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ON THE POSSIBLE BIPOLAR NATURE OF 21 MICRON *IRAS* SOURCES

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ABSTRACT

We report the discovery of another *IRAS* source (22574+6609) showing the unidentified 21 μm emission feature. Its overall energy distribution is similar to the well-known edge-on bipolar nebulae AFGL 2688 and AFGL 618. Ground-based optical and infrared observations of this object and two other 21 μm sources show that while all three have very similar infrared properties, they differ greatly in the visual region. We suggest that all three of these 21 μm sources are intrinsically similar bipolar nebulae viewed at different orientations.

Subject headings: infrared: sources — stars: circumstellar shells — stars: mass loss

1. INTRODUCTION

The *IRAS* sky survey has revealed many cool sources with color temperatures between 100 and 200 K. While some of these sources are extremely evolved asymptotic giant branch (AGB) stars (Kwok, Hrivnak, & Boreiko 1987), others may be in a post–AGB stage of evolution. The low color temperature of these sources suggests that the photospheres of the central stars may be heavily obscured by circumstellar dust, and indeed most late AGB stars are found to have a very faint optical counterparts down to ~20 mag (Kwok et al. 1987). It was therefore a surprise when we found during our program of ground-based identification of *IRAS* sources that some very cool *IRAS* sources have bright optical counterparts (e.g., 18095+2704; Hrivnak, Kwok, & Volk 1988). Associations of cool *IRAS* sources with bright stars by positional coincidence have also been found by Parthasarathy & Pottasch (1986), Pottasch & Parthasarathy (1988), and Tram et al. (1990). Spectroscopic observations of these sources show that many have F and G spectral types and could be post–AGB stars which left the AGB a few hundred years ago (Hrivnak, Kwok, & Volk 1989; Waters, Waelkens, & Trams 1990; van der Veen, Habing, & Geballe 1989).

The increasing number of proto–planetary nebulae (PPN) candidates that have been found with bright optical counterparts makes it tempting to assume that optical brightness is a common feature of PPN. In this paper, we report the association of two *IRAS* sources with bright stars and discuss them together with a third cool *IRAS* source possessing a very faint optical counterpart but which is otherwise similar in all aspects. All three process the newly discovered 21 μm emission feature (Kwok, Volk, & Hrivnak 1989). We suggest, in light of their similar infrared properties, that the three objects might possess bipolar structures.

2. OBSERVATIONS

The three new sources were located by manually searching the areas around the *IRAS* positions, using a bolometer at 10 μm. At this wavelength, source confusion should not be a problem, and the correctness of our identifications is confirmed by the good agreement between our 10 and 25 μm measurements and those of *IRAS* at 12 and 25 μm. All three objects were located close to their *IRAS* positions, and their coordinates, with an accuracy of ±5″ in R.A. and ±7″ in declination, are listed in Table 1. Finding charts for the three are given in Figure 1 (Plate 11). Two of the three objects have relatively bright optical counterparts and can be seen in Palomar Observatory Sky Survey (POSS) prints.

Mid-infrared observations, together with the identifications, were made at the 3.6 m Canada-France-Hawaii telescope (CFHT) on Mauna Kea, Hawaii, in 1985 August. The telescope was in the f/35 infrared configuration, and an aperture of 10″.5 and a throw of 20″ in declination were used. The detector was a helium-cooled Ge bolometer, with nine broad-band filters having central wavelengths ranging from 7.8 to 25 μm, including the standard *N* and *Q* filters. Several infrared standard stars were observed each night. Measurements of these three objects are listed in Table 2. The characteristics of these filters and flux calibration factors are given by Kwok, Hrivnak, & Milone (1986).

Near-infrared observations of all three objects were kindly obtained by R. Joyce with the 1.3 m telescope at Kitt Peak National Observatory (KPNO) in 1987 October. They were observed with the BT InSb photometer, using a 15″ aperture and a throw of 40″ in declination. The data for 22574+6609 were obtained by blindly integrating at the source position, as the source was too faint in the near-infrared to permit "peaking up" the signal. Thus the measurement for this source may be less precise than the formal errors indicated. IRAS 04296+3429 was also kindly observed by P. Whitelock with the 0.75 m telescope at the South African Astronomical Observatory (SAAO). The latter observations were made one month later and show the object to have a similar brightness. All of these observations are listed in Table 2.

