PART 2. AN INFRARED STUDY OF PLANETARY NEBULAE

2.1 Introduction

Planetary nebulae (PN) are circumstellar clouds of gas and dust formed through the ejection of the stars' outer envelopes during their asymptotic giant branch (AGB) and post-AGB stages of evolution. The clouds are often in the form of a shell exhibiting some symmetry that expands outward from the central star. Multiple shells, filaments, and bright knots of ionized gas emission are common structures in these nebulae.

PN are an especially interesting and important class of objects for a number of reasons. First, the PN stage is the transition of stars from the AGB to white dwarfs. The nebulae are the ejected outer envelopes of these stars, so a knowledge of the properties of mass loss rates and time scales for ejection, and the composition of the ejected material will help in understanding this evolutionary process. As the nebula expands, it will encounter any material previously ejected by the star in earlier stages of evolution at lower velocities. Both the ejection process and the expansion into previously ejected material will affect the morphology of the nebula. Therefore, a study of PN morphology will provide information on both processes. Also, emission from dust grains and large molecules has been observed in many PN. In some PN the conditions of grain formation such as composition, radiation from the central star, density of the nebula, etc. can be determined from observation, thereby shedding light on the processes of grain and large molecule formation, evolution, and destruction. Finally, PN are an important factor in the return of gas and dust to the interstellar medium (ISM). The total mass which they return to the Galaxy is about 0.5 $M_{\odot}$/yr (Knapp, Rauch, and Wilcots 1990).

It is difficult to discuss the general properties of PN since this class contains a wide assortment of objects of varied morphology, composition, and stage of development. In listing typical parameters, one would also wish to distinguish from objects that are observationally similar, but are not members of the class of PN because they don’t represent this phase of stellar evolution. Kohoutek (1989) gives several "typical" properties of PN and their central stars. PNs usually display some symmetry in their emission structure: bipolar, circularly or elliptically symmetric disk or ring, with a sharp outer boundary. There are often multiple shells or haloes. The observed morphology is highly dependent on the angle of inclination of the nebulae and the wavelength of observation. Typical diameters range from 0.1 to 0.2 pc. Electron density is usually in the range 10^3 to 10^4 cm^{-3}, and electron temperatures from 9000K to 15000K. The total mass of the nebula is typically 0.1 to 0.2 $M_{\odot}$. Expansion velocities are often non-isotropic and approximately 25 km/sec. PN spectra show mostly recombination lines of H and He, and collisionally excited lines of C, N, O, Ne, Mg, Si, S, Cl, and Ar. Continuum emission is observed from free-bound, free-free , and two-photon processes. In the infrared, there is thermal emission from dust, along with emission features from silicon carbide (SiC) and other large molecules and grains, as well as unidentified infrared (UIR) emission lines. The central stars have the following typical properties: surface temperatures ranging from 25000K to 200000K, luminosity of approximately $5 \cdot 10^3$ $L_\odot$, radii of from 0.005 to 1.5 $R_\odot$, and progenitor masses of 0.8 to 6-8 $M_\odot$. Mass loss rates from the central stars are from approximately 10^{-10} to 10^{-7} $M_\odot$/yr, although much higher rates of ~10^{-4} $M_\odot$/yr may occur during the hypothetical "superwind" phase which creates the nebular shell (Schönberner 1987). Typical central star spectral types are WR, Of, OVI, cont. O, sdO, and peculiar. The central stars can be separated into two groups based on whether the atmospheres are H-rich or H-poor.

2.1.1 Planetary Nebulae Formation, Structure

There are two levels of models necessary to understand PN. The first is a model of the actual three-dimensional structure of the nebula to explain the observed morphology. A model is necessary since only the two-dimensional "projection" of the emission from the usually optically thin nebula can be observed, at some unknown inclination angle. Details of the nebular structure (including local density and temperature variations), obscuring gas and dust, and interaction with the ISM all combine to make this a non-trivial problem. The second level are models which seek to explain the process of nebula formation and evolution: mechanisms for stellar mass loss, formation and shaping of the nebular shells by stellar winds, and the formation and evolution of dust and large molecules in the stellar atmosphere and the nebula. The two levels of models are closely linked, of course, since the morphology of the nebula is dependent on the mechanism of its formation.

Determining the actual three-dimensional structure of PN is not straightforward since it involves solving for the density, temperature, and velocity structure simultaneously. Also, one single model of PN structure cannot explain all of the observed nebular morphologies. However, many nebulae are similar in observed morphology and can be grouped into various classes. Balick (1987) has presented CCD images of 51 PN and organized them into three general groups: round, elliptical, and butterfly, shown in Figure 2.1. There are also three levels in each class: early, middle, and late, which suggest an evolutionary sequence within a class. An additional group of irregular and peculiar PN contain the examples that don’t fit into the first three classes. Some of these nebulae, such as NGC 7027, may appear to be irregular at some optical wavelengths because of heavy obscuration near the source, but in IR or radio images can be seen to be a member of one of the three classes (elliptical for NGC 7027). Other nebulae, such as NGC 6543, show multiple shell structure when observed in some fine structure lines, but are single-shelled in others.

The second level of PN models must explain the formation processes that produce the observed nebular properties and morphologies. One group of models that describe PN formation and evolution are interacting winds models (Lazareff 1981, Kahn 1983, Volk and Kwok 1985). The shapes and dynamical evolution of the nebulae are explained by the interaction between stellar winds emitted by the central star during its late stages of evolution. These models explain the formation of PN as resulting from a slow and fast wind stage. First, a red giant star nearing the end of the AGB sheds its envelope in a slow wind phase, with a mass loss rate of 10^{-5} to 10^{-4} $M_\odot$/yr, and a velocity of ~10 km/sec. This process continues for approximately 10^4 yr, as the star evolves to a small radius, high effective temperature star. At this stage, the star generates a lower density fast wind, with mass loss rates of $10^{-8.5}$ to $10^{-6.5}$ $M_\odot$/yr and velocities of $1\text{-}2{\cdot}10^3$ km/sec. The fast wind encounters the material previously ejected in the slow wind, forming an inward-facing shock front on the inner edge. The gas at the shock is heated to approximately 10^5 to 10^7 K, and the pressure of the hot gas pushes the material into an expanding shell, forming the nebular structure.

A model with isotropic winds would be sufficient to explain only the simplest PN structures, such as round, highly-symmetrical nebulae such as BD+30°3639 or IC 418. In fact, most PN show more complex structure. Zuckerman and Aller (1986) studied the shapes of 139 PN and found that, in the spatially resolved PN, 50% showed bipolar symmetry, and 30% were elliptical. Many PN also exhibit filamentary radial structures, knots of emission, and multiple shells. Clearly this cannot be easily accounted for by an isotropic wind expanding into free space.

There are several ways in which nonspherical nebulae could be produced. One possibility is anisotropies in the stellar wind from the central star. If the slow wind deposits much more material in the equatorial regions compared to the polar direction, or if the wind velocity is direction dependent, elliptical or bipolar structures can be created. When the fast wind begins to sweep the material into a shell, the density structure of the previously emitted envelope can determine the resulting nebular shape. Expansion will progress faster in the lower density polar regions, depending on the actual density gradient. A slight gradient will produce elliptical nebulae, whereas extreme gradients will produce bipolar nebulae, with very little expansion in the equatorial region.

Several mechanisms have been proposed to generate anisotropic winds. They can be separated into two groups: models that describe mechanisms for a single central star, and models that assume that the star is a close binary. For a single star, stellar rotation is one possible way in which an asymmetric wind can be produced. This mechanism is usually dismissed since, by the time a star expands to its AGB size where most of the mass loss is expected, the surface velocity is such a small fraction of the escape velocity that it cannot have a large effect on the mass loss rate (Soker and Livio 1989). However, D’Antona, Mazzitelli, and Sabbadin (1987) have suggested that there is a transfer of rotational momentum from the envelope to the core, which results in an enhancement of the equatorial magnetic field, causing more equatorial mass loss. This process would be more efficient for high mass stars.

A second group of models assumes that the central star is a close binary, and anisotropic mass loss occurs from the interaction between the two stars (Livio *et al.* 1979, Morris 1981). When the primary in the system evolves to the red giant stage, it fills its Roche lobe and begins losing mass through the first Lagrangian point L_1 to the second star. The envelope of the second star expands and begins to lose mass through the second Lagrangian point L_2, which leaves the binary system and forms the PN. One problem with this model is that only a few central stars of PN have been determined to be close binaries of the type necessary on this model. These identifications are difficult to make because the central star is often obscured by the nebula itself. Another difficulty was brought up by Zuckerman and Aller (1986), who showed that in a sample of 139 PN, there were too many exhibiting bipolar symmetry to be explained by the binary ejection mechanism alone.

The number of contrasting models is an indication of the uncertainty of how PN actually form. At present, only a few central stars have been confirmed to be close binaries of the type described in the models above. Also, the late stages of stellar evolution are as yet not well modelled, especially in the case of PN where significant mass loss occurs, either by a single star, or by a close pair. A better understanding of these processes will lead to a clearer picture of PN formation.

2.1.2 Infrared Emission from Planetary Nebulae

In some of the first infrared observations of PN, it was found that some nebulae have an "excess" of emission in the infrared over that which one would expect from recombination in the nebula and continuum flux from the central star (e.g., Gillett, Low, and Stein 1967, Woolf 1969, Willner, Becklin, and Visvanathan 1972). This excess was subsequently attributed to emission by dust, heated by Lyman α, other ultraviolet and visible line radiation, and Lyman continuum flux from the central star.

Measurements of the integrated flux from PN have shown that the IR spectrum typically peaks near 35 µm (Moseley, 1980). The characteristic dust temperatures are near 100K. However, the spectrum is usually not fit well by this single temperature blackbody at shorter wavelengths, having a spectral shape that indicates the presence of warm and hot dust components. There are also several recombination and fine-structure lines which can make significant contributions to the total flux in the near- and mid-IR.

In the near-IR, there are several components which contribute to the total flux. There is nebular emission from recombination and collisionally excited lines, and hydrogen bound-free continuum. In some nebulae, there is continuum emission from hot dust. Also, there is usually a significant emission component from the PN central star. In the mid-IR, possible components are a warm (≈200K) dust continuum, and emission lines due to [NeVI] (7.9 µm), [ArIII] (9.5 µm), [SIV] (10.8 µm), [NeII] (12.8 µm), [NeV] (14.5 µm), and [NeIII] (15.5 µm), and possibly others. In some PN, there is a feature attributed to SiC grains near 11.3 µm, and in others, a silicate feature near 9.7 µm.

In addition to these sources of continuum and line emission, it was soon discovered that there were several broad emission lines at 3.3, 7.7, 8.6, and 11.3 µm (Gillett, Forrest, and Merrill 1973). Also associated with these lines is a broad emission "plateau" that extends from approximately 11.5 to 13 µm. These spectral features have been referred to as "unidentified infrared" (UIR) features, and have since been detected in many other PN, as well as other galactic and extragalactic sources (see reviews by Willner 1982, Puget and Leger 1989). The UIR features have been shown to correlate with each other, and with the nebular carbon to oxygen (C/O) ratio (Cohen *et al.* 1986). This correlation with the carbon abundance suggests that the features originate from carbon grains or molecules. Several possibilities have been studied, including polycyclic aromatic hydrocarbons (PAHs) (Leger and Puget 1984), quenched carbonaceous composites (QCCs) (Sakata *et al.* 1987), or hydrogenated amorphous hydrocarbons (HACs) (Duley 1985).

For PN that are less carbon rich (C/O≈1) the UIR features are relatively weaker and often a broad plateau of emission is seen from 10.5 to 12.5 µm, attributed to silicon carbide (SiC) (Willner *et al.* 1989, Barlow 1983). In oxygen-rich PN (C/O<1), emission from silicates are seen with little or no SiC or UIR emission. When the PN is oxygen-rich, all the carbon is locked up in CO, allowing only oxygen-rich grains to form, such as silicates. For PN with C/O unity or greater, the oxygen is then depleted by the formation of CO, allowing only grains containing carbon such as SiC, graphite, and the grains responsible for the UIR emission to form.

