcett series in absorption is again dominant in these spectra. These H I lines presumably originate in the photospheres of these stars.

An absorption feature at 1.504 μm is seen in all but one of the PPN spectra, and is strongest in the cooler objects; this is attributed to Mg I. Additional weaker lines can be seen in the spectra of the program objects, especially the cooler ones. A library of near-infrared spectra from 1.428 to 2.5 μm has recently been published (Lancon & Rocca-Volnerange 1992) which shows many of these same features in spectra of F and G supergiants, but they are not identified.

The object 07134 + 1005 was observed on two successive

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[2] This is a likely cause of the reported Mg I emission at 1.503, 1.575, and 1.711 μm in IRC + 10420 by Thompson & Boroson (1977), who used a G2 Ib reference star with Mg I absorption at these wavelengths.

TABLE 1
OBSERVING LOG

		CALIBRATION STAR		
NAME	BAND	Name	Assumed Magnitude	Assumed Temperature (K)
1990 Jun 26 (UT)				
17436+5003	*H*	BS6536 (G2 Ib–IIa)	1.10	5500
18095+2704	*H*	BS6536	1.10	5500
1990 Jun 27				
17436+5003	*K*	BS7162 (F9 V+K1 V)	3.90	6000
18095+2704	*K*	BS7162	3.90	6000
19475+3119	*K*	BS7162	3.90	6000
22272+5435	*K*	BS7162	3.90	6000
1990 Sep 25				
17436+5003	*H*	BS6220 (G8 IIIb)	1.45	4900
18095+2704	*H*	BS6223 (Klp)	1.81	5200
19500−1709	*H*	BS6223	1.81	5200
19114+0002	*H*	BS6223	1.81	5200
19475+3119	*H*	BS7754 (G8 IIIb)	1.50	4800
20000+3239	*H*	BS7754	1.50	4800
20004+2955	*H*	BS7754	1.50	4800
AFGL 2688	*H*	BS7753 (G8 III)	3.30	4800
20572+4919	*H*	BS7753	3.30	4800
22223+4327	*H*	BS8961 (G8 III–IV)	1.44	4800
22272+5435	*H*	BS8961	1.44	4800
BS 382 (F0 Ia)	*H*	BS321 (G5 Vp)	3.40	5100
BS 1017 (F5 Ib)	*H*	BS915 (G8 III+A2 V)	1.08	4800
04296+3429	*H*	BS1656 (G4 V)	3.41	5400
05113+1347	*H*	BS1656	3.41	5400
05381+1012	*H*	BS1656	3.41	5400
07134+1005	*H*	BS1656	3.41	5400
07430+1115	*H*	BS1656	3.41	5400
1990 Sep 26				
19500−1709	*K*	BS7340 (F0 IV–V)	3.40	7100
BS 7193 (K1 III)	*K*	BS7340	3.40	7100
19114+0002	*K*	BS7377 (F3 IV)	2.57	7100
20000+3239	*K*	BS7653 (A4 III)	4.20	8400
20004+2955	*K*	BS7653	4.20	8400
22223+4327	*K*	BS8266 (A5 V)	4.60	8200
22272+5435	*K*	BS8266	4.60	8200
BS 8313 (G5 Ib)	*K*	BS219 (G0 V)	1.96	5900
BS 382 (F0 Ia)	*K*	BS219	1.96	5900
BS 1017 (F5 Ib)	*K*	BS219	1.96	5900
04296+3429	*K*	BS1203 (B1 Ib)	2.66	17000
05113+1347	*K*	BS1543 (F6 V)	2.07	6400
05381+1012	*K*	BS1543	2.07	6400
07134+1005	*H*	BS2918 (G0 V)	4.68	5900
BS 1865 (F0 Ib)	*H*	BS2918	4.68	5900
1990 Sep 27				
05113+1347	*L*	BS1343 (G8 III)	2.79	4800
07134+1005	*L*	BS2918 (G0 V)	4.50	5800
1990 Oct 1				
18095+2704	*L*	BS6707 (F2 II)	3.15	7000
19475+3119	*L*	BS7653 (A4 III)	4.30	8500
1991 Nov 4				
19114+0002	*K*	BS 7231 (F1 V)	5.80	6400
22223+4327	*K*	BS 8130 (F2 IV)	2.70	7000
22272+5435	*K*	BS 8130	2.70	7000

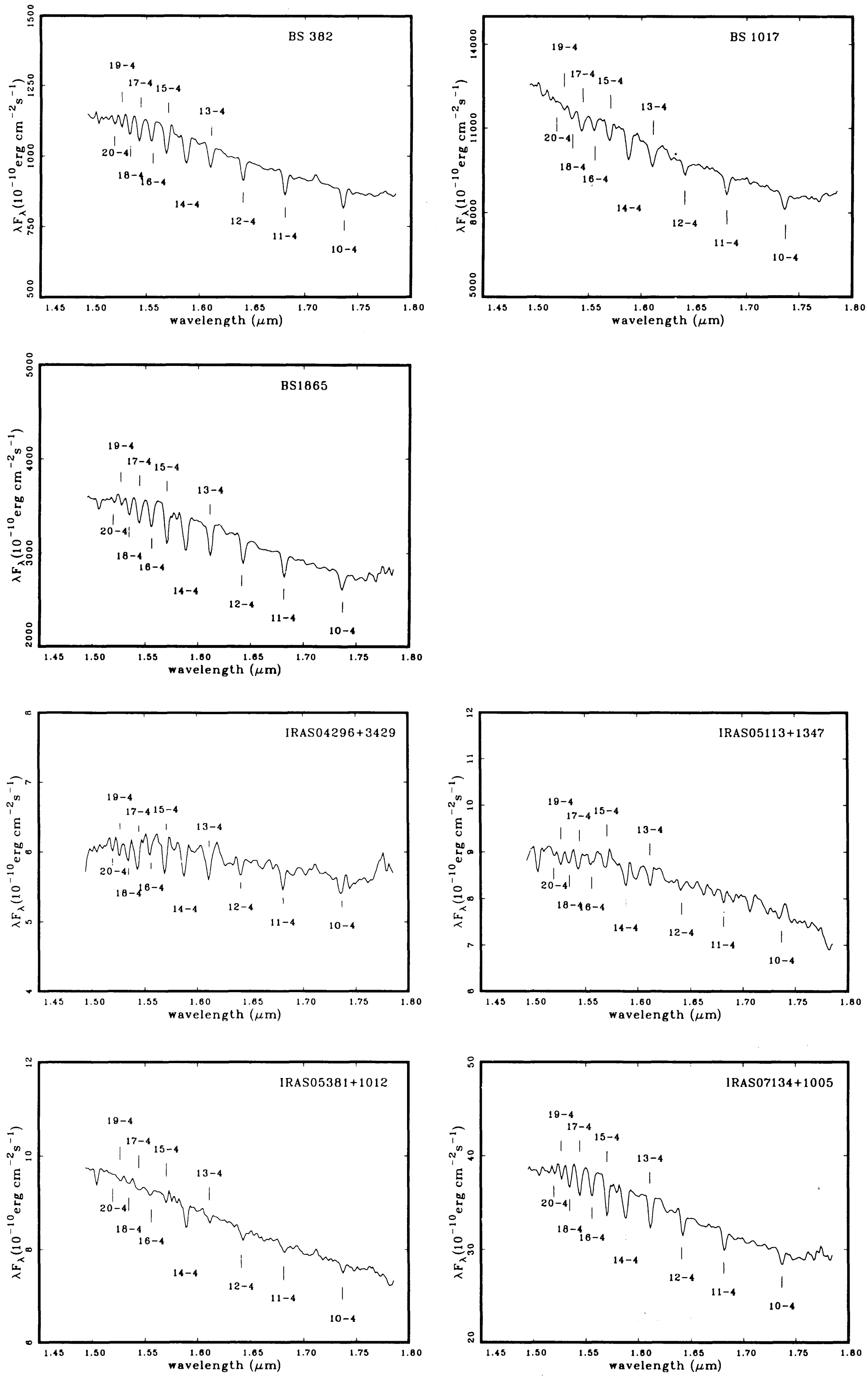

FIG. 1.—*H*-band spectra of three normal yellow supergiants: BS 382 (F0 Ia), BS 1017 (F5 Ia), and BS 1865 (F0 Ia), and of 14 proto–planetary nebulae. The positions of the hydrogen Brackett lines are indicated. All of the spectra are from 1990 September.