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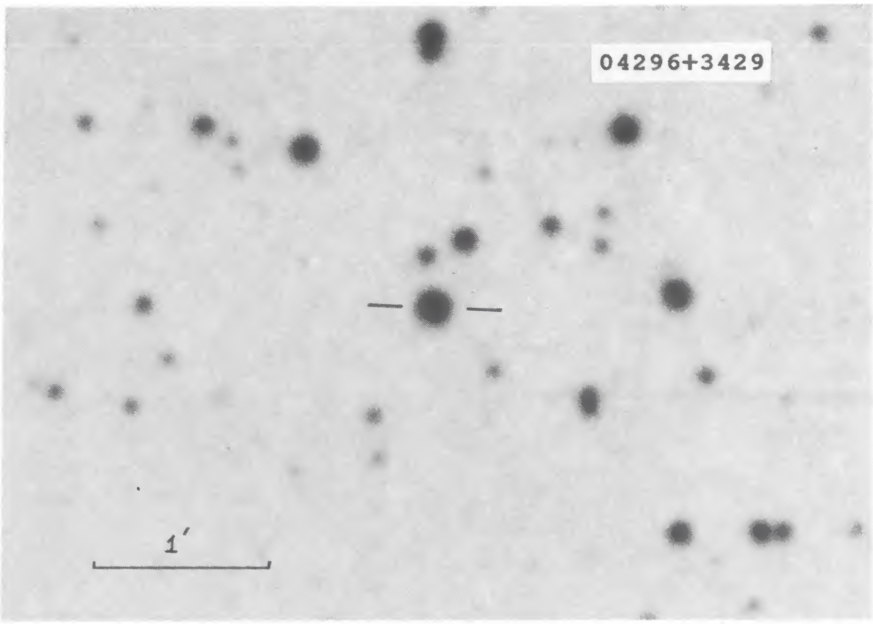