Many of the models of dust formation and fragmentation make specific predictions for the spatial distribution of the dust that can be readily evaluated by high-resolution IR observations. For example, if the emission at the various UIR wavelengths is caused by the same molecules or grains, then the spatial distribution of the emission should be the same. Also, if the carbon grains have an inhomogeneous spatial distribution, or are progressively destroyed in the PN as it ages as suggested by Natta and Panagia (1981), then studies of the spatial distribution of the dust emission will provide information about these grains. In addition, the infrared emission may be a good tracer of warm material external to the PN responsible for its shape, which may be in the form of circumstellar disks or clouds.

2.1.3 The Planetary Nebulae in This Study

The purpose of this study is to examine the spatial distribution of IR emission in various types of PN in order to gain a better understanding of the structure and evolution of these objects. This dissertation includes representative examples of several different types of nebulae, to provide an overview of the characteristics of PN as viewed in the IR. The specific goals of this study are to determine the spatial distribution of emission from dust, UIR features, SiC emission near 11 μm, and forbidden line emission. Using the images of the nebulae at different wavelengths, the temperature structure of the dust can also be determined, and the emission features can be separated from the continuum emission. The spatial distribution of the emission can also be compared to the distribution in the radio continuum and emission lines in the optical, providing information on the structure of the PN. The IR structure may help explain the formation and shaping of the PN by stellar winds.

The PN were selected for this study based on a number of criteria. A few practical criteria limited the scope of the PNs to be studied. First, the nebulae had to have a small enough angular size on the sky (<30") yet large enough to be clearly resolved with the IR cameras used (>2-3"). The nebulae also were chosen to be relatively bright in the IR so that images in several bands could be obtained in a short time so that several objects could be studied. Most of these PN have been studied before in the IR and at optical and radio wavelengths, so this information could be used to help interpret the new data.

The seven PN in this study can be divided into four groups, according to their IR characteristics. Three of the groups contain PN with different sets of IR emission features. The first group contains the IR-bright PN BD+30°3639 and J 900. The members of this group typically have a high C/O ratio (>>1) and exhibit excess IR emission at near-, mid-, and far-IR wavelengths. UIR feature emission is seen at most or all of the UIR wavelengths. There is usually a strong mid-IR continuum emission from these PN. These nebulae are in the same class as NGC 7027. The second group, which contains IC 418, has a different IR signature. These objects, which have a C / O ratio typically ~1, show weak or no UIR feature emission and a weaker mid-IR continuum. An emission feature attributed to SiC is seen in these nebulae near 11 µm. The PN NGC 6572 is also in this group. The third group contains the PN NGC 2392 and NGC 6543. These nebulae have C / O ratios usually <1 and except for the far-IR show little or no "excess" IR emission that can be attributed to dust. There is no evidence of UIR or dust continuum emission in the mid-IR, and little or no emission in the near-IR in excess of the central star and recombination emission from the nebula. The fourth group in this study is separated by morphology and presumably, by evolutionary sequence. The objects in this group, M 2-9 and AFGL 2688, are bipolar nebulae (BPN) and are usually considered to be proto-planetary nebulae (PPN) or PN in their early stages of formation.

Table 2.1 summarizes some of the observational characteristics of these nebulae, collected from the literature. The PNs NGC 7027 and NGC 6572 are also included for comparison. Some parameters (e.g. the distance) are not well determined, with the values in the literature varying for a particular nebula by as much as a factor of 2 or more. The values given here have not been evaluated for their quality, but whenever possible the values are from the same source, for consistency.

Table 2.1 General Characteristics of the Planetary Nebulae In This Study

Parameter	BD+30° 3639	J 900	NGC 7027	IC 418	NGC 6572	NGC 6543	NGC 2392	AFGL 2688	M2-9
Distance (kpc)	0.6 {3}	3 {2}	1.1 {4}	0.42 {6}	0.42 {3}	0.53 {4}	0.94 {7}	1.0 {14}	0.9 {20}
V (km/sec)	26 {6}	18 {6}	18 {6}	12 {6}	16 {6}	20 {6}	54 {6}	100 {23}	7 {24}
T(e⁻) (10^4K)	0.80 {6}	1.15 {6}	1.4 {6}	0.85 {6}	1.05 {6}	0.83 {6}	1.3 {6}	...	...
Central star type	WC9 {6}	...	...	Of {6}	Of+WR {6}	O7+WR {6}	O7f {6}	F5 Ia {16}	B1 {19}
Morphology class	E	E	E	E	DL	P	E	BP	BP
Central star temp. (10^3K)	27 {18}	...	310 {9}	32 {18}	60 {18}	45 {18}	...	6	44 {18}
Dust Temp(°K)	175 {6}	...	90 {25}	190 {6}	180 {6}	125 {6}	95 {6}	200 {17}	140 {21}
C/O ratio	1.6 {10}	4.0 {13}	3.1 {14}	1.3 {11}	1.1 {12}	2.2 {12}	0.58 {12}	...	...
Mass Loss rate (10^{-6} $M_\odot$/year)	20 {1}	30 {1}	81 {1}	6.6 {1}	6.7 {1}	13 {1}	...	3 {23}	33 {22}
LNP IRE	5.46	1.39	...	1.9	1.98	2.37	1.16	...	68.5
LNP Dust Temp (°K)	109	104	...	130	125	92	75	...	98
LNP Distance (kpc)	.73	1.82	...	.41	.47	.64	1.22	...	2.37

References:

1. Taylor, Pottasch, and Zhang 1987
2. Gathier, Pottasch, and Pel 1986
3. Pottasch 1983
4. Acker 1978
5. Zuckerman and Aller 1986
6. Pottasch 1984
7. Natta and Panagia 1981
8. Morris 1981
9. Walton *et. al* 1989
10. Pwa, Pottasch, and Mo 1986
11. Torres-Peimbert and Pena 1981
12. Flower and Penn 1981
13. Aller and Czyzak 1983
14. Knapp *et al.* 1982
15. Ney *et al.* 1975
16. Crampton *et al.* 1975
17. Forrest *et al.* 1975
18. Kaler and Jacoby 1991
19. Calvet and Cohen 1978
20. Kohoutek and Surdej 1980
21. Kwok, Hrivnak, and Milone 1986
22. Kwok *et al.* 1985
23. Kawabe *et al.* 1987
24. Bachiller, Martin-Pintado, and Bujarrabal 1990
25. Moseley 1980

Explanations to Table 2.1:
The first column (Parameters) lists the particular nebular characteristic. The other columns give the value of the parameter for each nebula. There are two rows for each parameter. The top number gives the value of the parameter, and the number below it in brackets gives the reference for that value, referring to the list given above. The following are parameter abbreviations used in the table: V - expansion velocity, relative to rest frame of PN, LNP - Lenzuni, Natta, and Panagia 1989, IRE - Infrared Excess, defined as the ratio of the IR luminosity to the Ly α luminosity. The morphological classes given are as follows: E = Elliptical, BP = Bipolar, P = Pecular, DL = Double lobed. Note that members of the E class may also have two lobes of emission superimposed on the overal elliptical shape.

2.1.4 Observing Procedures and Data Reduction

The observations presented here were carried out on Steward Observatory telescopes by a number of observers including myself. Also participating in the near-IR observations were William Hoffmann and Giovanni Fazio. In the mid-IR observations with the MIRAC, the other observers were William Hoffmann, Giovanni Fazio, Lynne Deutsch, and Jeff Regester.

2.1.4.1 Near-IR Observations

In the following sections, near-IR images of the following nebulae are presented: IC 418 at J, H, and K; BD+30°3639 at K; NGC 2392, NGC 6543, and J 900 at H and K, and AFGL 2688 at J, H, K, and Br γ. All of these observations were obtained with the 64x64 Hg:Cd:Te array camera (Rieke, Rieke, and Montgomery 1987) on the Steward Observatory 2.3 m telescope at Kitt Peak. The general observing procedure was to take a short (5 to 40 sec.) exposure on the source, followed by an exposure at a telescope offset of 60" off the source of the same duration. The two images were then differenced to remove signal from the sky. A number of these image pairs were taken at each wavelength for the object being observed.

The following sequence was followed for each PN observed. First, images were taken of the standard star used for the flux calibration. These exposure times were relatively short (2 to 10 sec.) to avoid saturation, since the calibration stars are fairly bright. Next, images were obtained of an SAO catalog star near the PN (about half the number to be taken on the PN). The purpose of these observations was to obtain a measurement of the point spread function (PSF) of the array at the time of the PN observations. The SAO star would be typically a few arcmin from the PN, so this would provide a good measurement of the PSF for that time and part of the sky. Next, images of the PN were taken. Typically 32-64 images were obtained at each filter, at 20-60 seconds per image, depending on the magnitude. For all of the PN presented here, the sizes of the nebulae were smaller than the field-of-view of the array, so each on-source frame contained an image of the entire nebula. After these images were taken, more images (about half the number taken on the PN) were taken of the SAO catalog star nearby. Finally, more images of the flux standard star at the same wavelength were obtained.

The data were reduced in the following way: first, "bad" pixels were removed from all the images by linearly interpolating between neighboring "good" pixels. The bad pixels were identified by their large digital values compared to the average value of the remainder of the image, or by showing no response to different flux levels. The number of bad pixels was typically 5-10 in the 64x64 pixel image, and were isolated in separate parts of the array. A gain matrix was calculated for each filter used, for each PN. The gain matrix was calculated by taking the reciprocal of the average of all the off-source images taken in the PN observations, normalized to the average value. Then for all the on- and off-source pairs, the off-source image was subtracted from the on-source image, and the difference multiplied by the gain matrix. The result is an image where the instrumental inhomogeneities and background have been removed, leaving the source on a flat background. This process is frequently called a "flat field correction". In this description, I refer to the off-source image of blank sky as a "flat field". The matrix that corrects for the pixel-to-pixel gain variations in the flat field-subtracted images is referred to as the gain matrix.

The images were then reformatted by expanding each instrumental pixel to 4x4 subpixels, to allow for shifting the images by 1/4 pixel increments when aligning and averaging the images. The offsets between the images were determined by a two-dimensional cross correlation algorithm (Barnea and Silverman 1972, Tresch-Fienberg 1985). The images were registered to the nearest 1/4 pixel and averaged together to obtain the final image. Since there are small offsets between images, the extreme edges of the final image have slightly less integration time than the center of the image where the PN is located, but all points on the nebula have the same amount of on-source integration time. The images of the standard stars were then evaluated with the IRAF routines in DAOPHOT to determine the calibration factors to use with the PN images. Fluxes for the near-IR standards observed were taken from Elias *et al.* (1982).

2.1.4.2 Mid-IR Observations

In the following sections, mid-IR images of the following PN are presented: IC 418 at 11.7 µm; BD+30°3639 at 10.0, 11.2, 12.4, 12.8, and 13.2 µm; and M 2-9 at 8.8 and 9.8 µm. These images were obtained with MIRAC. The wavelengths were chosen to sample the warm dust continuum and the [NeII], UIR features, and SiC emission in these nebulae. The procedures used to obtain images are different because of the large telescope and sky background contributions, and noise in the sky background. Gain matrices were calculated from blank sky images taken at 1 and 2 airmass, in the "Grab" mode where a single image is taken with tracking off and no telescope modulation. The average image at 1 airmass is subtracted from the average image at 2 airmass to obtain the signal. The reciprocal of each pixel is taken and the image normalized so that the average value is 1. This procedure is done for each filter or CVF position used during the night of observing. This gain matrix compensates for all pixel-to-pixel gain variations in the array itself, along with sensitivity variations across the field dependent on the telescope.

When observing the sources, a combination of chopping the secondary and "wobbling" or "nodding" the telescope was used. The source is placed in the first chop beam and a short (5-20 sec on-source) pair of integrations are taken. The chopper throw was typically 20-30", usually toward the north, at a frequency of 5-10 Hz. Then the telescope is pointed at the second nod beam position completely off the source, and another chop pair is taken. These four images are combined into a single "observation" by taking the difference between the image in each chop pair, and then the second chop difference is subtracted from the first. The result is then multiplied by the gain matrix. This produces an image for which the sky and telescope background have been removed and the instrumental response of the camera have been corrected. At this point, the data reduction process proceeds in the same manner as the near-IR reduction described above, where the images are registered to the nearest 1/4 pixel and combined to produce the final picture.