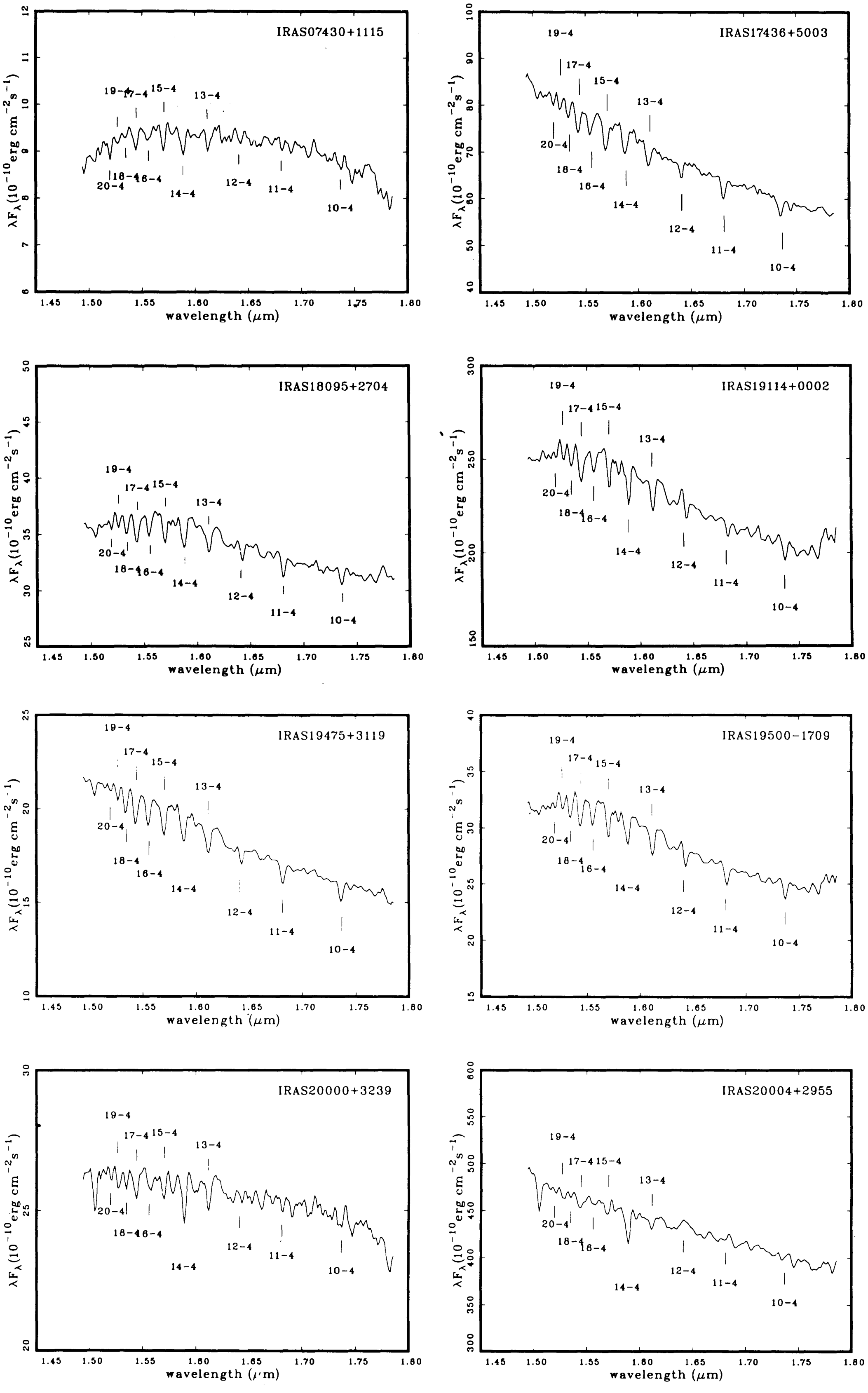

FIG. 1—*Continued*

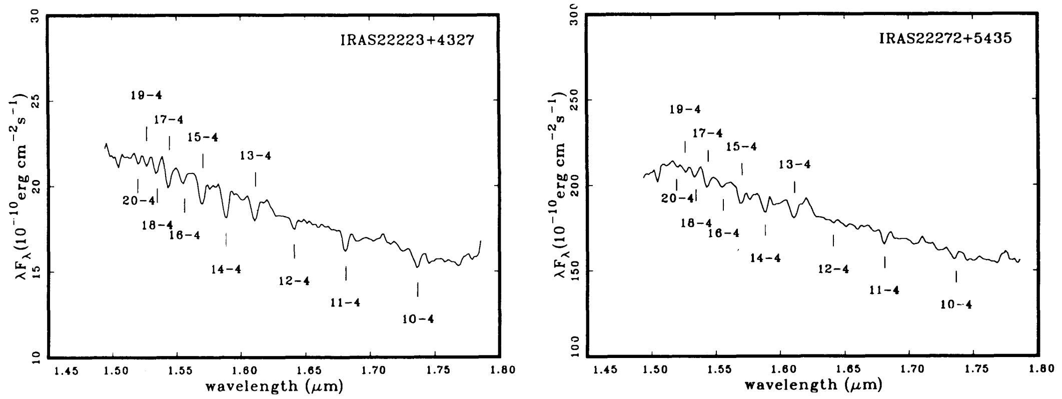

FIG. 1—*Continued*

nights, using a different reference star each night. The two spectra appear the same; the continuum level on the second night is 10% higher, which is at the level of accuracy in the absolute calibration of the spectra. In a previous study of the infrared spectrum of 07134+1005, we cited the apparent existence of blueshifted emission components of the H I lines (Kwok et al. 1990). After now examining a larger sample, we are in a better position to evaluate the appearance of the spectra of these objects and to decide what features are due to emission or absorption. It now seems that the apparent H I emission features were probably rather due to these additional unidentified absorption features causing us to misplace the continuum level too low.

The continua of almost all of the spectra show a decrease with wavelength, as expected in the photosphere of a warm (5000–7000 K), although somewhat reddened object. The only expectations are the spectra of 04296+0429 and 07430+1115, where the decrease is less than in the other objects and which in fact appear to show local maxima at ~1.56 and ~1.58 μm, respectively, and the spectra of the two objects described below.

The spectra of 20572+4919 and AFGL 2688 differ substantially from the others described above, and are shown separately in Figure 2. (Note the smaller range in the vertical scale of the spectra in Fig. 2 as compared with the spectra in Fig. 1. These are also the faintest sources.) The spectrum of 20572+4919 is notable for its lack of hydrogen Brackett absorption features, this in spite of the fact that the object has an F spectral type in visible light. There are, in fact, no clear absorption features in the spectrum except perhaps the 1.504 μm feature. The spectrum also has a different shape than the other objects, appearing flat with a slight minimum around 1.6 μm. AFGL 2688, the Egg Nebula, is a well-known PPN, with clearly resolved bipolar lobes displaying an F5 I spectral type (Crampton, Cowley, & Humphreys 1975). We chose to observe this object for comparison, and obtained a spectrum of the brighter lobe. The Brackett lines are clearly seen. Most notable is an emission feature at 1.559 μm, which is blended on the long-wavelength side with the Brackett 4–16 absorption line. There is also a probable emission features at 1.605 (or 1.603 and 1.607) and a possible one at 1.778 μm; however, it is hard to know exactly where the continuous level of the source lies. In the 2 μm window, a number of H_2 emission lines have been detected by Thronson (1982). In the visible spectrum of AFGL 2688, moderately strong emission at 5162 Å and weak emission at 5631 Å are attributed to C_2 (5165, 5635 Å), moderately strong emission at 4073 Å to [S II] 4069+4077 Å, and weak emission is seen in the Na D lines (Crampton et al. 1975; Humphreys, Warner, & Gallagher 1976). The continuum of this source is also flat.