FIG. 1*a*

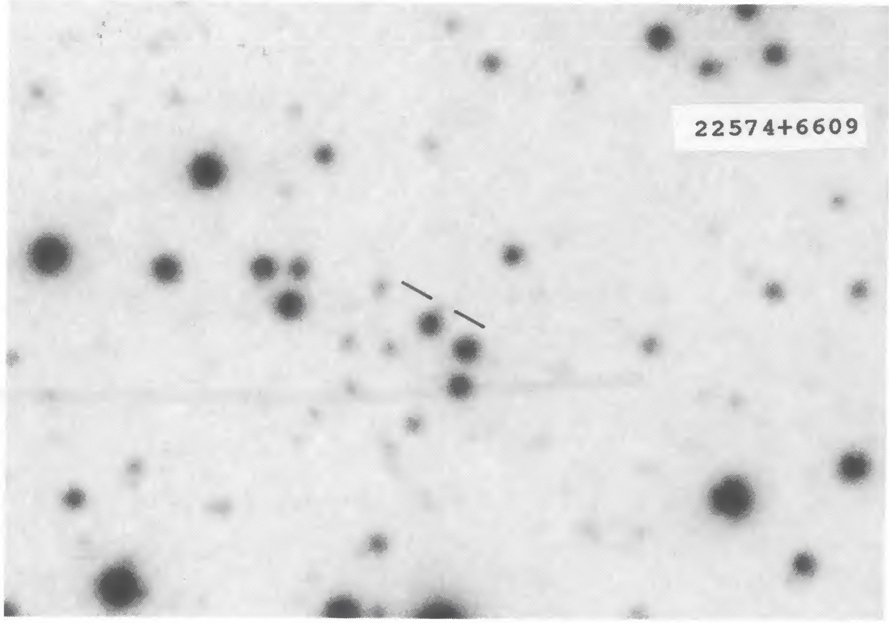

FIG. 1*b*

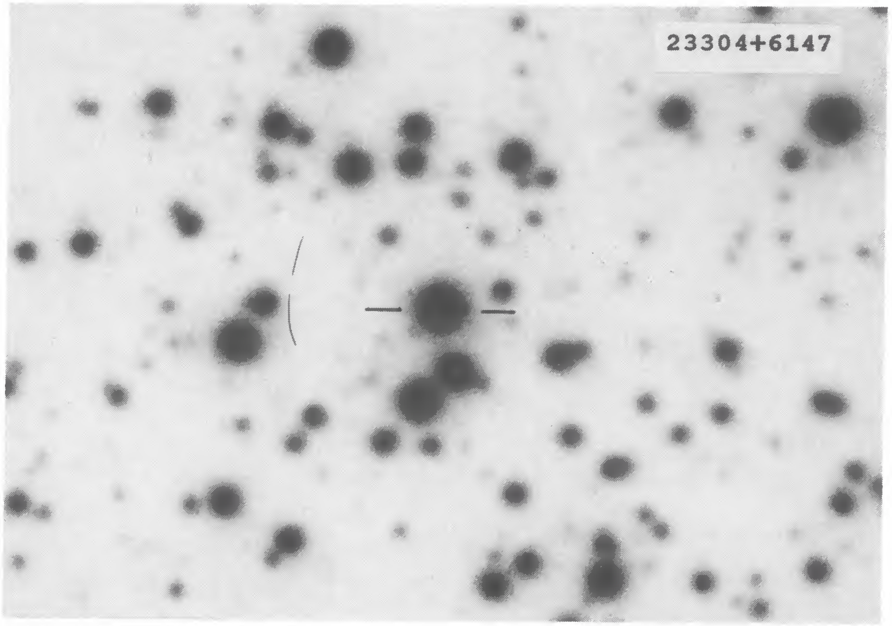

FIG. 1*c*

FIG. 1(*a*)–(*c*).—Finding charts from the Palomar Observatory Sky Survey near-infrared (I) or red (E) prints for IRAS 04296+3429 (E), 22574+6609 (I), and 23304+6147 (I). East is left, and north is up. The 1′ scale is shown in Fig. 1*a*.

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TABLE 1

POSITIONS OF PROGRAM OBJECTS

IRAS Identification	R.A. (1950)	Decl.	l	b
04296+3429.........	$04^h29^m41^s.2$	+34°29′44″	166.2	−9.0
22574+6609.........	22 57 25.0	+66 09 43	112.0	+6.0
23304+6147.........	23 30 26.3	+61 47 24	113.9	+0.6

Visible photometry for IRAS 23304+6147 was obtained with the University of Hawaii (UH) 0.6 m telescope located on Mauna Kea. The telescope was equipped with a single-channel photometer with GaAs detector. The *UBV* and *RI* observations were transformed to the standard Johnson and Cousins photometric systems, respectively, through the observations of nightly standard stars. IRAS 04296+3429 and 23304+6147 were kindly observed by H. C. Harris, using a CCD on the U.S. Naval Observatory (USNO) 1.0 m telescope in Flagstaff, Arizona. The *BV* and *I* observations were also transformed to the Johnson and Cousins systems, respectively, with an uncertainty of a couple of percent due to the use of somewhat nonstandard filters. These observations are also listed in Table 2. The two different sets of observations of 23304+6147 suggest variability at the 10% level.

No optical counterpart for 22574+6609 was seen on the television monitor or on the POSS prints. In order to search for a fainter optical counterpart, a *V* band CCD image was obtained on 1989 December 29 at the CFHT by O. Le Fevre on our behalf. A 15 minute exposure was taken at the prime focus and reveals a faint optical counterpart.

Spectral classification for the two objects with bright optical counterparts, 04296+3239 and 23304+6147, indicates that they are G supergiants (Hrivnak & Kwok 1991).

3. FLUX DISTRIBUTION

The observations of the sources in the various wavelength regimes were combined to show the observed flux distribution of each. These are displayed in Figure 2, where for plotting purposes we have multiplied the data for 23304+6147 and 04296+3429 by 10^4 and 10^2, respectively. Although the *IRAS* and ground-based observations were separated by as much as 7 yr, evidence suggests that these sources do not vary greatly in brightness, at least not in the infrared. The *IRAS* variability probability was low for each, 11%, unmeasured, and 9% for 04296+3429, 22574+6609, and 23304+6147, respectively. Also, good agreement exists between the *IRAS* measurements and ours made two yr later. Flux calibration factors for the visible-band photometry were taken from Bessell (1979).

The three sources display remarkable similarities in the mid-infrared and far-infrared spectral regions. Their infrared continuum can be represented by blackbodies of $T \sim 200$ K and they all show emission features at 8 μm. They differ significantly, however, at shorter wavelengths, with 04296+3429 and 23304+6147 displaying "double-peaked" flux distributions, the latter object being relatively brighter. The shorter wavelength flux can be understood as light from the reddened stellar photosphere and the longer wavelength flux as that due to the circumstellar dust.

The similarity in the mid-infrared and far-infrared spectra among these sources suggests that they are intrinsically similar. While it is possible to model the "double-peaked" energy distributions assuming spherical symmetry (Kwok et al. 1989; Hrivnak et al. 1989), the large difference in the photospheric components suggests that the objects may possess a bipolar morphology. In this case, if the dust exists around the star in a torus which is optically thin longward of 5 μm, then the flux distribution of all three sources could be explained by the same

TABLE 2

OBSERVED MAGNITUDES OF PROGRAM OBJECTS

A. Mid-Infrared

IRAS Identification	Date	[7.8]	[8.7]	[9.8]	[10.3]	N	[11.6]	[12.5]	Q	[25]
04296+3429.........	1985 Aug 22	2.45	2.27	2.02	1.81	1.50	0.73	0.68	−1.08	−2.0
22574+6609.........	1985 Aug 24	2.67	2.45	2.44	2.25	1.91	1.20	0.99	−0.70	−1.7
23304+6147.........	1985 Aug 23	2.77	2.61	2.40	2.14	1.78	0.86	0.63	−1.31	−2.3