2.1.5 Presentation of the Planetary Nebulae Observations

In the following sections, the observational results and analysis are presented. All the images presented are oriented with N at the top and E at the left, unless otherwise noted. The axes around the image show arsec Right Ascension along the bottom of the image, and arcsec Declination along the left edge. The contours are labeled with letters that are described in the caption for each figure.

Each of the following sections describes the results for a single object. The first part of each section briefly describes the general characteristics of the nebula, including its morphology, optical or radio images, continuum and line emission, or other relevant data. A short summary of the IR characteristics of the nebula is also given, describing the near- and mid-IR photometry and previous imaging studies. A brief description of the observations is given, providing details about the data taking that were not covered in the above summary of observing methods, and information such as the date, direction of chopping and nodding the telescope, and integration time. The calibrated images are then presented, along with an analysis of the data. At the end of each section is a conclusion which summarizes the most important results discussed in that section.

Following the sections that cover the individual objects there is a section that compares the nebulae as members of three different groups. The groups are defined by their near- and mid-IR emission characteristics and their optical and IR morphology. The nebulae are also compared to other PN which have been observed in the infrared. The implications of these observations concerning the various models of dust formation and UIR emission are also discussed.

2.2 BD+30°3639

The PN BD+30°3639 is an optically bright, round, highly symmetric low-excitation nebula (see Figure 2.2). The nebula is usually considered young, because of its high surface brightness, symmetric shape, and small inferred intrinsic size. The distance to BD+30°3639, however, is very uncertain, with estimates ranging from 0.5 to 2.8 kpc (Pottasch 1983, Taylor *et al.* 1987, Martin 1987, Masson 1989). Radio continuum images (Basart and Daub 1987, Masson 1989) have shown that the structure is double-lobed, with peaks at the north and south positions of a nebular ring.

The infrared emission from BD+30°3639 has been studied extensively. Early observations showed the nebula to have excess IR emission (Woolf 1969, Gillett and Stein 1969). Russell, Soifer, and Merrill (1977) observed the UIR features around 3.3 µm in their near-IR spectrum. Moseley (1980) observed far-IR continuum emission, along with a strong feature near 30 µm. Aitken and Roche (1982) obtained an 8-13 µm spectrum showing UIR and [NeII] emission features, which were confirmed in the IRAS measurements of BD+30°3639 (Pottasch *et al.*, 1986). Results of near-IR imaging of BD+30°3639 by Roche (1989) and Smith *et al.* (1989) are reported, and mid-IR imaging studies of BD+30°3639 have been carried out by Bentley *et al.* (1984), Hora *et al.* (1990) and Ball *et al.* (1991).

2.2.1 Observations: BD+30°3639

The planetary nebula BD+30°3639 was observed in the K band on December 14, 1989 at the 2.3 m telescope on Kitt Peak, with the Steward Observatory 64x64 Hg:Cd:Te array camera. Images were not obtained at other NIR wavelengths on this run due to poor weather. The images were taken as alternating on- and off-source 25 sec integrations. Off-source frames were obtained by nodding the telescope 1 arcmin to the north. Small (0.5 to 2") offsets were introduced before each on-source frame. The final image at each wavelength was constructed from 16 of these individual images. The IR standard star HD 203856 was used for flux calibration. The PSF standard was a field star in the same frames as BD+30°3639.

The PN BD+30°3639 was also observed on June 2-3, 1991 using MIRAC at the Steward Observatory 2.3 m telescope on Kitt Peak. Images were obtained at 10.0, 11.2, 12.4, 12.8, and 13.2 µm using the CVF. Ten columns were read out during these observations, and the telescope was rastered across the source. The images presented here are a mosaic of the 35-40 individual 10 second nod sets taken at each wavelength.

Images at each of the six wavelengths are shown in Figure 2.3. Table 2.2 gives the measured fluxes of BD+30°3639 at each of the six wavelengths. The total time listed is on-source time in seconds. In the case of the 2.2 µm image, the flux of the central star has been given, and the nebular flux is the total flux measured from the system minus the central star contribution (the image at 2.2 µm with the central star subtracted is presented below). The resolution given is the measured FWHM of the profile of the standard star used for the flux calibration at that wavelength.

Table 2.2 Observations of BD+30°3639

Wavelength (µm)	Total Time(sec)	Nebula Flux(Jy)	Stellar Flux(Jy)	Resolution (arcsec)
2.2	400	.448	.084	1.3
10.0	540	51.0	...	1.5
11.2	400	96	...	1.5
12.4	220	89	...	1.7
12.8	240	138	...	1.7
13.2	420	88	...	1.6

2.2.2 Discussion: BD+30°3639

2.2.2.1 BD+30°3639 2.2 µm Image

The image of BD+30°3639 at 2.2 µm contains contributions from recombination emission, continuum emission from hot dust, and emission from the central star. Since the properties of the nebular emission are being studied, it is useful to remove the emission from the central star. The raw images of BD+30°3639 contained another star in the field, which made alignment of the individual images very accurate, and as a result, also provided a good measure of the instrumental PSF. This reference star was scaled and subtracted from the raw image, and the result is shown in Figure 2.4. Source profiles of both the original and central star-subtracted images are shown in Figure 2.5. The E-W profile is slightly irregular in the central part of the nebula due to a slight mismatch of the profiles, but overall the central star is well subtracted to reveal the nebular structure.

The image of BD+30°3639 in Figure 2.4 shows the nebular emission to be in a ring shape, with two bright lobes, in the northern and southern portions of the ring. The northern lobe is slightly brighter than the southern one. This is very similar to the spatial distribution of emission seen in radio continuum images of this nebula (Basart and Daub 1987, Masson 1989). The 4.885 GHz image of BD+30°3639 from Masson (1989) is reproduced here in Figure 2.6 for comparison. The images match very closely, with the only significant difference being an extension of the northern lobe to the east in the mid-IR images (e.g., at 11.2 μm shown in Figure 2.3c), suggesting another concentration of emission in the northeast portion of the ring. As seen in the distribution of the mid-IR flux described below, there is also an enhancement of the emission in this location in several of the images, which also points to an origin in dust emission.

2.2.2.2 BD+30°3639 Mid-IR Images

Mid-infrared images of the PN BD+30°3639 have been published previously, by Bentley *et al.*(1984), who scanned a single element detector across the nebula at several wavelengths, by Hora *et al.* (1990) using the AMCID camera, and most recently by Ball *et al.* (1991). Our previous observations using the AMCID camera (Hora *et al.* 1990) were carried out on the IRTF, with a pixel scale of 0!78 / pixel, compared to 0!66 / pixel on the 2.3 m with the MIRAC. The diffraction-limited image size on the IRTF is approximately 1" at 10 µm, and the effects of atmospheric seeing and image alignment errors can be expected to slightly increase the point source image size. However, due to charge-spreading effects that were characteristic of the AMCID array, the actual FWHM of a point source image was spread anisotropically to approximately 1!5 in R.A. and 2!7 in Dec. The AMCID images were deconvolved using maximum entropy, which removed some but not all of the effects of this non-circular PSF. In addition, the AMCID observations used broad band filters (approximately 10-15% bandwidth) which were not centered on the UIR features or placed at continuum wavelengths. The present observations were chosen to sample the UIR feature at 11.3 µm, the [NeII] line at 12.8 µm, and continuum wavelengths around these features.

One issue addressed in previous studies has been the spatial distribution of the spectral features in the nebula, relative to the continuum emission. This is important to models of the dust formation and destruction. Some possible carriers of the UIR emission may be destroyed within the ionized zone. Bentley *et al.* and Hora *et al.* find that the UIR emission was slightly more extended than the continuum emission, although by a small amount. Ball *et al.*, however, report finding no difference in the spatial extent of the UIR or [NeII] feature emission compared to the continuum image.

To address this issue, the spatial distribution of the emission has been compared in several ways. First, the source profiles of the images, both in R.A. and Dec, are compared. These are shown in Figure 2.7. The profiles have been normalized so that the peak value is 1, and shifted so that the eastern peaks are aligned. In general, the profiles are very similar in size and shape between wavelengths. The eastern lobe in the E-W profiles, and the northern lobe in the N-S profiles are the brighter lobes. There is a central minimum in each of the profiles, with some differences in the detailed location and structure between the main lobes. However, several significant differences exist in the spatial extent of the nebula at the wavelengths observed. For example, in both R. A. and Dec., the 11.2 µm profile has the greater extent than the profiles in the continuum wavelengths of 10.0 and 13.2 µm. The difference is small, but the 11.2 µm image is consistently among the largest size for each set of profiles, both in width of the profile, and the separation between peaks. The image at 11.2 µm also had one of the smallest resolutions reported (see table above) so the larger size is probably not related to an instrumental effect. Table 2.3 summarizes the profile sizes from the data in Figure 2.7.

Table 2.3 Sizes of BD+30°3639

	E-W FWHM	S-N FWHM	Distance between peaks	
Wavelength	size	size	(E-W)	(S-N)
(µm)	(arcsec)			
2.2	5.6	5.2	3.6	3.4
10.0	5.7	5.1	3.5	2.6
11.2	6.2	5.4	3.8	3.0
12.4	6.2	4.7	3.6	2.8
12.8	6.1	5.0	3.8	2.8
13.2	5.9	5.0	3.3	2.8
UIR[1]	6.5	5.6	3.6	3.8
[NeII][2]	6.8	5.2	4.0	3.3

[1] Calculated from the 11.2 µm image minus a scaled 10.0 µm image
[2] Calculated from the 12.8 µm image minus a scaled 13.2 µm image

These results compare well with the conclusion of Bentley *et al.*(1984) and Hora *et al.* (1990) that found the emission at UIR wavelengths to be spatially more extended than at continuum wavelengths. A new result is the observations at 12.8 µm which shows a larger extent in the E-W profiles, but a S-N profile that is very similar to the continuum wavelengths. The similarity between the 13.2 µm and the 10.0 µm image profiles confirms that the distribution of the continuum emission is accurately measured.

2.2.2.3 BD+30°3639 Temperature, Optical Depth Images

By assuming that the IR radiation at 10.0 and 13.2 µm is thermal emission from dust grains, a temperature image for the nebula can be calculated. This calculation was performed in 4x4 sub-pixel bins (each bin equal in area to 1 detector pixel) for those regions where the S/N was greater than 10 in both images. Expressing the intensity of emitted radiation by a modified Planck law $Q_\lambda B_\lambda(T)$ per unit wavelength, where $Q_\lambda \propto \lambda^{-n}$ is the wavelength-dependent emissivity of the grains, the temperature T, can be calculated from solving the following equation for T:

$$\frac{I_{13.2\mu m}}{I_{10.0\mu m}} = \frac{Q_{13.2\mu m}\ B_{13.2\mu m}(T)}{Q_{10.0\mu m}\ B_{10.0\mu m}(T)} \tag{7}$$

For this calculation, the emissivity exponent n was taken to be 2, consistent with graphitic grains (Dwek *et. al* 1980). The result of this calculation for is shown in Figure 2.8. The points of highest temperature are on the ring of emission, with a central minimum, similar to the intensity images. However, the minimum temperature is not at the position of the central dip of the intensity map, but is located at the position of the southern lobe. The temperatures in the region calculated range from approximately 160K to 190K, and the average temperature over the region is 172K ± 10K. This is in excellent agreement with the value calculated based on mid-IR spectral data from the nebula obtained previously (Pottasch *et al.* 1986). It is also interesting to note that the highest temperature region is in the eastern lobe of the nebula, although there is another peak at the position of the northern lobe. The eastern lobe is where additional UIR emission is observed.