The flat continua in these two sources can be understood when one looks at their flux distributions from the visible

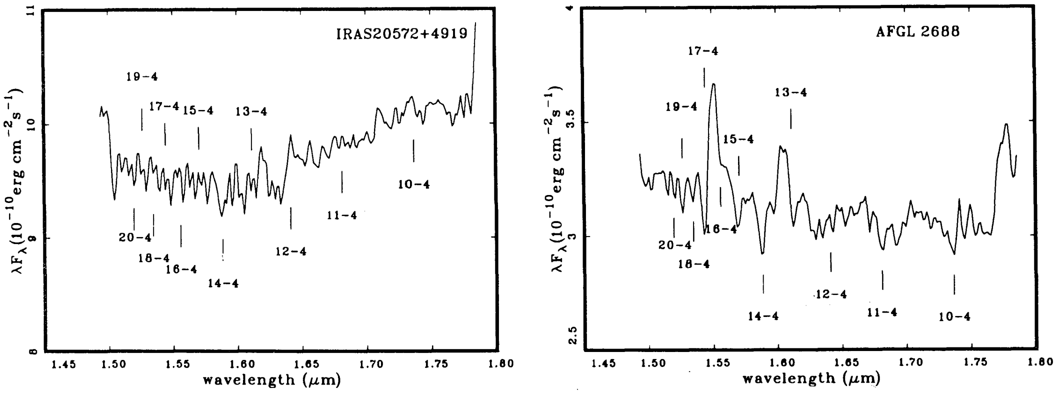

FIG. 2.—*H*-band spectra of 20572+4919 and AFGL 2688

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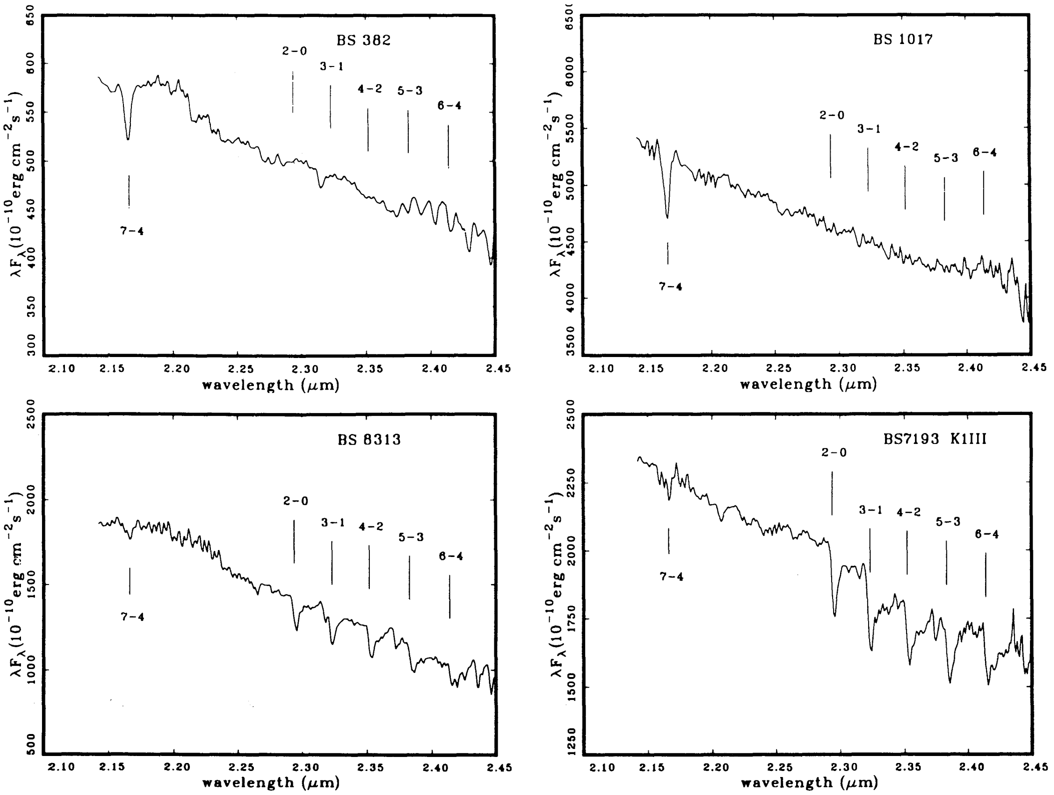

FIG. 3*a*

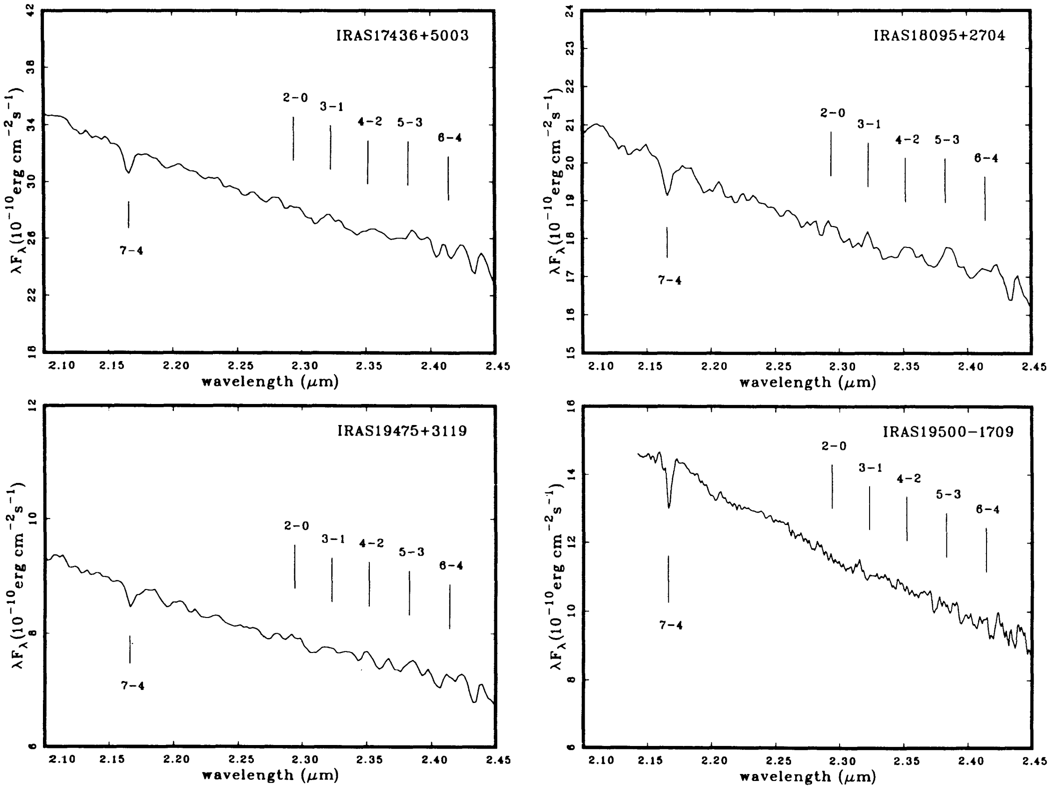

FIG. 3*b*

FIG. 3.—*K*-band spectra for (*a*) four normal yellow supergiants; (*b*) four of our program objects (all F stars) without the CO bands; (*c*) four program objects (all G stars) showing the CO bands in absorption; (*d*) four program objects (all G stars), two without CO bands and two showing CO in emission. Positions of the CO bandheads of the $\Delta v = 2$ transitions as well as the hydrogen Brγ (7–4) line are indicated. Note that the resolution is a factor of two lower for 17436+5003, 18095+2704, and 19475+3119 in (*b*); these three spectra are from 1990 June while the rest are from 1990 September.