B. Near-Infrared

IRAS Identification	Date	J	H	K	L	M	Observatory
04296+3429.........	1987 Oct 6	9.61	8.64	8.21	7.30	6.30 ± 0.14	KPNO
	1987 Nov 23	9.70	8.69	8.22	...	...	SAAO
22574+6609.........	1987 Oct 7	13.60	12.57	11.53	8.39	6.78 ± 0.25	KPNO
23304+6147.........	1987 Oct 7	8.55	7.83	7.67	7.11	6.33 ± 0.20	KPNO

C. Visible

IRAS Identification	Date	U	B	V	R_C	I_C	Observatory
04296+3429.........	1988 Oct 18	...	16.20	14.21		11.64	USNO
22574+6609.........							
23304+6147.........	1988 Oct 18		15.37	13.06		10.43	USNO
	1989 Aug 24	17.3	15.52	13.15	11.79	10.50	UH

NOTE.—Observational uncertainties as follows: (1) mid-infrared: ±0.10 at shorter wavelengths; ±0.15 at 12.5 μm, ±0.15 at *N* and *Q*, and ±0.20 at 25 μm; (2) near-infrared: ≤ ±0.03 except as marked; and for 22574+6609 where they are ±0.12 (*J*), ±0.05 (*H*), ±0.05 (*K*), ±0.06 (*L*); (3) visible: ±0.02 (*V*, *R*, *I*), ±0.03 (*B*), ±0.5 (*U*).

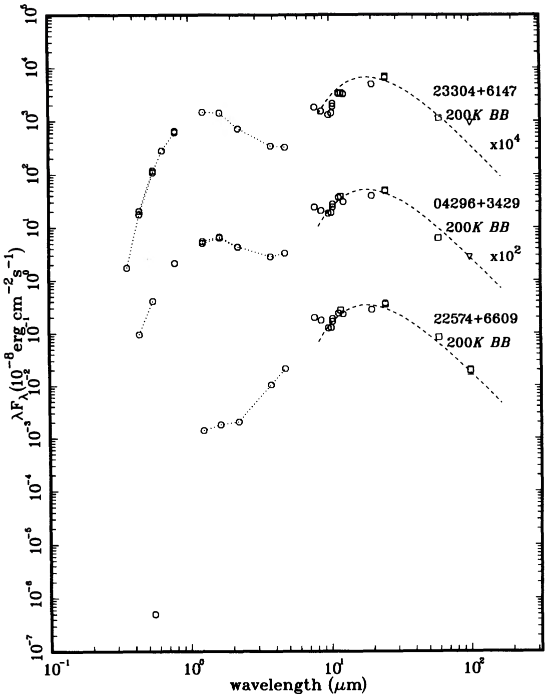

FIG. 2.—Energy distributions for the three candidates for bipolar proto–planetary nebulae. The data have been multiplied by factors of 10^4 and 10^2 for IRAS 23304+6147 and 04296+3429, respectively. The ground-based measurements from Table 1 are plotted as open circles and the *IRAS* measurements as open squares. Upper limits are represented by inverted triangles. Color corrections have been applied to the *IRAS* measurements. Blackbody curves are also plotted in each spectrum for comparison purposes.

model with a change in the orientation of the torus to the line of sight. In the case of 23304+6147, one would be looking at a source with the polar axis tilted more toward the observer and in the case of 22574+6609, the polar axis is at a smaller angle of inclination and relatively little of the photospheric light is observed.

There exist several well-known examples of bipolar nebulae which are considered to be objects in the PPN phase. The best studied are AFGL 2688 (Egg nebula, Ney et al. 1975; Humphreys, Warner, & Gallagher 1976) and AFGL 618 (IRAS 04395+3601, Westbrook et al. 1975). AFGL 2688 is not in the *IRAS* Point Source Catalog, version 2 (1988), nor in the *IRAS* Small Scale Structure Catalog (1988). However, we were able to extract a spectrum for AFGL 2688 from the *IRAS* Low Resolution Spectrometer (LRS) data base. The spectrum is almost featureless with a color temperature of ~170 K. In comparison, the continuum of AFGL 618 resembles a 200 K blackbody with an emission feature at ~8 μm.[3]