From the observed intensity and calculated temperature images, the opacity distribution of the dust can be determined. Assuming that the radiation from the nebula at a particular frequency I_ν is from dust grains at a temperature T emitting a blackbody spectrum $B_\nu(T)$, and that the temperature T accurately represents these grains, the following transfer equation can be solved:

$$I_\nu = \left(1 - e^{-\tau_\nu^{warm}}\right) B_\nu(T)\, e^{-\tau_\nu^{cold}} \qquad \textbf{(8)}$$

where τ_ν^{cold} is the absorption optical depth of dust between the nebula and the observer, and τ_ν^{warm} is the optical depth of the emitting grains in the nebula. Figure 2.9 shows an image of BD+30°3639 where the quantity τ_ν^{warm} was calculated from the 10.0 µm image and the temperature image from Figure 2.8 for all points where the temperature is defined, assuming that the quantity τ_ν^{cold} is zero. The emission is optically thin everywhere in the nebula, with an average opacity of $6.3 \cdot 10^{-4} \pm 1.3 \cdot 10^{-4}$. There are density enhancements along the ring of the nebula, with the brightest peaks in the north and south positions. Instead of a central minimum, however, there seems to be a slight enhancement in the center of the nebula.

Between the 11.3 µm UIR feature and the 12.8 µm [NeII] feature, BD+30°3639 exhibits an emission "plateau", seen in many different sources and predicted by many PAH emission models (e.g., d'Hendecourt and Léger 1987, Tielens *et al.* 1987). The emission of BD+30°3639 from the 12.4 µm image therefore includes a contribution from this emission plateau, which is a much smaller spectral feature that the 11.3 µm or 12.8 µm feature. As seen from the source profiles, the image is larger than the continuum region in the E-W direction, but smaller in the N-S (FWHM size; the distance between the peaks is similar to the continuum images). This is consistent with the 12.4 µm emission resulting mainly from the warm dust continuum, with a small contribution from the UIR emission plateau.

2.2.2.4 BD+30°3639 [NeII], UIR Feature Images

The image of BD+30°3639 at 12.8 µm is centered on the bright [NeII] feature in this PN. Using the image at 13.2 µm, the contribution of the continuum flux can be subtracted from the image and obtain an image of the spatial distribution of the [NeII] flux in the nebula. The continuum level at 12.8 µm was estimated from the 13.2 µm image by assuming that the continuum flux follows the temperature derived from the 10.0 and 13.2 µm images. The result of this calculation is shown in Figure 2.10. The image shows that the [NeII] emission is primarily concentrated in the northern and southern parts of the nebular ring. This image shows a strong similarity to the distribution of the 6 cm continuum emission from the nebula, as seen in the VLA images by Masson (1989). The [NeII] emission, as a tracer of the emission from the ionized gas regions, confirms the peaks of emission in the northern and southern regions as shown by the radio images. Comparison of the 12.8 µm image with the continuum and UIR feature image at 11.2 µm shows that the distribution of [NeII] emission is similar to the dust emission, but the enhancements of emission in the eastern and western regions of the dust images are not present in the [NeII] image.

Similarly, an image in the UIR feature at 11.2 µm can be constructed by subtracting the 10.0 µm continuum image from the 11.2 µm image. This result is shown in Figure 2.11. As with the [NeII] image, the flux is from the outer edge of the ring, with peaks in the northern and southern parts of the nebula. However, a feature present here that is not in the [NeII] image is the enhancement in the east lobe of the nebula. Figure 2.12 shows profiles through these two images, with the profile of the 10.0 µm continuum image included for comparison. Here the profiles have not been shifted, but are properly aligned to the correct position on the sky. The UIR profiles are larger than the continuum in both profiles, in FWHM size and position of the peaks. The [NeII] image is close to the same size as the continuum in the S-N profile (FWHM is similar, although the peaks have a larger separation), but is larger in the E-W profile, almost the same as the UIR profile. One ambiguity about the [NeII] image is that at 12.8 µm, the image may have a contribution from the 11-13 µm emission plateau, which is not subtracted out by the 13.2 µm continuum image. This would have the most effect in the E-W profile, since it passes through a minimum of the [NeII] emission. The broadening of the profile in this direction therefore may be related to this effect.

Near-IR images of BD+30°3639 have been published previously. The images from Roche (1989) are reproduced here in Figure 2.14. Two images are shown, one at Br γ, and the other at 3.28 µm, the position of the UIR feature emission. The image at Br γ is very similar to ours at K, showing peaks to the north and south of the central star. Their image at 3.28 µm is different, showing an enhancement in the NE part of the emission ring. This is where an enhancement of the emission also appears in the 11.2 µm feature map (see Figure 2.11 above). This indicates that the 3.28 and 11.2 µm features have a similar spatial distribution, and provides evidence that the UIR emission is from a single population of grains.

2.2.4 Conclusions: BD+30°3639

The PN BD+30°3639 has been observed at six IR wavelengths. Calibrated images are presented, along with derived temperature, dust opacity, and [NeII] and UIR feature emission images. The following conclusions can be drawn:

1. The spatial distribution of the emission is similar in each of the mid-IR images. However, slight differences in source size and structure are observed, with the 11.2 µm image, which includes emission from the UIR feature at 11.3 µm, appearing slightly more extended than the continuum images. Subtracting the continuum image at 10.0 µm from the 11.2 µm image shows the UIR emission coming from the outer rim of the ring.

2. The calculated temperature image shows that the average nebular

temperature is 172K, with the highest temperature regions along the ring of the nebula. The opacity image shows the emission to be optically thin throughout the nebula, with opacity maxima in the northern and southern regions on the ring.

3. The [NeII] feature image shows the flux to be located in the nebular ring, with peaks in the northern and southern lobes. This is in excellent agreement with the radio images of the nebula, confirming that the ionized gas emission peaks are in these lobes. The mid-IR continuum emission, although also present in these N and S lobes, differs in that there is also significant emission from the E and W lobes of the nebula.

4. The image of BD+30°3639 at 2.2 µm shows the spatial distribution of the emission to be in a ring, with intensity maxima in the N and S lobes. The spatial distribution matches the radio image very closely, except for an additional peak in the NE part of the nebular ring. This is consistent with the emission resulting from recombination emission from the ionized gas, along with a contribution from hot dust.

2.3 J 900

The PN J 900 (PK 194 +2°1) is a circularly shaped high-excitation nebula of small angular size (approx. 5" FWHM). It was determined from JHK photometry to have a significant contribution from dust emission (Whitelock 1985). The excess emission was observed to be higher in K than in H. Mid-IR spectrophotometry (Aitken and Roche 1982) showed that the spectrum of J 900 is very similar to those of other nebulae such as NGC 7027 and BD+30°3639, with UIR features at 11.3, 8.6, and 7.7 µm. In addition, there are fine structure lines of [S IV] at 10.52 µm and [NeII] at 12.8 µm.

2.3.1 Observations

The PN J 900 was observed in the H and K band on December 14, 1989 with the 64x64 Hg:Cd:Te array camera on the SO 2.3 m telescope. The images were taken as alternating on- and off-source 40 sec integrations. Off-source frames were obtained by nodding the telescope 1 arcmin to the north. Small (0.5 to 2") offsets were introduced before each on-source frame. The final image at each wavelength was constructed from 45-50 of these individual images. The IR standard stars HD 44612 and HD 40335 were used for flux calibration. The nearby star SAO 095673 was observed as a PSF reference for the nebula observations.

2.3.2 Results and Discussion: J 900

Calibrated contour images of J 900 are presented in Figure 2.15. The emission is dominated by the central star of the nebula, so that the nebular structure is not easily separated out in these images. It is evident, however, that the nebula is extended to the NW and SE of the central star, with the NW extension the brightest. The nebula is roughly 5" in diameter, measured along a line passing through the major peaks.

The central star was removed from these images by subtracting a scaled image of a star that was in the same field as the J 900 observations, which gave an especially accurate determination of the PSF for the image. The star was aligned with the image of the nebula using a cross-correlation algorithm, and scaled according to a model that assumes the emission results from three components, the central star and the two lobes. Contour images of J 900 with the central star subtracted are shown in Figure 2.16, and grayscale images are shown in Figure 2.17.

The structure of the nebula is seen to be double-lobed, with the brightest lobe to the NW of the central star. It is also evident that the lobes are in slightly different positions in the H and K images. A line passing through both peaks is at a PA of 24° W of N in the H image, and a PA of 16° W of N in the K image. The lobe separation is also different, with the H lobe peaks separated by 2!85 and the K lobe peaks separated by 2!07.

Table 2.4 lists the results of the J 900 photometry, for the entire source, and for the central star separated from the nebula.

Table 2.4 Photometry of J 900

	Flux (10^{-2} Jy)		Magnitudes	
Filter	Star + Nebula	Star	Star	Nebula
H	2.81	.180	14.9	12.0
K	9.68	.860	12.7	10.2

The correlation studies of the UIR bands by Cohen *et al.* (1986) showed that J 900 also exhibited UIR emission in the 3.3 and 6.2 µm bands, in addition to the 7.7, 8.7, and 11.3 µm bands observed by Aitken and Roche (1982). The relative band strengths matched well with the general correlations of band strengths. Cohen *et al.* also compared the fraction of nebular far-IR luminosity with the C/O ratio and found a strong correlation, with J 900 having the highest value of both for six nebulae, the others being NGC 7027, BD+30°3639, IC 5117, IC 418, and NGC 6572.

Of these five, J 900 is closest in its IR characteristics to BD+30°3639 and NGC 7027, the common IR emission factors being high intrinsic UIR emission, high C/O ratio, high excitation, and near-IR excess. In addition, the observations presented here have shown that the IR spatial structure is also similar, with two lobes of emission around the central star. The asymmetry in the flux between the two lobes is larger here than in the other nebula, but the larger distance to J 900 makes the spatial structure and the geometry of the source more difficult to determine. The observed asymmetry could be from either an intrinsic difference in luminosity, a higher relative extinction in the SE lobe than the NW lobe, or an inclination of the source that causes the NW lobe to appear brighter.

2.3.3 Conclusions: J 900

We have observed the PN J 900 at H and K with a resolution of 0!56 per pixel. Calibrated images are presented showing the distribution of near-IR flux. The following conclusions can be drawn:

1. The nebula is seen to have a double-lobed structure at both wavelengths. The images in which the central star have been subtracted show that the NW lobe is brighter than the SE lobe at both wavelengths.

2. There are slight differences in the PA and position of the lobes at the different wavelengths, which may be in part due to the geometry of the source.

2.4 IC 418

The PN IC 418 is a young, low-excitation, elliptically shaped nebula with bipolar symmetry (see Figures 2.18, 2.19). This bright shell is enveloped in a much larger faint halo. A good review of the observational characteristics of IC 418 is given by Hoare (1990). The distance to IC 418 is not well known, with values in the literature ranging from 0.42 kpc (Pottasch 1984) to 2.0 kpc (Méndez *et al.* 1988).

The infrared emission from IC 418 shows several distinct components. The near-IR emission shows an excess from what is expected from the nebular gas and the star itself (Willner, Becklin, and Visvanathan 1972). A second component in the near- and mid-IR is the UIR features, seen at 3.3, 3.4 (Russell, Soifer, and Merrill 1977), 6.2, 7.7 (Cohen *et al.* 1986) and possibly 11.3 µm (Willner *et al.* 1979). There is also a broad feature at 11.2 µm which is attributed to SiC emission (Willner *et al.* 1979). In addition, there is a broad feature which peaks near 30 µm (Moseley 1980, Forrest, Houck, and McCarthy 1981) which has been attributed to magnesium sulfide by Goebel and Moseley (1985). There is also another component responsible for the continuum emission in the mid- and far-IR, which is assumed due to carbon grains that are larger than those responsible for the near-IR emission (Hoare 1990).

2.4.1 Observations and Data Reduction: IC 418

The planetary nebula IC 418 was observed at both near- and mid-IR wavelengths, on the Steward Observatory 2.3 m and 1.5 m telescopes. Table 2.5 lists some details of the observations.