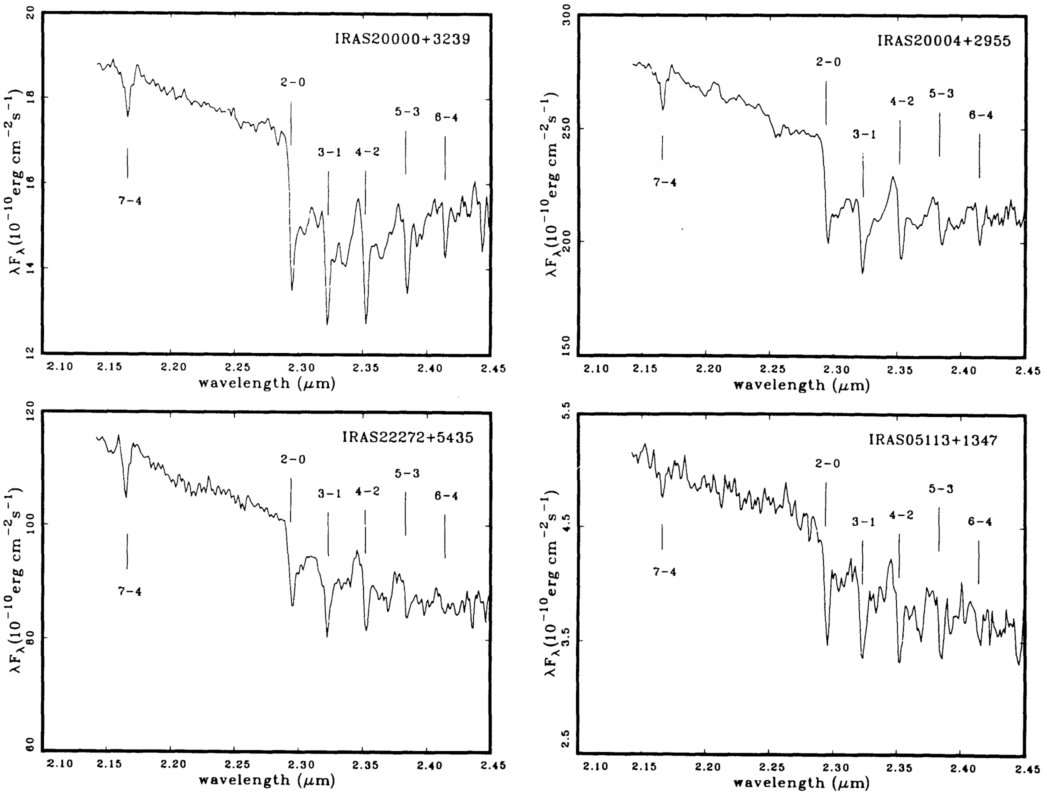
IRAS20000+3239
IRAS20004+2955
IRAS22272+5435
IRAS05113+1347
2-0
3-1
4-2
5-3
6-4
7-4
$\lambda F_\lambda (10^{-10}$erg cm^{-2}s$^{-1})$
wavelength (μm)
2.10
2.15
2.20
2.25
2.30
2.35
2.40
2.45

FIG. 3c

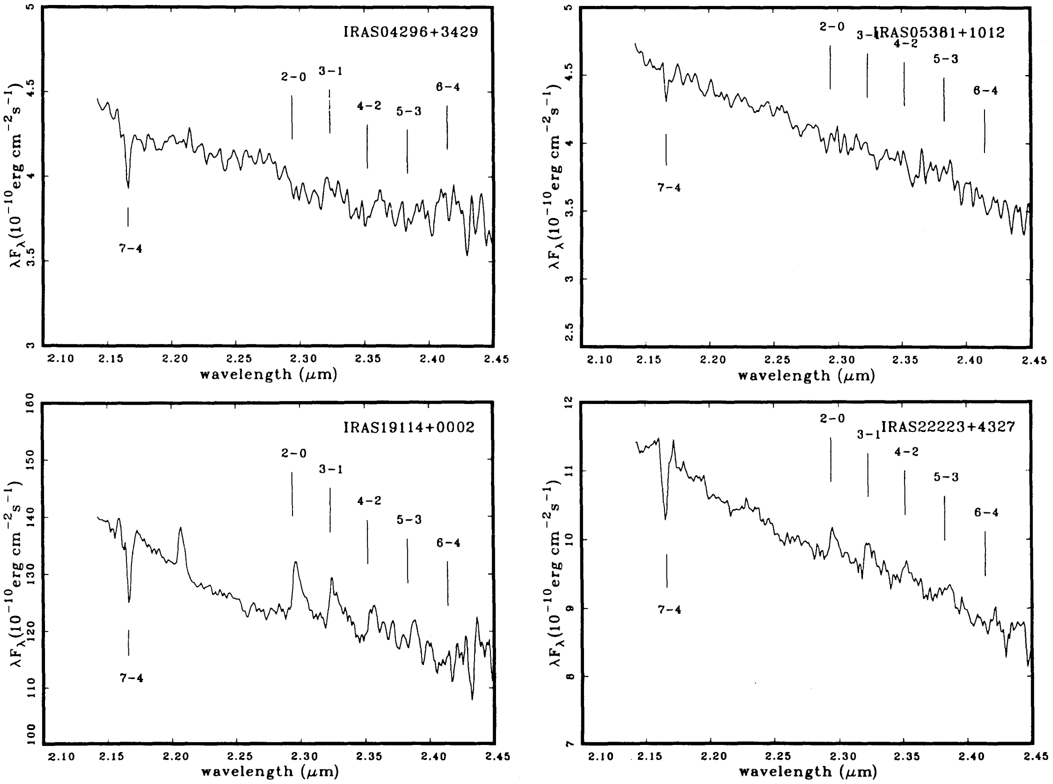
IRAS04296+3429
IRAS05381+1012
IRAS19114+0002
IRAS22223+4327
2-0
3-1
4-2
5-3
6-4
7-4
$\lambda F_\lambda (10^{-10}$erg cm^{-2}s$^{-1})$
wavelength (μm)
2.10
2.15
2.20
2.25
2.30
2.35
2.40
2.45

FIG. 3d

through 100 μm. In contrast to the other sources, which are clearly double peaked with resolved photospheric and circumstellar components, near-infrared emission "fills in" the region between the two peaks in the flux distributions of these two sources, yielding the flat continua seen. Thus one is not simply looking at the photospheres of these two objects in the *H* band, which is presumably why one does not see the expected Brackett lines in 20572+4919.

4. *K*-BAND SPECTRA

The *K*-band spectra range from 2.13 to 2.53 μm, and contain the Brackett line $n = 4-7$ (Brγ, 2.166 μm) and the CO first-overtone ($\Delta v = 2$) vibrational-rotational bands at 2.3 μm. Spectra of nine program objects were observed in 1990 September, along with four supergiants and giants. In addition, four program objects were observed in 1990 June, one of which was among those observed in 1990 September. The reference stars used range in spectral type from B1 to G0. These early type objects were chosen because of their lack of CO features. The only strong stellar line in the reference stars is Brγ, which we artificially removed by linear interpolation across the line, so that in the program objects its true strength could be seen.