In Figure 3 we have plotted the energy distribution of these two objects. The data for AFGL 2688 have been multiplied by a factor of 10^2. The LRS spectra have had two linear baselines removed, one for each bank of the LRS. The rms noise levels for the first and last 20 channels of each bank were used to determine the baseline. If the two halves of a spectrum did not match, a procedure similar to that described in *IRAS* Explanatory Supplement (1988) was applied to join the two bands. The combined spectrum was convolved with the 12 μm instrumental profile and the resultant integrated flux was then compared with the survey 12 μm flux. The spectrometer fluxes were then scaled to agree with the survey fluxes. An absolute calibration error of the LRS has been found by Volk & Cohen (1989). Although such calibration errors are small for the cool objects under discussion here, we nevertheless corrected the spectra using the average spectra of seven bright stars as standards following the method of Volk & Cohen. Also plotted for AFGL 618 are the four *IRAS* photometric measurements, which have had color corrections applied. The optical and near-infrared ground-based observations show significant excesses above the dust component for AFGL 2688, but less so for AFGL 618. The short-wavelength excess in the first object is undoubtedly due to the reddened photosphere of the F2–5 I central star (Crampton, Cowley, & Humphreys 1975; Cohen & Kuhi 1977). The central star of AFGL 618 (B0, Westbrook et al. 1975) is highly obscured, probably as the result of the torus being aligned edge-on with respect to our line of sight. Simple integration of the fluxes under the photospheric and dust components shows that approximately 99.6% and 98.8% of the total observed fluxes are emitted from the dust components of AFGL 2688 and AFGL 618 (neglecting interstellar absorption). These numbers suggest small inclination angles of the polar axes in these objects and are consistent with their prominent and extended bipolar morphologies seen in the plane of the sky. High-resolution molecular maps of AFGL 2688 also support this interpretation (Bieging & Nguyen 1988).

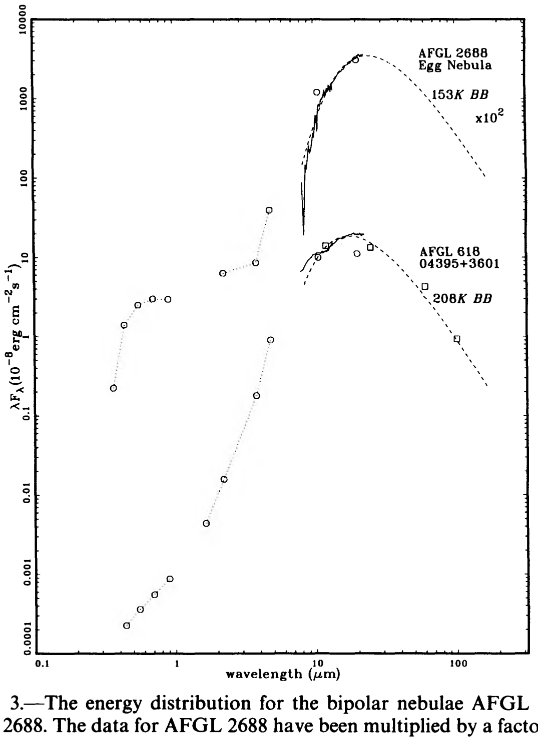

FIG. 3.—The energy distribution for the bipolar nebulae AFGL 618 and AFGL 2688. The data for AFGL 2688 have been multiplied by a factor of 10^2. The ground-based data for AFGL 618 are from Westbrook et al. (1975). For AFGL 2688, the ground-based infrared data are from Ney and Merrill (1980, aperture 26″); and the optical data are from Ney et al. (1975). Also shown are eye-fitted blackbody curves for the dust components.

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[3] Another example of a candidate for a bipolar PPN is OH 17.7 − 2.0 (IRAS 18276−1431). We had previously questioned the association by LeBertre and collaborators (see LeBertre et al. 1989 and references therein) of this source with an optical counterpart, based upon our 10 μm photometric position (Kwok, Hrivnak, and Volk 1990). However, our more recent observations indicate that our earlier position was slightly in error, and suggests and association with the object they labeled as A1.

The three new *IRAS* sources which we have observed thus show a progression in their optical and near-infrared flux distributions reminiscent of that seen in bipolar nebulae. IRAS 22574+6609 is similar to AFGL 2688 in its relative flux distribution, suggesting, in the simplest model, a similar orientation in the sky. The other two new sources would be seen more pole-on. The question can be raised as to whether it is likely that bipolar lobes could be observed in these sources. Since the infrared flux from the three sources is similar, it is reasonable to assume that they are at approximately the same distance from us. Of these three, IRAS 22574+6609 would be the most likely candidate, as it would seem to have such lobes most nearly in the plane of the sky. Some simple values for the separation of such lobes can be calculated based upon comparison with AFGL 2688. The infrared flux of the latter is 100 times greater, suggesting that IRAS 22754+6609 is 10 times farther away. The separation of the two lobes in AFGL 2688 is 8″ leading to a corresponding separation of 0″.8 in IRAS 22754+6609. Such lobes could be detected by high-resolution imaging with a large telescope.