Table 2.5 IC 418 Observation Log

Date	Inst[†]	Wavelength (μm)	Scale ("/pix)	Telescope	On source Int. time(sec)[‡]
12/13/89	1	1.6 (H)	.58	2.3 m	320 (20)
12/14/89	1	2.2 (K)	.58	2.3 m	680 (40)
3/ 6/90	1	1.2 (J)	.58	2.3 m	560 (40)
12/ 6/90	2	11.7	1.0	1.5 m	60*(10)

[†] Hg:Cd:Te array camera, 2=MIRAC

[‡] The number in parenthesis is the number of seconds in a single integration

*Average integration time for a position on mosaic image

The J, H, and K images were taken as alternating on- and off-source 40 sec integrations. Off-source frames were obtained by nodding the telescope 1 arcmin to the north. The final image at each wavelength was constructed from 32-48 of these individual images.

Two standard star observations were done in each wavelength before and after the nebular observations. First, a flux standard was observed in the same manner as the PN, except that the integrations were typically 5 seconds to avoid saturating the detector. Second, a nearby SAO star was observed as a point source reference. Frames were taken at the same operating parameters as the PN observations. Table 2.6 details which standards were used for the PN observed. The FWHM size is given for both the RA and Dec profiles of the PSF standards. These image sizes are for the final images, the sum of all the individual integrations, so the effects of seeing, errors in image registration, and telescope drift are included.

Table 2.6 PSF Standard Stars for IC 418 Observations

Filter	Star	FWHM (") RA	Dec
J	SAO 150440	1.31	1.32
H	SAO 150445	1.56	1.55
K	SAO 150445	1.18	1.16
11.7 µm	α Boo	2.5	2.5

For the MIRAC observations at 11.7 µm, the camera was equipped with four signal processor channels, so a 4x32 section of the array was used. The on-source integration time of each observation was 10 sec. Chopping was 23" to the north, and the telescope was nodded 30" N between each chop pairs. The array was scanned across the source in approximately 1.5" steps in Dec (along the short dimension of the array) to cover the entire nebula. A total of 5 separate scans were performed, along with a number of integrations with the nebula centered on the array. In the final coadded image, each position has an average of 60 seconds on-source integration time. Alpha Boo was used as a flux calibration reference.

2.4.2 Results and Discussion: IC 418 NIR Emission

Calibrated contour images of IC 418 at J, H, and K are shown in Figure 2.20. The general features of the nebula are the same in each image: the overall shape of the nebula is ellipsoidal, with emission lobes on either side of the central star. In all of the images, the east lobe is brighter than the west lobe, and the central star is the brightest point on the nebula. The K and H images are very similar, with similar relative intensity and position in the lobes, and a break in the ring structure northwest from the central star. Grayscale images of IC 418 at J and K are shown in Figure 2.21, for comparison to the optical image.

2.4.2.1 IC 418 Morphology and Sizes

There are important similarities between the NIR images presented here and the images at optical wavelengths in Louise *et al.* (1987). In their Hβ image, there are two main lobes of emission. A line drawn between these lobes passing through the center of the nebula has a position angle (PA) of 68°, similar to the PA for the H and K images of 70° and 76°, respectively. The separation of the peaks of the lobes is 8.8", close to that observed in the J image. The image at [OII] by Louise *et al.* shows a similar double-lobed structure, with the peaks of emission at approximately the same location and separation.

Despite the similarity between the near-IR images, however, significant differences are seen. The largest differences are between the J image and the H and K images. One difference is that the brightest lobe of emission from the nebula in J is rotated approximately 45° from the position of the brightest lobe in the H and K images, at a PA of 25°. In addition to the rotation, the E lobe in the J image also appears to be located slightly closer to the center of the nebula, compared to the H and K images. Another difference between the images is in the local minimum in the ring structure visible in the northwest part of the H and K images, as well as the optical images. This minimum is absent in the J image -the ring structure extends through this region without any break. The smaller west emission lobe also differs in the J image. This lobe is not present as a discrete local maximum in the J image. Instead, the intensity varies smoothly from the northern part of the nebula along the west side to the southern part, where there is a local minimum common to all the images.

These differences in spatial distribution of the flux can also be seen in the source profiles. Figure 2.22 shows the profiles for each of the images, normalized to the level of the brightest (E) lobe of emission and centered on the central star. The profiles are at a PA of 70°, and averaged over a width of !56. The spatial extent of the near-IR emission is similar in each of the bands, but it can be seen that there is a trend of larger source extension with increasing wavelength for the NIR images: the J image is smallest, then the H and finally the K image being the largest. The FWHM of the J source profile is 1!1 narrower than the K source profile, and 1!2 narrower measuring between the local maxima (the peaks corresponding to the nebula ring) of the source profile on either side of the central star. Table 2.7 gives the fluxes of IC 418 and the size at each wavelength as measured from these profiles through the main lobes.

Table 2.7 Observed Parameters of IC 418

Filter	Flux (Jy)	FWHM size (")	Nebular peak separation (")
J	.82	11.33	8.58
H	.73	12.25	9.24
K	1.24	12.47	9.76
11.7 µm	29	11.59	7.31

Also apparent in these profiles is the trend in the relative brightness of the emission near the central star, relative to the emission in the nebular ring. The J image has the brightest central emission relative to the lobes, followed by the H and then K image. This shows the increasing flux contribution of the nebula at the longer wavelengths.

2.4.2.2 IC 418 Central Star Subtraction

One would like to be able to separate out from the nebular flux the flux emitted by the central star. One approach is to use the standard star observations to determine the instrumental PSF, and assume the central star is contributing to the image in this way. The standard star image would then simply be scaled properly and subtracted from the observed image to give an image of the nebula alone. However, for the IC 418 images at J, H, and K, the central peak of the nebula is wider than the standard star image, and so the central peak cannot be totally subtracted from the nebula image.

This is illustrated in Figure 2.23, which shows a profile of the nebula data at J with the theoretical profile of the nebula without contributions from regions near the central star. The nebular profile assumes that the nebular emission is from an optically thin ellipsoidal shell. When the central star is subtracted to this level, however, the resulting profile does not match the theoretical profile of Figure 2.23. Instead, two peaks remain on either side of the central position, indicating that the wings of the peak are not being matched well by the standard star.

This incomplete subtraction is shown in Figure 2.24, which presents three profiles at each wavelength: one with the star scaled and subtracted up to the point where it would begin to show a central hole (called "Case A" here for ease of reference), one with the central star subtracted to the level shown in Figure 2.23 ("Case B"), and one with the star subtracted so that the central hole goes to near zero ("Case C"). Case A corresponds to a residual emission peak at the position of the central star, Case B results in a central ring of emission inside the main nebular ring, and case C shows that the wings of the central maximum are still not completely subtracted when the central flux is subtracted to zero. There is some irregularity in the profile in the central region after subtraction, due to errors in the image registration.

These three cases are not the only possibilities (the flux of the star could be intermediate between these discrete levels) but it is useful to examine these cases. Case C can be discarded immediately, since some nebular flux is expected from the central position of the nebula. In the Case B profiles of Figure 2.24 that show a double peak where the star was subtracted (corresponding to a inner ring of emission), the width of the double peaks are narrower than the instrumental PSF as measured by the standard star observations. The minimum size for any real feature should be the PSF width, so this indicates that the ring is an artifact caused by incorrect scaling of the subtracted star.

In the case where the PSF was scaled to produce a single central peak, the feature is approximately equal to or greater than the width of the PSF. Therefore, Case A is consistent with the observations and more likely to be valid than Case B. For the same reason, the flux of the residual peak is not likely to be smaller than the Case A profile. Therefore, the Case A profile represents a lower limit to the non-stellar central flux. Figure 2.25 shows three profiles in Case A for each wavelength: the original data, the standard star scaled to the proper value, and the resultant IC 418 profile when this star is subtracted.

There are a number of ways in which this excess emission near the central star could be artificially created by the instrument or data reduction process. One possible cause of this effect is that the instrumental PSF in the nebula images was vastly different from that in the standard star observations. This is not likely, however, since several steps were taken to make sure the standard star images were prepared in the same manner as the nebula images. The observations of the PSF standard stars were taken immediately before and after the nebula observations at each wavelength. The integration times were similar, and a similar number of observations per source were done. The stars used were not excessively bright (see Appendix 4), so there is no reason to expect a flux dependent PSF difference between the stars and the nebula. When comparing the standard star images taken before and after the images of the nebula at a particular wavelength, there was no significant difference in the source profiles. This indicated that the conditions were stable throughout the observations at a particular wavelength.

In the data reduction, the standard star images were treated in the same way as the nebular images, using the same gain matrix and flat fielding technique. Offsets for the individual integrations were calculated using a spatial cross-correlation algorithm. This algorithm selected only the region near the central peak of the image to use in the calculation, so that in the nebular images, the fainter extended regions were not included. Therefore we conclude that the differences in image profiles between the standard stars and the nebula are real and not an artifact of the instrument.

From the profiles of the PSF-subtracted nebula in Figure 2.25, it can be seen that the largest relative contribution of the central star to the flux in the central region is in the K image. The subtraction of the scaled standard star profile is nearly complete, with only a small residual left. The central residual is larger in the J and H images, with the peak still just over twice the intensity of the brightest lobe.

2.4.2.3 Comparison, Discussion of Previous Studies of IC 418

The fact that the size of IC 418 increases with wavelength in the near-IR has been noted before by Willner, Becklin, and Visvanathan (1972) and Phillips *et al.* (1984). Willner *et al.* used apertures of increasing size at H and K, and found that the flux continued to increase significantly even after the entire optical nebula was within the aperture. Phillips *et al.* scanned a photometer with a 5!4 beam across the nebula in right ascension to measure the source profile, and found the nebular size increased with wavelength, and was larger than their standard star profile at H, K, and L. However, their profiles showed no emission extended beyond the central star in the J band. In their H and K scans, extended emission was detected, however it was at a distance of 10" from the center of the nebula, twice the size of the images in Figure 2.20. Most of the differences can probably be attributed to their lower spatial resolution and lower signal to noise. The faint nebular emission could have easily been lost in the wings of the bright central star profile at the shorter wavelengths.

This does, however, change their conclusions about the location of the temperature distribution of the dust. Phillips *et al.* (1984) had observed emission at K outside the ionized zone but no K-band emission inside that was not from the central star, and L-band emission that extends from near the central star to outside the ionized zone. They suggested that there was hot dust emission from outside the ionized zone and cooler dust emission from close to the central star. The images, however, show that there is emission in excess of the central star in J, H, and K, and no evidence of the temperature increasing with distance from the central star.

2.4.2.4 Sources of Near-IR Emission in IC 418

There are several components to the near-IR emission from IC 418. There is a component due to recombination emission from the nebulae. The total nebular flux between 2 - 4 µm is a factor of 2 greater that what is expected from the radio observations (Willner *et al.* 1979), implying the presence of hot dust. Willner *et al.* calculated a grain temperature of 1350 K for a 10" beam, and 950 K for a 44" beam, assuming a grain emissivity $Q_\lambda \alpha \lambda^{-2}$. However, they find it difficult to explain these high temperatures given the central star temperature of ~$3 \cdot 10^4$ K. Other mechanisms, such as free-free emission generated from interactions between electrons and H^- or H_2^- ions, or stellar radiation scattered from dust particles, were also not satisfactory to explain the excess.

Recently, Zhang and Kwok (1991) have measured the spectrum of IC 418 between 1.5 and 1.75 µm with a spectral resolution of $\lambda/\Delta\lambda = 1280$. The wavelengths measured cover the spectral region within the H band. There is an uncertainty in the measured flux from the nebula since the instrumental beam diameter was only 5", significantly smaller than the size of the nebula. They multiply the entire spectrum by a factor of 4 to correct for this; however, since the nebula shape is seen to differ as a function of wavelength, this will cause differences in the spectral shape as a function of position over the nebula. The main features of the spectrum in the wavelenght region from 1.5 to 1.75 µm are the series of Brackett emission lines of hydrogen, superimposed on a continuum. There are also small flux contributions from emission lines of He and Mg.