The observed "raw" spectra include many strong telluric absorption features, especially longward of 2.36 μm. Ratioing the program spectra by the reference spectra allows one to remove these features reasonably well, especially in the bluer half of the spectral range. However, longward of 2.4 μm the telluric features are not so well removed, as the drop-off in the grating efficiency and the atmospheric cutoff, with the increased number and strength of the telluric lines, contribute to amplify differences in the telluric features between the program and reference stars. The only stellar feature detected longward of 2.4 μm are those due to CO.

The observed *K*-band spectra are displayed in Figure 3. Note that the resolution is a factor of 2 lower for 17436+5003, 18095+2704, and 19475+3119 than the others. The Brγ line is seen in absorption in all of the program objects, appearing stronger in the F stars than in the G stars (at the same resolution), as expected.

The $\Delta v = 2$ vibrational transitions of CO are commonly seen in late-type (both oxygen- and carbon-rich) stars. The CO absorption bands are known to appear in early G stars, and to increase in strength with lower temperature and with higher luminosity (Kleinmann & Hall 1986). The spectra of our four supergiants and giants appear consistent with this, with BS 7193 (K1 III) and BS 8313 (G5 Ib) displaying ^{12}CO absorption bandheads ranging from v = 2–0 to 6–4, and BS 1017 (F5 Ib) and BS 382 (F0 Ia) showing an absence of CO features. BS 7193 also appears to show weak ^{13}CO bandheads from v = 2–0 (2.345 μm) and v = 3–1 (2.374 μm).

Among our program objects are four early F supergiants, 17436+5003, 18095+2704, 19475+3119, and 19500−1709, each of which displays a featureless spectrum apart from Brγ. Four of the cooler, late-G spectral type objects (20000+3239, 20004+2955, 22272+5435, and 05113+1347) show strong CO bandhead absorptions ranging from v = 2–0 to as high as v = 6–4, in agreement with what has been observed for late-type objects. This suggests that the CO absorption bands in these program objects are photospheric in origin. However, not all of the late-type stars show this same type of CO absorption spectrum. For 04296+3429 and 05381+1012, which possess early-G optical spectra, the *K*-band spectra are featureless in the CO region. Of particular interest, two of the objects (19114+0002 and 22223+4327) show CO in emission, with the v = 2–0 and 3–1 bandheads clearly present and the 4–2 bandhead present but affected by a close telluric feature.

Most interesting of all, it appears that the CO spectrum of 22272+5435 changed from emission to absorption in a three-month interval. A spectrum in 1990 June shows the CO bands in emission (Fig. 4), but the CO was in absorption in 1990 September (see Fig. 3). The strength of the features and the number of levels, v = 2–0 to 8–6, are much greater than in the other two CO emission sources. One might argue that we are simply seeing the effect of CO absorption in the reference star. To assure ourselves of the reality of this emission, the "raw" spectra were closely inspected. CO features are clearly absent (or very weak) in the reference star BS 7162 (F9 V+K1 V, angular separation 1″) and are clearly seen in emission in 22272+5435. While the K1 V component would be expected to possess CO absorption, it would be much weaker than in the cool supergiants displayed and would be diluted by the F9 V star, which is about 2 times brighter at 2.2 μm. The same reference star spectrum was used for three other stars that night (see Table 1), with no indication of emission in any of them. Thus we believe the CO emission in 222272+5435 to be real. The continuum level is the same to within 10% in the spectra observed 3 months apart.

The three objects that showed CO emission in 1990 were observed again in 1991 November 4, at lower resolution. The CO features in 19114+0002 and 22223+4327 were still in emission, and in 22272+5435 they remained in absorption as when observed in 1990 September. The 1991 November *K*-band spectra are shown in Figure 5. Again, the continuum levels agreed with our previous observations to within ∼10%.

The emission flux measurements above continuum for these three objects are listed in Table 2. They are estimated to be uncertain by about 30%, due to the uncertainty of where the continua lie. We also have listed the change in flux between the absorption spectrum of 22272+5435 in 1990 September and the emission spectrum in 1990 June.

The Na I doublet at 2.206 and 2.209 μm is a strong emission feature in 19114+0002, present in the spectra of both 1990 September and 1991 November (but is not present in 22223+4327, the other CO emission object), and it is perhaps present in emission in 20004+2955. It is seen in absorption in BS 7193. Na I emission at 2.206 and 2.209 μm has been pre-

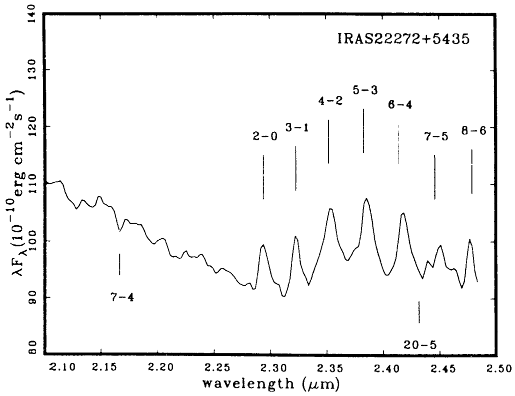

FIG. 4.—*K*-band spectrum of 22272+5435 taken on 1990 June 27. Note that the resolution is a a factor of 2 lower than in Fig. 3.

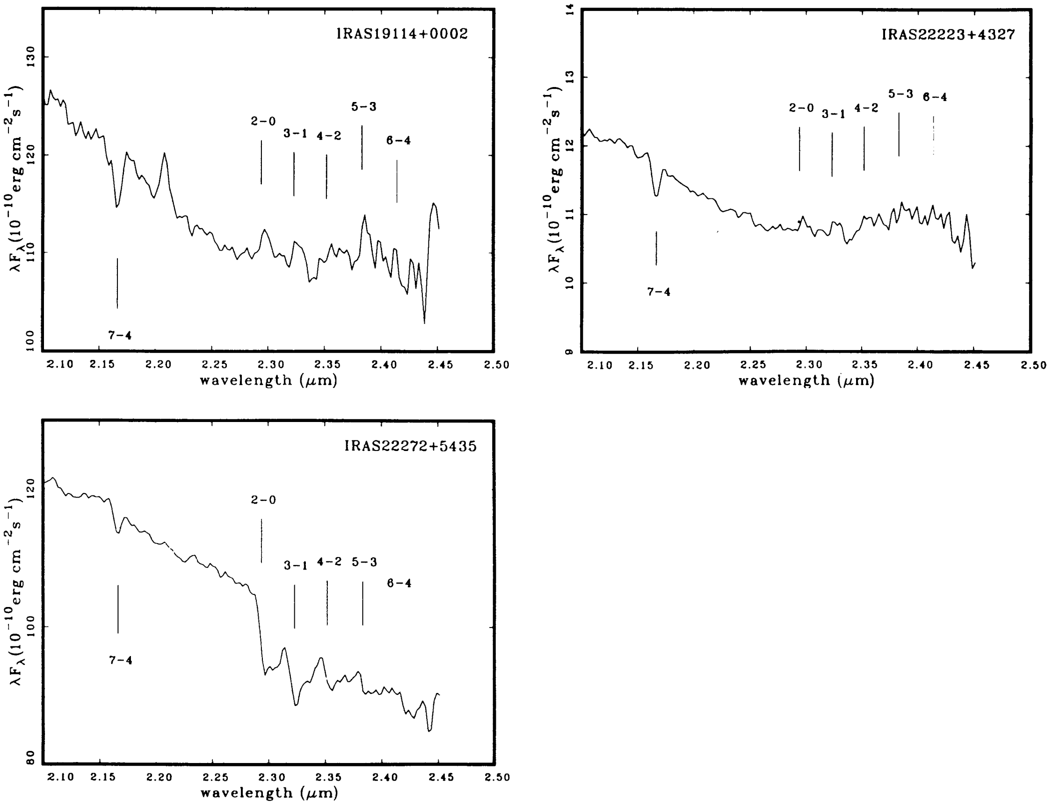

FIG. 5.—*K*-band (CGS4) spectra of 19114+0002, 22223+4327, 22272+5435 observed in 1991 November 4. Positions of the CO bandheads of the $\Delta v = 2$ transitions as well as the hydrogen Brγ (7–4) line are indicated. Note that the resolution is a factor of 2 lower than in Fig. 3.