Figure 4 (Plate 12) shows the V band CCD image of IRAS 22574+6609, as obtained with a 15 minute exposure on the CFHT. Aperture photometry leads to $V = 24.0$ mag, with an estimated uncertainty of ±0.5 mag. Unfortunately, the seeing was unusually poor for the site, ~1″.6. While the brightness contours suggest that the object is slightly extended from NE to SW, this does not appear to be statistically significant compared with other objects in this field of similar magnitude. Observations at higher resolution are necessary to confirm our suggestion that IRAS 22574+6609 is a bipolar nebula.

4. DISCUSSION

4.1. *Circumstellar Chemistry*

The infrared spectra of these three *IRAS* sources are similar to one another. The *IRAS* LRS spectrum of 22574+6609 is shown in Figure 5. Although the quality of the spectrum is not very high, broad emission features at 8 and 21 μm are clearly evident. Also notable is the relatively flat continuum between 12 and 18 μm. The spectrum is in general agreement with the CFHT broad-band filter observations. These spectral properties are also observed in the LRS spectra of 04296+3429 and 23304+6147, which have previously been published and discussed in detail together with two other PPN candidates IRAS 07134+1005 and 22272+5435 (Kwok et al. 1989). IRAS 22574+6609 is therefore the fifth object found to have the unidentified 21 μm feature. IRAS 04296+3429 and 23304+6147 (and 22272+5435) display strong absorption features due to carbon molecules in their optical spectra (Hrivnak & Kwok 1990). This suggests that carbon may be involved in the formation of the 21 μm emission feature. Thus the optical and perhaps the infrared spectra of these *IRAS* sources suggest that they are carbon-rich.

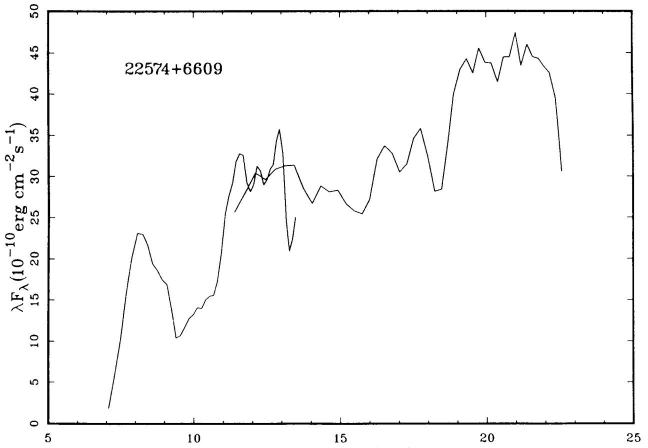

FIG. 5.—The LRS spectrum of 22574+6609. The spectrum has been smoothed over three channels.

By comparison, the LRS spectrum of AFGL 2688 is almost featureless and is usually attributed as due to graphite. There is a dip in the spectrum of AFGL 618 around 11 μm, which could be due to the SiC feature in self-absorption. Perhaps the difference between the LRS spectra of our three new sources and AFGL 618 and AFGL 2688 is due to the higher stellar temperatures or more advanced evolution of the latter two objects.

Since the circumstellar envelopes of PPN are likely to represent the remnants of the envelopes of their AGB progenitors, the presence or absence of OH and CO, HCN emissions can be used to infer the chemistry of these envelopes. Generally, oxygen-rich AGB stars have strong OH emissions whereas carbon stars have strong CO and HCN. CO emission has been detected from AFGL 618 and 2688 (Bachiller et al. 1988), from IRAS 04296+3429 and 23304+6147 (Woodsworth, Kwok, & Chan 1990), and from 22574+6609 by Likkel et al. (1990). AFGL 618 and AFGL 2688 have rich molecular emissions, particularly in carbon-chain molecules (HC_XN, Olofsson 1987; Bujarrabal et al. 1988). HCN has also been detected in IRAS 23304+6147 (A. Omont, private communication). IRAS 22574+6609 and 23304+6147 have both been observed for OH emission, but it has not been detected (Likkel 1989). In the infrared, none of the five objects discussed here has silicate dust features characteristic of oxygen-rich stars. It is therefore reasonable to conclude that all these objects are carbon-rich.