Zhang and Kwok (1991) estimate that the total flux due to line emission is about 25% of the total H-band emission observed. From recombination line theory, an estimated 39% of the J band and 4% of the K band flux is from emission lines. Even after correcting for the line flux, there is still an emission excess over that expected from the nebular and stellar continuum. They determine that the K excess could be accounted for by thermal radiation from 600 K grains, but the J and H excess implies a color temperature of 95000 K. One suggested possibility of a field star included in the aperture is ruled out by the images presented here, but does not rule out a close companion.

Another possibility for the flux excess is emission from small grains. These hot grains would be expected to be closer to the central star than the emission from the 600 K or the warm or cool dust emssion seen at mid- or far-IR wavlengths. Since the temperature of the grains would have to be >1000 K, the emission from the hot grains would be greatest at J, and decreasing at H and K.

From the point-source subtracted profiles of Figure 2.25, one possible identification of the excess radiation is apparent in the central flux left after subtraction of the central star. The emission is located near the central star, only slightly more extended than the instrumental PSF. The excess is largest at J, smaller at H, and almost not present at K, implying a high temperature. It is helpful to separate the flux in each band into the nebular, stellar, and central excess components using the spatial information of the images presented here. Table 2.8 gives the flux for each separate component. The "halo" component is described in §2.4.2.5 below.

Table 2.8 IC 418 NIR Component Fluxes

(Flux in Jy)

Filter	Total	Nebula	Star	Central Excess	Halo
J	.823	.655	.086	.082	0
H	.732	.524	.064	.032	.112
K	1.24	.938	.073	.011	.218

Willner, Becklin, and Visvanathan (1972) calculated the expected flux at H and K based on radio observations to be .46 and .54 Jy, respectively. The excess flux does not seem to be emitted by a single spatial component as separated in Table 2.8. In fact, the emission from the nebula alone is above the expected values, implying that some of the excess emission must come from the nebular ring. The emission from the central region attributed to the star does not follow the expected blackbody spectrum for a 30000 K star-- the color temperature calculated from the J and H emission is ~2600 K. If the "central excess" flux is attributed to the star, this results in a J - H color temperature of ~3600 K. This effect could be caused by dust emission near the central star that has not been spatially resolved. Also, Zhang and Kwok’s (1991) suggestion of a close companion is not ruled out.

Significant emission is also seen in the halo in the H and K bands. The relative flux in each band is ~17%, much less than what was suggested by Willner *et al.* (1989) in their multiple aperture photometry. The emission in the halo region could have contributions from thermal emission from grains, and from scattered starlight. Polarization observations of this region would aid in separating out the components of emission.

2.4.2.5 IC 418 Halo Emission

There have been previous reports of evidence for an extended shell of emission around IC 418. Willner, Becklin, and Visvanathan (1972) showed that the flux continued to increase out to a beam size of 40" at K. Taylor and Pottasch (1987) detected neutral hydrogen in the circumnebular shell. Their observations showed 21 cm emission and absorption towards the nebula, with a velocity relative to the system of 13.2±0.5 km/sec. Taylor, Gussie, and Goss (1989) mapped the 21 cm emission and found it to be extended by approximately 1 arcmin in Right Ascension and 2 arcmin in Declination. Monk, Barlow, and Clegg (1989) detected a faint halo in [OII] and Hγ extending at least 110 arcsec in diameter. They attributed the emission to scattered light from small (<.03 µm for carbon or silicate) particles.

We have shown in the source profiles in Figure 2.22 above that the nebula is more extended in the longer near-IR wavelengths, based on separation of the lobe peaks. There is also evidence for a low level emission from the nebula in the H and K images that extends well outside the ionized zone where most of the flux is emitted. Figure 2.26 shows the profiles of the images plotted again on a greatly magnified vertical scale. This shows the emission from the H and K bands extending out beyond the edge of the nebula, to approximately 14" from the lobe peak. In contrast, the J emission terminates shortly after the edge of the major lobe of emission in the nebula, at no more than 7" from the lobe peak. The K emission is brighter than the H emission, relative to the lobes of the nebula. The J image is not as high signal to noise as the K and H images, but it is clear that, relative to the lobe peak, the emission drops much lower at a given distance.

The color temperature of the emission outside the ionized zone can be calculated using the H and K images. The resulting temperature image has a roughly flat distribution, with an average temperature of 1500K. If there is a significant contribution from scattered light in the halo, the relative contribution will be greater at H, so the temperature would be lower. Spatially resolved polarization images of IC 418 would help distinguish between thermal emission and scattered light in the nebula.

2.4.3 IC 418 Mid-IR Emission

The contour image of IC 418 at 11.7 µm is shown in Figure 2.27. This filter samples the spectral feature in the spectrum of IC 418 from 11 to 12.5 µm, which is attributed to SiC emission. Evidence of weak UIR emission at 3.3 and 7.7 µm has been detected (Willner *et al.* 1979), so there may be some weak contribution from the UIR feature at 11.3 µm, as well as from the UIR plateau feature. There is also a large contribution at 11.7 µm from mid-IR continuum emission from the nebula. The relative importance of these contributions to the total emission are not known precisely, but the mid-IR continuum and the SiC feature contributions are approximately equal, with a minor contribution from the UIR features.

Significant differences between this image and the near-IR images are apparent. The signal-to-noise ratio is lower in the 11.7 µm image than in the J, H, and K images, but the major structure of the nebula is clearly visible. There is a small peak at the central star position, and other peaks around the ring of the nebula. There are E and W lobes corresponding to those seen in the J-K images, and two additional peaks in the N and S parts of the nebula.

A profile through the 11.7 µm image is shown in Figure 2.22, along with the near-IR profiles. The peaks of the 11.7 µm image fall inside of the peaks of the J image, which was the most compact of the J-K images. This would indicate that most of the SiC and warm dust emission is coming from within the region where the recombination and hot dust are emitting. The central emission peak in the 11.7 µm image is also interesting. There will be no significant flux from the star itself at 11.7 µm. Since we do not have an image of IC 418 in the continuum without contribution from the SiC feature, the flux from each separate component cannot be determined, only the total from both components.

The mid-IR emission detected from the position of the central star indicates the presence of dust or SiC. This is in the same position as the excess flux seen in the central regions of the J, H, and K images. Therefore, this provides additional evidence for the interpretation of the distribution of non-stellar near-IR flux as a central peak rather than a ring.

2.4.4 Dust Emission in IC 418

SiC has been thought to form in carbon star envelopes (Treffers and Cohen 1974, Merrill and Stein 1976). The envelopes of these stars have the conditions necessary for particles to form: high densities ($\geq 10^9$ cm^{-3}) and cool temperatures (1000-2000K) (Salpeter 1974, Seab 1988). Experimental results by Frenklach, Carmer, and Feigelson (1989) have shown that SiC can form at higher temperatures (above 2800K) and therefore would be the first particles to form in C-rich envelopes. They have proposed that SiC may act as nucleation sites for larger carbon particles and formation of PAH molecules.

The observations at 11.7 µm presented here are consistent with this model of SiC formation and growth. Since the carbon abundance is not very high (C/O ratio ≈ 1.3) the carbon is locked up in CO and SiC, leaving little carbon for the formation of amorphous grains or PAHs. The UIR emission from IC 418 is in fact much weaker than in other IR-bright nebula, as shown by Cohen *et al.* (1986) who compared the 7.7 µm feature flux to total far-IR luminosity. The spatial distribution of the 11.7 µm emission also indicates that it is different from the UIR features or continuum that are located in or just outside the ionized zone (e.g., in NGC 7027 or BD+30°3639). The presence of emission near the central star indicates that the SiC at that location may have formed recently and may still be forming.

The SiC emission is only one component of the IR emission. The IR spectrum of IC 418 peaks near 30 µm, consisting of a broad thermal continuum with an emission feature near 30 µm attributed to MgS. Models of the SiC emission have shown that it cannot account for the far-IR emission, by 2-3 orders of magnitude (Stephens 1980, Hoare 1990).

Hoare (1990) presents two different models for the mid- and far-IR emission. Both use SiC and MgS to create the spectral features at around 11.2 and 30 µm, and the continuum is produced by graphite emission in one model and amorphous carbon in the other. The amorphous carbon model fits the *IRAS* data slightly better than the graphite model, however both models have difficulty reproducing the near- and mid-IR continuum emission, where hot dust and UIR features will have a contribution. A plot of the surface brightness of IC 418 at 12, 100, and 450 µm for the amorphous carbon model is shown in Figure 2.29. The model's 12 µm surface brightness compares well with the observed surface brightness of the 11.7 µm image, shown in Figure 2.28. This figure is a plot of the average surface brightness in an annulus as a function of increasing radius from the center of the nebula.

2.4.5 Conclusions: IC 418

The PN IC 418 was observed at J, H, K, and at 11.7 µm. Calibrated images are presented here, along with source profiles and ratio images. The following conclusions can be drawn:

1. The distribution of emission is very similar at J, H, and K, and is similar to the size of the Hβ image. However, there is a detectable difference in the size of the images, with the FWHM and the distance between the peaks increasing with wavelength in the near-IR.

2. There is a peak in the flux distribution of the nebula after subtracting out the flux contribution from the central star. This residual peak is strongest at J and is progressively weaker at H and K. This excess at the central position is coincident with the local maximum in the 11.7 µm image and perhaps indicates a compact shell interior to the main shell of emission.

3. The spatial distribution of the emission at 11.7 µm, attributed to SiC and continuum thermal emission from warm dust, is significantly different from the other images, being less symmetrical and having additional knots of emission. Also, the FWHM size is smaller than in the near-IR and optical images, indicating that the emission may be originating from within the ionized zone. Additional evidence of this is the emission peak at the position of the central

star.

4. Evidence for an extended halo is seen in the K and H images. The halo extends approximately 13" further than the peaks of the main lobes, for a total nebular diameter of 36" along the minor axis and 40" along the major axis of the nebula. Emission is not detected in the halo in the J band, or at 11.7 µm.

5. The location of the 11.7 µm emission within the ionized region is unique to IC 418, since in most nebulae exhibiting detectable 10 µm continuum emission, it is seen to be coextensive or located just outside the ionized zone. There are emission contributions from warm dust and possibly UIR features at this wavelength, in addition to the SiC emission feature. The other nebulae with UIR and dust continuum emission, however, do not exhibit emission near the central star position. This suggests that this central emission is from the SiC feature, which is expected to form at higher temperatures than the hydrocarbon carriers of the UIR emission, so it can be formed and survive closer to the central star.

2.5 NGC 6543

The PN NGC 6543 does not readily fit into any of the simple morphological classes that describe most PN (see discussion of classes in introduction above). Its appearance in optical low-excitation lines is that of two ellipses at nearly right angles to each other, centered on a star (Figure 2.30). Along with this large scale structure, there are tails and filaments of emission connecting the ellipses and extending out beyond them. In addition, there is a faint nebulosity of elliptical form that extends well beyond this bright inner structure. One difficulty in explaining the observed structure is that the appearance of the nebula is significantly different in the low-ionization emission lines, Hα, [OI], [O III], and radio continuum (Balick and Preston 1987).

Several models have been proposed to explain the observed morphology. The multiple shell appearance was first explained by helical structures (Munch 1968, Carranza *et al.* 1968). Phillips and Reay (1977) propose a triaxial closed shell model. Hippelein *et al.* (1985) suggest a simple wind-blown model and try to match it to the observations. Balick and Preston (1987) propose a model of two pairs of bipolar lobes with axes that intersect at the center of the nebula. This was based on their kinematic observations of NGC 6543 in Hα and [N II]. The structure is very ordered but complex. The difficulty in interpreting these image is not only in determining the structure, but in proposing a possible mechanism to produce that structure.

2.5.1 Observations: NGC 6543

The planetary nebula was observed in the K and H bands on March 6, 1990 with the Steward Observatory 64x64 Hg:Cd:Te array camera. The images were taken as alternating on- and off-source 60 sec integrations. Off-source frames were obtained by nodding the telescope 1 arcmin to the north. Small (0.5 to 2") offsets were introduced before each on-source frame. The final image at each wavelength was constructed from 50 of these individual images. The IR standard star HD 136754 was used for flux calibration. The nearby SAO star 017713 was observed as a PSF reference.