viously observed in IRC +10420 (F8 Ia) by Thompson & Boroson (1977), in HR 8752 (~G5 0–Ia) by Lambert, Hinkle, & Hall (1981), and Kleinmann & Hall (1986), and in the F supergiants ρ Cas, 89 Her, IRC +10420, and ν Sgr (Lambert et al. 1981). McGregor, Hyland, & Hillier (1988b) and McGregor, Hillier, & Hyland (1988a) also observed Na I emission on six early-type supergiants, including five (of the 10) with CO emission.

There is no evidence for H_2 emission in any of these objects, in contrast to the *K*-band observations of the PPNs AFGL 618 and 2688. The bipolar PPNs AFGL 618 (B0) and AFGL 2688 (F5 I) have been observed in the 1.9 to 2.5 μm range at a resolution of 0.0004, a factor of 8 higher than our observations. They each display a number of emission lines from H_2 rotation-vibration, which are attributed to shock excitation in the outflowing circumstellar envelopes. In AFGL 618, Brγ appears weakly in emission, while in AFGL 2688, no Brγ feature appears; no CO emission or absorption appears in either of these objects (Thronson 1981, 1982). Thus these new spectra are significantly different from those of the well-known

TABLE 2

EMISSION FLUX MEASUREMENTS

Object	Feature	Flux λF_λ ($\times 10^{13}$ ergs cm^{-2} s^{-1})	Δ Flux ($\times 10^{-13}$ ergs cm^{-2} s^{-1})
19114+0002.........	CO (2–0)	35	...
	CO (3–1)	34	...
	CO (4–2)	23	...
	Na I	16	...
22223+4327.........	CO (2–0)	1.6	...
	CO (3–1)	2.1	...
	CO (4–2)	1.0	...
22272+5435.........	CO (2–0)	40	120
	CO (3–1)	39	128
	CO (4–2)	95	159
	CO (5–3)	89	126
	CO (6–4)	54	...

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bipolar PPNs AFGL 618 and AFGL 2688. The rich H_2 emission spectra of AFGL 618 and AFGL 2688 could be the consequence of the high-velocity outflow observed in CO millimeter emission in these two objects (618: Gammie et al. 1989 and Cernicharo et al. 1989; 2688: Young et al. 1992 and Jaminet et al. 1992).

5. *L*-BAND SPECTRA

We present in Figure 6 the spectra of four objects observed in the *L* band, which includes the region of the 3 μm emission features. The 3.3 μm emission feature found in many planetary nebulae and H II regions is a member of a family of emission features which are believed to be due to PAH molecules. High spectral resolution observations of the young planetary nebulae NGC 7027 and IRAS 21282+5050 show emission features at 3.29, 3.40, 3.46, and 3.52 μm (de Muizon et al. 1986, Nagata et al. 1988, Lowe et al. 1991). Our spectrum of 07134+1005 shows the 3.3 μm emission feature, as previously reported (Kwok et al. 1990). The 3.3 μm emission feature may be present but weak in 05113+1347, and is absent in 18095+2704 and 19475+3119 which appear featureless. IRAS 05113+1347, along with two other PPN observed by Geballe et al. (1992), display G-type spectra, and are the coolest known objects to show the 3.3 μm feature.

6. DISCUSSION

6.1. H I *Lines*

The series of hydrogen absorption lines observed in the *H*-band spectra of these PPN is similar to the hydrogen lines seen in normal F supergiants. The hydrogen lines in the PPNs extend to late-G spectral types. In the G8 Ia star 20000+3239 the lines, although weaker, can still be seen. It is likely that the absorption lines are formed in the extended atmospheres of the stars.

6.2. CO *Bands*

In the *K*-band, the fact that strong CO absorption bands are observed in most PPNs of mid-G spectral type and later, but are absent in the F and G0 stars, is consistent with the expectation from normal late-type giants and supergiants. Again, the absorption bands are likely to be formed in the extended atmospheres.

However, in three PPNs, the CO bands are detected in emission. The presence of CO in emission from a late-type supergiant is highly unusual. The only other late-type supergiants we are aware of which show CO emission are the luminous supergiant HR 8752 (~G5 0–Ia), which was observed at high resolution by Lambert, Hinkle, & Hall (1981), and two early G supergiants in the Large Magellanic Cloud (McGregor, Hillier,

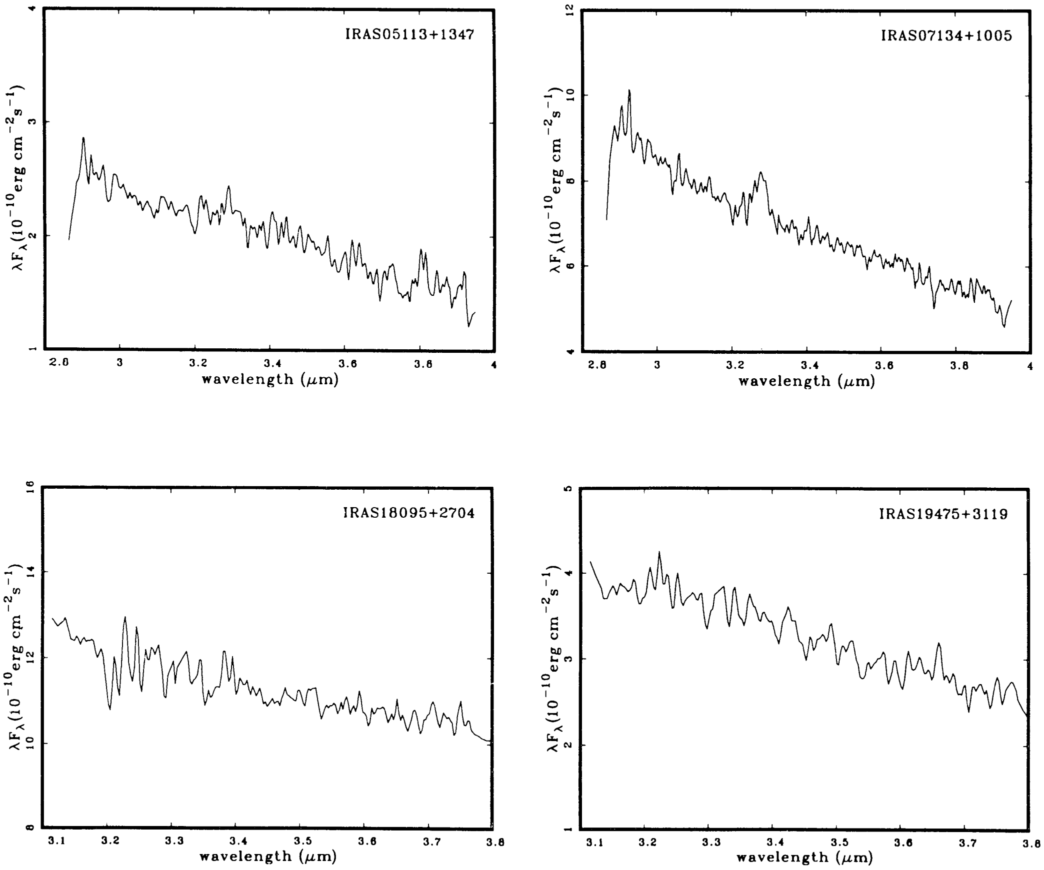

FIG. 6.—*L*-band spectra for the 05113+1347, 07134+1005, 18095+2704, and 19475+3119. (Note that we have manually removed the residual telluric feature at 3.31 μm due to the *Q* branch of the CH_4 fundamental stretching mode. This strong feature did not divide out well.)