4.2. *Momentum and Radiative Fluxes in Proto–Planetary Nebulae*

In a number of papers, Knapp (Knapp & Morris 1985; Knapp 1986) has found that the momentum flux to luminosity ratios for PPN and planetary nebulae have values exceeding unity. This ratio is defined as

$$\beta = (\dot{M} V c / L) , \qquad (1)$$

where $\dot{M}$ is the mass-loss rate determined by CO observations, V is the terminal expansion velocity, c is the speed of light, and L is the radiative luminosity of the star. Bipolar nebulae represent some of the most extreme cases. Whereas late-type stars generally are found to have $\beta \sim 1$, AFGL 618 and AFGL 2688 both have $\beta \sim 7$ and the values are even higher for planetary nebulae (Knapp 1986). This change in β from AGB stars to PPN to planetary nebulae has been interpreted to imply an absolute decrease in luminosity during the evolutionary transition between these phases (Knapp 1987, 1989; Zuckerman 1989).

The data derived for these new bipolar nebulae candidates lead to similarly large values of β. We have calculated the total fluxes of these candidates, including a correction for interstellar extinction. Extinction values in these lines of sight were determined from the work of Neckel & Klare (1980) and Burstein & Heiles (1982). Values of A_v are 1.2, 3.2, and 2.5 mag for 04296+3429, 22574+6609, and 23304+6147, respectively. Combining these values with the average extinction law deter-

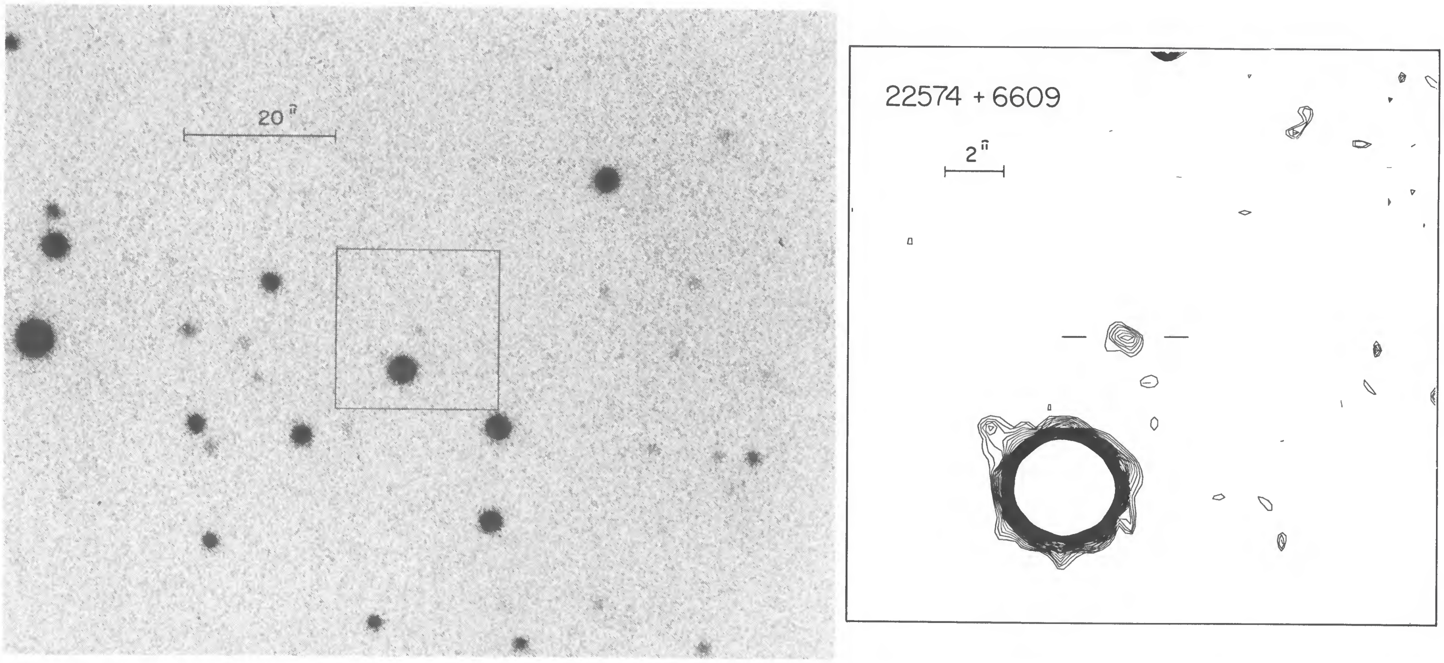

FIG. 4.—The *V* band CCD image of IRAS 22574+6609. East is left and north is up. The left panel shows the field, centered on the faint source. The box indicates the field for the expanded image displayed in the right panel, which shows brightness contours. The source is indicated with tick marks. Note that the highest brightness contours have been suppressed for the star SE of the source.