Contour images of the PN NGC 6543 at H and K are presented in Figure 2.31. The near-IR nebular emission is dominated by a bright lobe of emission to the north of the central star. This lobe is present in both the H and K images, although in the K image the flux in this lobe is much brighter relative to the central star than in the H image. Table 2.9 summarizes the sources of emission from the nebula and the star. The second column lists the total flux from the system, including the star and the nebula. The third column gives total nebular flux, and the fourth column gives the total flux emitted by the central star. The fifth column lists the bright lobe excess, which is the difference between the flux from an 18 square arcsec region centered on the bright lobe, and the flux from the same size area centered on the fainter lobe south of the central star. The last column gives the percentage of flux emitted by the bright lobe, compared to the total nebular flux.

Table 2.9 Photometry of NGC 6543

Flux (Jy)

Filter	Star + Nebula	Nebula	Star	Bright Lobe excess	Percent in Br. lobe
H	.233	.203	.030	.008	4%
K	.211	.198	.013	.082	41%

In addition to the star and bright lobe, there is emission from the rest of the nebula roughly equivalent to the size and structure seen in optical images (e.g., Balick 1987). A grayscale image of NGC 6543 at K is presented in Figure 2.32. The basic structure is an ellipsoidal shell centered on the star, with the major axis oriented roughly E-W. In addition to this, roughly on the north and south edges there is a filament of emission extending north and to the east from the top of the nebula, and south and to the west from the bottom of the nebula. This has been referred to as a "pinwheel" structure because of these filaments. The structure could also be considered to be two overlapping ellipses, at right angles to each other.

2.5.2 Discussion: NGC 6543

Radio continuum images of NGC 6543 which show the distribution of the ionized gas are similar to the optical excitation line images, shown here in Figure 2.30. An image of NGC 6543 at 8.1 GHz (Terzian 1978) shows the same double elliptical shell structure seen in the optical images. Images at 20 cm and 6 cm by Bignell (1983) show the double elliptical shell appearance clearly, and images at [SII] and [OIII] show a similar structure. Part of the larger elliptical shell seems to be separated from the nebula in the [OIII] image, but the image is fairly symmetrical.

The H and K images presented here have unique features compared to the images at radio and optical wavelengths. The basic underlying structure is similar, with the double ellipse structure seen in both H and K images. However, in the infrared images, the dominant nebular feature is the bright lobe north of the central star. As seen from the fluxes given in Table 2.9, the lobe accounts for 4% of the emission at H, and 27% of the total emission in K.

Some of the first near-IR observations of NGC 6543 (e.g., Willner *et al.* 1972) indicated that there was little evidence for a near-IR emission excess that could be attributed to dust. However, if the IR emission was from the same sources as the radio or optical emission, one would expect the emission to have a similar relative distribution of flux. These images therefore provide evidence that there is a near-IR excess of emission that is not well mixed with the ionized gas and is localized in a lobe north of the central star. The amount of excess emission is estimated by the values in Table 2.9, column 3. Based on the values in Table 2.9, the average color temperature of this region is 606 K. This excess, could result from sources other than warm dust, such as Br γ or other line emission within the K band. However, there is no similar bright lobe in Hα or the low excitation line emission, suggesting that the excess is not associated with the gas emission.

Balick and Preston (1987) propose a model of two pairs of bipolar lobes with axes that intersect at the center of the nebula (Figure 2.33). The ellipses visible in the images represent the places where the lobes intersect. This model was motivated mainly by the observed structure of the nebula in optical and radio images. In order to evaluate their model and others, they studied the velocity structure of NGC 6543 in Hα and [NII]. The images they present also show this apparent structure of two overlapping ellipses whose major axes are at a 90° angle with respect to each other, seen in Figure 2.30. Several features are defined, including a [NII] nucleus, ellipse, and N and S caps and tails. The ellipse shows a clear expansion outward from the nucleus, at a projected velocity of 20 km/sec, with the south side approaching, and a true velocity of 30 km/sec, assuming the ellipse is a tilted circular feature. The lobes, visible in the Hα and [OIII] images, and the [NII] caps have little net observable motion.

The bright lobes in the K and H images presented here are in the same spatial position in the model as the northern intersection of the lobes, and the limb-brightened edges of two of the lobes. If the material responsible for the emission was present mainly on the surfaces of the lobes and the intersections of the lobes, one would expect a higher flux from these regions. This enhancement is present in the radio and optical images of the nebula. However, the NIR emission is above what is expected if the emission is solely from recombination emission, since the near-IR flux is predominately from a single position in the nebula. The excess NIR emission from the northern lobe could be from other sources besides hot dust, such as line emission in the K band. However, such emission would be expected to be distributed similar to the optical line emission. If the emission is from dust, these near-IR images suggest that the dust is mostly localized in this N lobe, and is not well mixed with the gas in the nebula.

2.5.3 Conclusions: NGC 6543

We have observed the PN NGC 6543 at H and K with a resolution of 0!56 per pixel. Calibrated images are presented showing the distribution of the NIR flux. The following conclusions can be drawn:

1. The structure of the nebula visible in the optical and radio images is present in the near-IR images. However, the relative brightness is very different between the near-IR and other images, with a bright lobe present to the north of the central star.

2. The emission from the bright N lobe may be due to dust emission in the nebula, which was not previously observed with broad-beam spectroscopy since the excess emission is a small percentage of the total near-IR flux of the nebula.

2.6 NGC 2392

The planetary nebula NGC 2392 (the "Eskimo" nebula) is a multiple-shell nebula of roughly elliptical shape, shown in Figure 2.34. The bright nebular ring has a complex structure, consisting of two shells that are at points connected by filaments. The ellipsoid is flattened on the south edge. Surrounding this bright nebular shell is a faint outer shell, with roughly twice the diameter of the inner ring. This outer shell is not continuous and consists of bright radial filaments around most of its circumference, except for a shell fragment on the south edge, which is a short continuous arc. This entire structure is enclosed in a faint roughly circular halo (Balick 1987, Balick, Preston, and Icke 1987, Barker 1991).

The isovelocity images of Balick, Preston, and Icke (1987) have shown that the nebula is a roughly ellipsoidal expanding shell, with the major axis of the ellipsoid aligned with the observer’s line of sight. The outer filamentary shell and the largest diameter of the inner shells is roughly at zero systemic velocity. The largest velocity regions are close to the position of the central star for both positive and negative velocities.

The characteristics of the IR emission from NGC 2392 are not complex or unusual. In the near-IR region, broad beam spectrophotometry has shown no IR excess over what is expected from recombination emission and stellar flux (Willner, Becklin, and Visvanathan 1972, Cohen and Barlow 1974). The midand far-IR spectrum shows no feature emission, and a weak IR continuum (Volk and Cohen 1990). From the *IRAS* observations of the cool dust, Lenzuni, Natta and Panagia (1989) determined a temperature of 75K, moderate for most PN.

2.6.1 Observations: NGC 2392

The PN NGC 2392 was observed in the K and H band on March 7-8, 1990 with the 64x64 Hg:Cd:Te array camera on the Steward Observatory 2.3 m telescope. For the H image, no calibration star image was obtained due to clouds so the image was scaled assuming the total flux of the nebula is .21 Jy (Khromov 1974). The calibration factor that resulted from this assumption was consistent with calibration factors for this filter obtained on previous nights. The images were taken as alternating on- and off-source 45 sec integrations. Off-source frames were obtained by nodding the telescope 1 arcmin to the north. Small (0.5 to 2") offsets were introduced before each on-source frame. The final image at each wavelength was constructed from 45-50 of these individual images. The IR standard star HD 84800 was used for flux calibration. The nearby star SAO #079428 was observed as a PSF reference for the nebula images.

2.6.2 Results and Discussion: NGC 2392

Contour images of NGC 2392 are presented in Figure 2.35, and grayscale images are shown in Figure 2.36. As with NGC 6543, many of the features visible in the optical images are seen in the images at H and K. The central star dominates the flux, and the ellipsoidal nebula surrounds it, offset slightly to the north. The southern end of the nebula seems somewhat flattened, just as in the optical images (Balick 1987), and the double shell structure is visible to the north of the central star. The faint halo and filaments of emission outside the main shell that are prominent in the optical images are not seen here, but may be too faint to detect in these images. The 1 sigma noise in the images is .17 mJy / arcsec^2 at H and .04 mJy / arcsec^2 at K.

The striking features of the nebula, however, are the bright lobes of emission to the NW of the central star in the K image. The lobes are located on the outer rim of the main nebula, the northern lobe on the outer shell only, and the southern lobe on the intersection between the inner and outer shells. Table 2.10 gives the fluxes for the various components of the system. Column 2 gives the total flux for the system. Column 3 and 4 give the excess flux for the northern and southern bright lobe, respectively. This is the excess flux over what is observed in the nebula on the opposite side of the shell. The percentages given for each lobe are the percent of the total nebular flux coming from the lobe. Column 5 gives the flux of the central star.

Table 2.10 Photometry of NGC 2392

Flux (Jy)

Filter	Star + Nebula	Star	Nebula	Bright lobe excess North	Bright lobe excess South
H	.21	.164	.046	.000 (0%)	.001 (2%)
K	.211	.039	.171	.007 (4%)	.008 (5%)

As with NGC 6543, the spatial distribution of the flux at K suggest that there is a region of excess emission above what is expected from recombination emission from the ionized zone. However, a similar excess is not seen in the H filter. If the excess is due to dust emission from that location of the nebula, it would imply that the dust is much cooler here than in NGC 6543. Again, the excess emission could also result from line emission from that location in the nebula.

2.6.3 Conclusions: NGC 2392

The PN NGC 2392 was observed at H and K, and calibrated images at these wavelengths have been presented. The following conclusions can be drawn:

1. The images show the near-IR source morphology to be similar to the optical appearance, with a flattened ellipsoidal structure surrounding the central star. The outer filaments and halo were not detected at the sensitivity of these

images.

2. The NW lobe of the nebula shows enhanced IR emission above what would be expected from the optical morphology. The effect is slightly visible in the H image but is readily apparent at K. One possible source of this excess is hot dust emission in this lobe of the nebula, which is not hot enough to have significant emission in the H band.

2.7 AFGL 2688

The object AFGL 2688 (the "Egg Nebula") is a bipolar nebula with symmetric lobes, oriented approximately 15° east of north (Figure 2.37). Optically, the north and south lobe sizes are 4!8 and 2!9 respectively, the southern lobe being about 2 magnitudes fainter than the northern lobe (Ney *et al.* 1975, Crampton *et al.* 1975). The lobes are approximately circular in shape, separated by about 8", with pairs of "horns" extending out from the ends away from the center of the nebula. AFGL 2688 is thought to be one of a class of proto-planetary nebulae (PPN), whose central star is evolving from a red giant with rapid mass loss (Zuckerman 1978).

The optical emission from the lobes is highly polarized, 50% and 62% for the northern and southern lobes, respectively, and oriented perpendicular to the axis of the nebula. The polarization, along with the optical spectrum, is consistent with the lobes being a reflection nebula illuminated by an F-type star (Ney *et al.* 1975).

Bipolar nebulae are thought to form from expansion of material through an existing distribution that is concentrated in the equatorial plane of the system (Balick 1987). This buildup of mass in the plane could be a result of mass loss from a binary system in its rotational plane, or from other mechanisms (see Figure 2.1). The material surrounding the star is in the form of a disk with a large equatorial density enhancement. The stellar wind quickly breaks out and forms a hole in the polar regions of the disk. The hole is small and initially confines the expansion to be solely in two narrow lobes. As the system evolves, the hole allowing material to escape grows, so the lobes will grow wider. The evolved system will consist of a faint outer bipolar halo, with a nearly toroidal disk of material near the central star system.