& Hyland 1988a). CO emission at 2.3 μm was also observed in ten early-type supergiants by McGregor et al. (1988b) and McGregor et al. (1988a); in one of these objects the CO emission was found to vary and was absent in some later spectra. Note that for one of our CO emission objects, 19114+0002, the high expansion velocity measured in the circumstellar envelope, 33 km s^{-1} (Likkel et al. 1991) is more typical of a normal supergiant than a post-AGB object. This raises the possibility that 19114+0002 is a massive supergiant rather than a low mass PPN, in spite of the characteristic double-peaked energy distribution. The existence of CO emission in young stellar objects has been well documented (Scoville et al. 1979; Scoville et al. 1983; Thompson 1985; Geballe & Persson 1987; Carr 1989).

Three possible mechanisms have been suggested for the CO overtone emission in Orion (Scoville, Krotkov, & Wang 1980): collisional excitation, radiative excitation by CO 4.6 μm fundamental transitions, or downward cascade through the vibrational states following electronic excitation by ultraviolet photons. The low temperature of the stars under study here make the third possibility unlikely. Also, in contrast to star-formation regions, the near-infrared continua of our objects are due to photospheric emission and not dust emission, and there are no excess 4.6 μm photons for radiative excitation in the fundamental band. The most likely explanation is collisional excitation in the circumstellar envelope. Since the CO molecule is excited to $v = 8$ in 22272+5435 and the excitation temperatures to the bandheads ($J = 51$) of $v = 2, 3, 4, 5, 6, 7$, and 8 are 1.3, 1.6, 1.9, 2.2, 2.5, 2.8, and 3.0×10^4 K, respectively, excitation to such high vibrational states will require extremely high density and temperature. One possibility is that the CO molecule is excited by a shock generated by a high-velocity outflow interacting with the circumstellar shell.

This would also provide an explanation for the Na I emission seen in 19114+0002 and perhaps 20004+2955. Thompson & Boroson (1977) attributed the Na I emission in IRC +10420 to excitation from the ground state by absorption of 3302 Å photons, a suggestion repeated by Lambert et al. (1981) for their F stars. However, this mechanism does not seem as likely at the lower source temperature of 19114+0002 (G5 Ia).

The most interesting case is that of 22272+5435, which changed from CO emission to absorption in a period of three months. Since the continuum level is basically unchanged between the two observations, one can assume that the absorption spectrum represents the normal state of the star. The atmospheric absorption spectrum is masked by circumstellar emission in the 1990 June observation. The emission from highly excited vibrational levels of CO is likely to be related to the onset of a sudden mass ejection from the central star, with the emission originating either at the base of the new wind where the density is high, or at the region of interaction between this flow and the outer dust/molecular envelope where the shock energy is dissipated.

The initiation of a fast stellar wind during the transition from the AGB to the planetary nebula stages has been suggested to be responsible for the compression and acceleration of the AGB envelope, and ultimately the formation of the planetary nebula shell (Kwok, Purton, & FitzGerald 1978). While such a fast wind has been observed in many central stars of planetary nebulae (Cerruti-Sola & Perinotto 1985), it has not been clear when it first begins. Recent observations of the PPNs AFGL 618 (BO), IRAS 19500−1709 (F3 I), and AFGL 2688 have found the presence of a high-velocity neutral flow (618: Gammie et al. 1989 and Cernicharo et al. 1989; 19500−1709: Bujarrabal, Alcolea, & Planesas 1992; 2688: Young et al. 1992 and Jaminet et al. 1992). If the excitation of CO in 19114+0002, 22223+4327, and 22272+5435 is the result of such a high-velocity flow, then the commencement of this wind can be as early as when the star has a G spectral type. It is also possible that during the early stages of this wind the flow is not steady, therefore resulting in the change between the emission (excited) and absorption (normal) states observed in 22272+5435.

Evidence of high-velocity outflow in PPNs is also seen in the optical region. The Hα line often has broad wings, or has P Cygni profiles, suggestive of outflow (Trams et al. 1989; Slijkhuis, Hu, & de Jong 1991). The estimated terminal velocities are several hundred km s^{-1}, of the same order as the expected escape velocities. Variable Hα emission has been seen in 19114+0002, with shell and inverse P Cygni profiles (Woodsworth & Hrivnak 1994).

The direct observation of the beginning of the fast wind is important in the understanding of the evolution of planetary nebulae. Trams et al. (1989) have argued that enhanced mass loss in the post-AGB phase has an important effect on the evolution of low-mass stars. Mass loss in the form of a fast wind will deplete the already-thin hydrogen atmosphere of the star, and hasten its evolution toward the blue side of the H–R diagram. However, Schönberner (1990) finds that there is reasonable agreement between the observations of PPNs and the thoeretical models which involve only a Reimers mass-loss formula.

6.3. *Unidentified IR Bands*

In the *L* band, 3.3 μm emission appears in one (07134+1005) and possibly a second (05113+1347) of the PPNs observed but not in the other two (18095+2704 and 19475+3119). In four other PPNs (05341+0852, 04296+3429, 22272+5435, and AFGL 2688) the 3.3 μm feature has been observed, along with an unusually strong 3.4 μm feature (Geballe & van der Veen 1990; Geballe et al. 1992). Both 3.3 and 3.4 μm emission features have been attributed to PAHs. An unknown emission feature at 21 μm has been discovered in the *IRAS* Low Resolution Spectrometer (LRS) spectra of three of these PPNs with the 3.3 μm feature: 04296+3429, 07134+1005, and 22272+5435 (Kwok et al. 1989). This 21 μm feature is not seen in the *IRAS* LRS spectrum of 18095+2704. The unpublished LRS spectra of 05113+1347 and 19475+3119 were obtained from the University of Calgary *IRAS* Data Analysis Facility, and are shown in Figure 7, along with the LRS spectra of 07134+1005 and 18095+2704 for comparison. The spectrum of 19475+3119 rises rapidly beyond 15 μm with no suggestion of a 21 μm feature, while the spectrum of 05113+1347 rises slowly from 11 to 21 μm, with the indication of a weak 21 μm feature. A recent ground-based 16–23 μm spectrum of 05113+1347 obtained at UKIRT supports the existence of the 21 μm feature. Taken together, these observations are consistent with the idea that a correlation exists between the presence of PAH features and the unknown 21 μm feature (Buss et al. 1990). The objects with the 21 μm feature all possess the 3.3 μm feature, although the converse is not true for AFGL 2688. Most of the 21 μm sources also possess the 3.4 μm feature, the clear exception being 07134+1005, which possesses the 3.3 but not the 3.4 μm feature. This object has an earlier spectral type, F5 I, than any of the other 21 μm sources, which are G I. Perhaps the lack of the 3.4 μm feature is related to the higher