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TABLE 3

DERIVED PARAMETERS

Object	Observed Flux (ergs s^{-1} cm^{-2})	Distance (kpc)	$4\pi FD^2$ ($L_\odot$)	$\dot{M}$ ($M_\odot$ yr^{-1})	V (km s^{-1})	β
AFGL 618	2.2 (−7)	1.3[a]	1.2 (4)	7.7 (−5)[b]	21.5	7.1
AFGL 2688	4.8 (−7)	0.3[c]	1.4 (3)	1.4 (−5)[b]	19.7	10.1
04296+3429	7.8 (−9)	<3.[d]	<2.2 (3)	<2.3 (−5)[e]	15.6	8.1
22574+6609	4.7 (−9)	<5.[d]	<3.8 (3)	<3.9 (−5)[f]	16.0	8.1
23304+6147	1.1 (−8)	1.3[e]	5.8 (2)	7.4 (−6)[e]	15.5	9.8

[a] Westbrook et al. 1975.
[b] Knapp & Morris 1985.
[c] Mason 1987.
[d] No distance information available. Upper limit assumed based on the location in the Galaxy.
[e] Woodsworth et al. 1990.
[f] Likkel et al. 1990.

mined by Cardelli, Clayton, & Mathis (1989), we dereddened the observed magnitudes in the visible and near-infrared to determine the extinction-corrected fluxes listed in Table 3. Note that these fluxes are somewhat lower than those listed by Kwok et al. (1989) and Woodsworth et al. (1990) for the same objects, because in these papers larger values for extinction were assumed, with extinction treated as a free parameter in the spherically symmetric model used. The total luminosities were then calculated based upon the distances, assuming isotropic radiation. Also listed are mass-loss rates estimated from CO observations. The value of β is calculated for each case. The distance values, although listed in Table 3, were not used in the derivations of β, which is distance-independent. The greatest uncertainty is the mass-loss rate, which is probably accurate only to within a factor of 3. Since the mass-loss rates are obtained from two different authors, there may also be systematic differences which affect the comparison between these two groups of objects. Keeping in mind these uncertainties, the five PPN objects are all found to possess similarly large values of β.

We have considered the possibility that the large values of β could be the result of the bipolar nature of the objects since the emergent radiation is obviously not isotropic (Cohen & Kuhi 1977). The lack of bright optical counterparts for AFGL 618 and AFGL 2688 implies that they are edge-on systems (see § 3). If this is the case, then a large fraction of the total flux emitted by the star in the form of visible light will escape in directions outside the observing zone of the observer. One can therefore question whether the high values of β are due to the underestimates of the luminosity, especially for the nearly edge-on systems. Preliminary results from a radiative transfer model with a bipolar geometry suggest that as much as 50% of the flux can be missed for an edge-on system (K. Volk, private communication). Thus this effect, though significant, does not appear to be able to explain the large values of β found in these systems.

Another possibility for the anomalous values of β is that CO is excited more efficiently in a PPN environment. For example, the dust temperature in the outer parts of the circumstellar envelope where most CO emission arises is probably higher in PPN because the detached shell is directly heated by starlight. Through radiative pumping with 4.6 μm vibrational transition photons, the CO molecules in PPN may have higher excitation temperatures than their counterparts in an AGB star envelope. The higher effective temperatures of the central stars of PPN may also have an effect on the radiative pumping process. If the excitation temperature of CO is indeed higher in PPN, then the mass-loss rates are probably overestimated when the formula of Knapp & Morris (1985) is used.

In summary, both the bipolar and proto-planetary nature of the objects could contribute to the large values of β, in addition to any possible change to the luminosity. Further detailed line and continuum transfer calculations are needed to quantify these suggestions.

5. CONCLUSIONS

We find that three recently discovered PPN candidates, each possessing 21 μm emission, have similar energy distributions in the mid- and far-infrared but differ greatly in the brightness of their optical counterparts. This difference can be easily explained by assuming that these objects all have bipolar symmetry, with the visual brightness depending upon the orientation of the system with respect to Earth. An edge-on system will have a faint optical counterpart, or, more likely, will display optical bipolar lobes, whereas a more face-on system will be stellar in appearance with a bright central star.

A bipolar morphology also implies that the amount of flux observable is a function of the orientation angle. When viewing an edge-on system, it is easy to underestimate the amount of total flux emitted by the object because a significant amount of visible photons may be emitted along the polar directions. A failure to take this into account could lead to an erroneously low estimate of the luminosity of the object. Given this uncertainty, we find that the five PPN discussed here, irrespective of orientation, all have similar momentum flux to luminosity ratios which are higher than the equivalent values in AGB stars. More detailed theoretical modeling of bipolar nebulae is needed to understand this discrepancy.

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