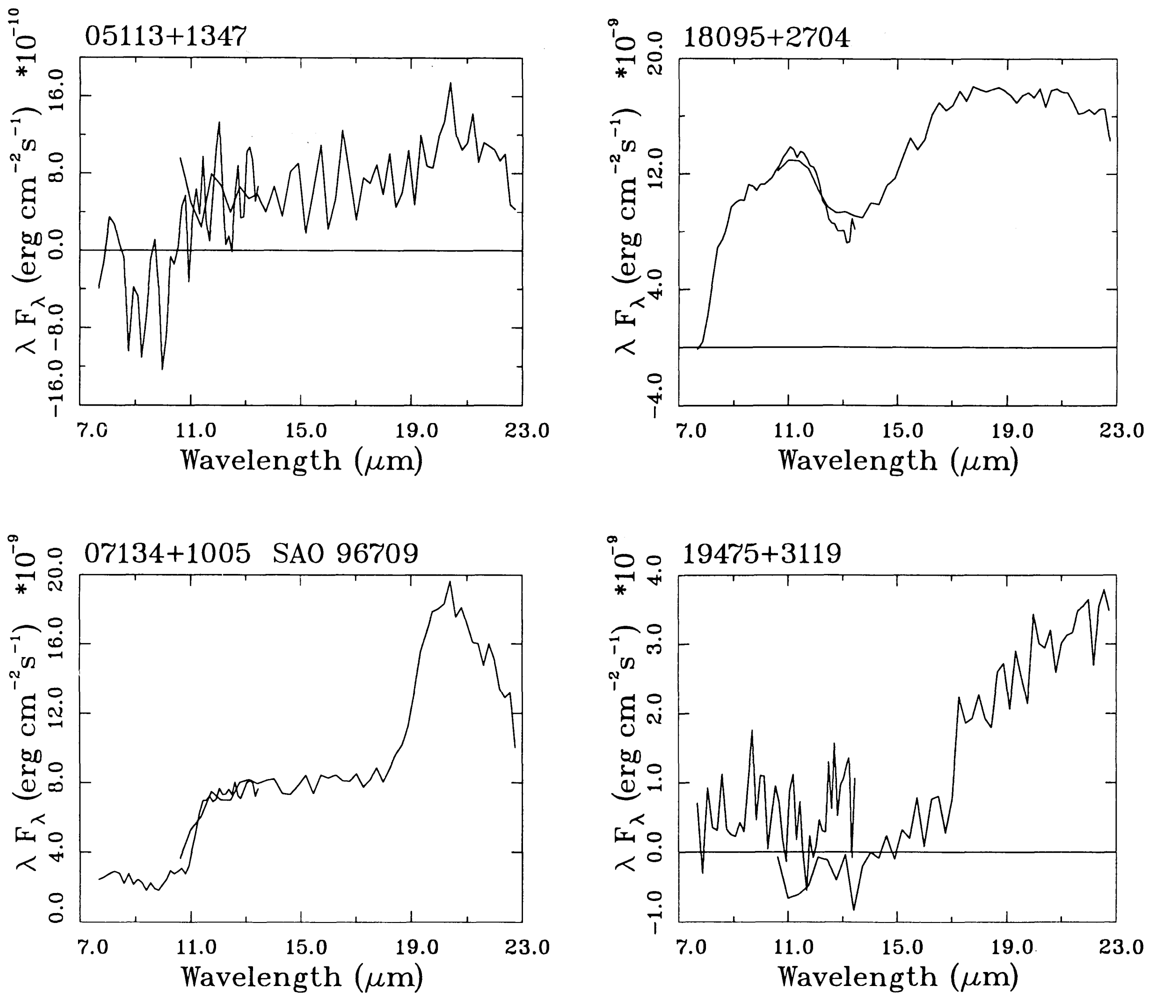

FIG. 7.—*IRAS* LRS spectra for the four PPNs with *L* band spectra (see Fig. 6). A strong 21 μm emission feature is seen in the spectrum of 07134+1005 and a weak 21 μm emission feature appears in 05113+1347. The spectra of the other two objects do not show the 21 μm emission feature.

central temperature of the source. For 05113+1347, the 3.3 μm feature seems to be only marginally detected and higher signal-to-noise spectra would be required to make a more definitive statement about the presence or absence of the 3.4 μm feature in this source. It would be desirable to obtain *L*-band spectra of the remainder of our program sources to further investigate this correlation.

7. CONCLUSIONS

We have obtained near-infrared spectra of 16 PPN in the *H* and *K* bands, and four in the *L* band. Up to 11 members of the hydrogen Brackett series have been observed in these objects. The *H*-band spectra of PPNs do not appear to be significantly different from those of normal F and G supergiants. Photospheric CO absorption bands (from $v = 2\text{–}0$ to up to $v = 6\text{–}4$) are also detected, primarily in PPNs of mid- to late-G spectral types. This also is similar to what is observed in normal supergiants. However, three objects have been found to show CO in emission, which is rare and is probably due to a new phase of outflow from the central star. Most interestingly, the CO spectrum of 22272+5435 was found to change from emission to absorption over a three-month interval, suggesting that this phase of mass loss may be sporadic. The 2 μm spectra of these new PPNs are different from those of the well-studied PPN AFGL 618 and AFGL 2688, which show H_2 emission which is not seen in any of these new PPN. In the *L* band, the 3.3 μm emission feature, which is thought to be due to PAH molecules, is seen in one and possibly two of the four objects observed. In Table 3 we have summarized our results, and also included a listing of observed dust features.

These observations provide important clues to help trace the evolution between the AGB and planetary nebulae phases, a previously little-observed transitional phase of stellar evolution. We see that the dust constituents change from primarily silicate and silicon carbide to molecular species that are related, but not identical to, the PAH features seen in PNs. The CO vibrational bands change in some cases from photospheric absorption to circumstellar emission. The neutral hydrogen lines also begin to appear as the stars evolve to intermediate spectral types before the atom is photoionized.

As the sensitivity and spectral resolution of infrared spectrometers continues to improve, kinematic studies of the envelope and mass-loss structures can be made. We expect that these present observations will serve as a starting point for many future fruitful spectroscopic studies, which will lead to a better understanding of the formation process of planetary nebulae.

TABLE 3

Summary of Observational Results

IRAS Number	Other Names	Spectral Type	l	b	H I[a]	CO[a]	Dust Features
04296+3429.........	...	G0 Ia	166.2	−9.1	a	n	3.3, 3.4,[b] 21 μm[c]
05113+1347.........	...	G8 Ia	188.8	−9.1	a	a	3.3 μm:
05381+1012.........	...	G I	195.5	−10.6	a	n	...
07134+1005.........	HD 56126	F5 I	206.7	+10.0	a	*n*[d]	3.3,[d] 21 μm,[c] PAH[e]
07430+1115.........	...	G–K I	208.9	+17.0	a	...	...
17436+5003.........	HD 161796	F3 Ib	77.1	31.0	a	n	...
18095+2704.........	...	F3 Ib	53.8	+20.2	a	n	silicate[f]
19114+0002.........	HD 179821	G5 Ia	36.6	−5.0	a	e	...
19475+3119.........	LS31 3797	F3 Ia	67.1	+2.8	a	n	...
19500−1709.........	HD 187885	F3 I	24.0	−21.0	a	n	...
20000+3239.........	...	G8 Ia	69.7	+1.2	a	a	...
20004+2955.........	BD+29 3865	G7 Ia	67.4	−0.4	a	a	silicate[g]
20572+4919.........	...	F	89.4	+2.4	n	...	...
22223+4327.........	DO 41288	G0 Ia	96.7	−11.5	a	e	...
22272+5435.........	HD 235858	G5 Ia	103.3	−2.5	a	e, a	3.3, 3.4,[b] 21 μm,[c] PAH[e]
...	AFGL 2688	F5 I	80.2	−6.5	a	n[h]	3.3, 3.4 μm[b]

[a] a = absorption, e = emission, n = not detected.
[b] Geballe et al. 1992.
[c] Kwok et al. 1989.
[d] Kwok et al. 1990.
[e] Buss et al. 1990.
[f] Hrivnak et al. 1988.
[g] Hrivnak et al. 1989.
[h] Thronson 1982.

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