The infrared emission in AFGL 2688 is in excess of that expected from a simple reflection nebula, and has been attributed to thermal emission from dust. The IR spectrum of AFGL 2688 cannot, however, be fit to a single blackbody, indicating that there are several components of dust with different temperatures. The near-IR emission is also due to scattered starlight from the obscured central source; the average polarization at 2.2 µm is 20% (Ney *et al.* 1975). Color temperatures of 200K and 120K have been derived for the wavelength ranges 8-13 µm and 16-24 µm, respectively. The IR spectrum is relatively featureless, with no UIR, SiC, or silicate absorption detected. The mid- to far-IR emission is fairly compact, concentrated in the center of the nebula between the two lobes. Ney *et al.* (1975) determined the size at 12.5 µm to be 1!0 ± 0!3 in R.A. and 1!5 ± 0!2 in Dec. Observations reported in Deutsch (1990) and Deutsch *et al.* (1991) confirmed that the source was compact, with deconvolved sizes of 1!37 in R.A. and 1!40 in Dec. Gatley, DePoy, and Fowler (1988), with B. Balick and B. Zuckerman, have imaged AFGL 2688 at 1.25 and 2.122 µm, and found the IR emission to be distributed in the optical lobes, as well as emission from the equatorial region surrounding the obscured central star.

2.7.1 Observations: AFGL 2688

The PPN AFGL 2688 was observed at J, H, K, and Br γ on December 12-14, 1989 with the 64x64 Hg:Cd:Te array camera. The images were taken as alternating on- and off-source 20 sec integrations (40 second integrations at J). Off-source frames were obtained by nodding the telescope 1 arcmin to the north. Small (0.5 to 2") offsets were introduced before each on-source frame. The final image at each wavelength was constructed from 32-40 of these individual images. The IR standard star HD 203856 was used for flux calibration. The nearby star SAO 070805 was observed as a PSF reference for the nebula observations.

2.7.2 Discussion: AFGL 2688

Calibrated contour maps of AFGL 2688 at J, H, K, and Br γ are presented in Figure 2.38. Grayscale images are shown in Figure 2.39. The structure of the nebula in the near-IR is similar to the optical structure. The nebula appears bipolar, with the north lobe brighter than the southern lobe. The "horns" of emission that extend out from the ends of the nebula are visible in some of the contour and grayscale images.

The contour images, however, show that the lobes, instead of being circular and of uniform brightness, are roughly elliptical, with the peak emission located closer to the center of the nebula than the center of the elliptical lobes. The assymetry between the lobes may be in part due to the orientation of the source, where the N lobe is tipped toward the observer at an angle of less than 30° (Kawabe *et al.* 1987). The spacing of the peak is different in the J, H, and K images. This is illustrated in Figure 2.40, which shows profiles of the source along the major axis of the nebula in the three bands. The profiles have been normalized to the maximum flux in each image, located in the northern lobe. The source separations are in sequence from largest to smallest J, H, and K. Also, the relative brightness of the southern lobe varies in each of the images.

The profiles in Figure 2.40 show other interesting characteristics which vary as a function of wavelength. In each of the profiles, there is a peak for each lobe, and then as the intensity drops off as one moves further away from the center. At a certain point, there is a "knee" in the profile where the intensity begins to drop off more rapidly. In the K image, the profile even begins to level off before beginning to drop off rapidly. This knee in the profile occurs in both the northern and southern lobe moving out from the lobe peak. The knee is at different locations and relative intensities, being further from the lobe peak and of lower relative intensity as the wavelength increases. Table 2.11 summarizes the results on source separations and brightness.

Table 2.11 AFGL 2688 Lobe Parameters[1]

Filter	Peak Sep.	Rel. Flux of S. Lobe	Peak-Knee Distance N	Peak-Knee Distance S	Knee-Peak Flux ratio N	Knee-Peak Flux ratio S
J	6.53	.39	2.49	1.33	.558	.73
H	5.86	.35	2.93	2.36	.356	.43
K	4.68	.25	4.06	3.27	.215	.44

[1] All distances are in arcsec.

The peak separation is the distance between the peaks of the northern and southern lobes. The relative flux of the southern lobe is the peak value of the southern lobe when the northern lobe has been normalized to 1. The peak-knee distance is the separation between the lobe peak and the knee outward from that peak, for each of the lobes. Similarly, the relative brightness of the knee is the ratio between the intensity at the knee to the value at the peak for that particular lobe. The numbers show that the knee-peak separation increases and the knee-peak relative brightness decreases as the wavelength is increased.

A feature that is not present in the optical images is weak IR emission from positions to either side of the minimum between the main lobes, at approximately 6" to either side. This is most apparent in the Br γ and K images of Figures 2.38 and 2.39 which show the fainter lobes to be located symmetrically on an axis perpendicular to the major axis of the nebula, running through the center. There is a faint tail which extends from the eastern minor lobe to the northern lobe. The low flux also precludes any detailed comparison of the structure of the minor lobes. Table 2.12 summarizes the flux measured in each of the four lobes. The lobes are identified as N, S, E, and W, with the N and S lobes being the main lobes as visible in the optical photograph, and the E and W lobes are the ones detected in the Br γ and K images.

Table 2.12 AFGL 2688 Fluxes (mJy)

Filter	Total	Lobes N	S	E	W	3 σ Noise (mJy/(")^2)
J	270	179	60	...	...	.035
H	288	198	79	...	...	.025
K	324	224	68	7.4	3.8	.009
Br γ	318	222	60	5.1	3.9	.093

The total flux does not equal the sum of the lobes, since there is a faint halo enveloping the entire system that is not included in the lobe fluxes. This halo extends out from the edge of the lobes by approximately 6" in all directions, so the general shape is ellipsoidal, with the major axis parallel to the major axis of the system. The halo emission is shown in Figure 2.41, where the image at K is plotted with a lower level contour and larger field than in Figure 2.38. The image has been smoothed using bilinear interpolation with a 2x2 instrument pixel window to help show the outer contour levels more clearly. The relative distribution of the emission in the K filter and the Br γ filter is the same, to the accuracy of the data. The similarity of the distribution is also apparent in the contour images in Figure 2.38, where the two images have been plotted with the same contour levels.

As mentioned previously, AFGL 2688 has been imaged previously by

Gatley, DePoy, and Fowler (1988). Their image at J is apparently identical to the image presented here, and their image at 2.122 µm (H_2), in which the continuum had not been subtracted, is very similar to the images at K and Br γ. The Br γ filter in the Hg:Cd:Te camera has a center frequency near the wavelength of Br γ emission at 2.166 µm, with a width of .2 µm. In the near-IR spectrum by Thronson (1982), no evidence of Br γ emission is detected. The spectrum is dominated by emission from H_2 rotation-vibration lines. In particular, strong emission was detected from the $V = 1 - 0\ S(1)$ H_2 line at 2.122 µm which falls within the bandpass of the Br γ filter. Therefore, the "Br γ" filter is sampling flux from the H_2 line as well as the surrounding continuum.

The K filter covers a bandpass of approximately .5 µm, which includes the bandpass of the Br γ filter. The K filter also includes emission from several additional H_2 lines, although these lines are much fainter than the H_2 line at 2.122 µm. There should then be a contribution of H_2 line flux to the total flux detected in the K filter. If the minor lobes were due solely to H_2 emission, one would expect a difference in the ratios of the major to minor lobe flux in the K filter ($\Delta\lambda$=.5 µm) and the 2.166 µm filter ($\Delta\lambda$=.2 µm), since the filters contain a different amount of continuum flux but the same amount of line flux. However, since the absolute value and the relative distribution of the flux is the same in the narrow bandwidth "Br γ" and the wide K filter, the flux observed is likely of a similar nature in both the major and minor lobes, and no significant difference in the spatial distribution between the H_2 emission feature and continuum flux is detected.

2.7.3 Comparison to Other Observations, Models of AFGL 2688

Heiligman *et. al* (1986) and Kawabe *et al.* (1987) have spatially resolved the CO emission from the nebula. Heiligman *et. al* detect an extension of the source parallel to the major optical lobes, centered between them. They also find that much of the emission is extended over a scale >30". Kawabe *et. al*, however, have found the emission to be extended perpendicular to the major axis of the system, centered between the main lobes. Their observations support a model in which there is an equatorial disk of material which confines the fast wind to be along the major axis of the nebula. Their model is illustrated in Figure 2.42. The central star is surrounded by a toroidal disk which is located at the equatorial plane. The disk confines the fast wind to flow along the polar axes of the system, creating expanding shells along the polar axis. The shell is cleared of material by the wind, allowing the star to directly illuminate the walls of the shell and creates the visible reflection nebulae.

A number of observations support the model of an equatorial disk. Ney *et al.* (1975) have reported that the optical emission is highly polarized at a position angle normal to the lobes, consistent with reflection of starlight from the central source. The obscuration of the central source points to a higher density in the equatorial plane. Several observers have reported evidence of a disklike structure. Nguyen-Q-Rieu, Winnberg, and Bujarrabal (1986) mapped the NH_3 and the J = 21 - 20 line of HC_7N in AFGL 2688 with 4" resolution. They found the NH_3 emission to be from the region between the optical lobes, with a size of 2"x12" with the long axis perpendicular to the polar axis. The emission is distributed in two maxima about the center, implying a toroidal structure. Kawabe *et al.* (1987) have reported CO J = 1 - 0 emission centered between the optical lobes, unresolved in the direction parallel to the polar axis, but extended perpendicular to the polar axis of the system with a size of 20-25". They also observe absorption toward AFGL 2688, indicating that the system is surrounded by a cool cloud of CO as well.

Bieging and Nguyen-Q-Rieu (1988) mapped the HCN emission in AFGL 2688, and found the emission to be extended roughly perpendicular to the polar axis of the system. The velocity structure observed implies a rotation of the toroid of approximately 1.2 km s^{-1} at a radius of 3!75 or $5.6 \cdot 10^{16}$ cm (assuming a distance of 1 kpc). Nguyen-Q-Rieu and Bieging (1990) observed the spatial distribution of $H^{13}CN$, HC_3N, and SiS in AFGL 2688. The molecular envelopes were seen to be elongated E-W, roughly aligned with the equatorial axis.

The near-IR images here also support this general model. The main lobes of reflected light are the dominant structure. The fact that the peak separations are smaller at the longer wavelength implies that the extinction within the source is higher closer to the center of the nebula, where the expanding disk will obscure some emission from the reflection nebula. The emission detected from the faint lobes to the east and west of the nebula in the equatorial plane may be either light scattered from the central star, or thermal emission from dust in an equatorial disk.

2.7.4 Conclusions: AFGL 2688

1. The PPN AFGL 2688 was imaged at J, H, and K. The overall structure in these images is very similar to the optical image, with a bright northern lobe and fainter southern lobe. However, in the Br γ and K image, fainter lobes are observed in the equatorial plane of the system, at equal distances to either side of the main axis of the nebula. This emission, along with the main lobes, is continuum emission in the spectral region covered by the K filter. Also, a faint outer halo is observed which envelopes all the lobes and is roughly elliptical.

2. The detailed structure of the lobes is different at J, H, and K, with the lobe peaks having a smaller separation, and the lobes a larger size (as measured by the peak-knee distance) for larger wavelength. The Br γ and K filter images are nearly identical, with no significant spatial variations in flux intensity detected.

3. The observations presented here are consistent with the general model for AFGL 2688 of an equatorial high density region confining the outflow of gas to be along the polar axis of the system.

2.8 M 2-9

The PN M 2-9 (the "Butterfly Nebula") is a bipolar nebula that is classified as "butterfly" (Balick 1987) or "bow tie" (Zuckerman and Gatley 1988). It is a member of a class of objects (including AFGL 2688) that are considered precursors to the PN stage. At optical wavelengths, M 2-9 is a highly symmetric nebula, with two conical shaped extensions to either side of the center of the nebula, with the major axis of the system oriented N - S and extending approximately 20" in both directions. There is also a bright core located at the center of the nebula. The structure of the nebula has changed significantly from the period 1952 to 1972 (Allen and Swings 1972), with several of the condensations in the nebula having moved by several arcsec, and a brightening in the wings and perhaps the core as well. The nebula has also been seen to change its appearance on timescales of 2-4 years (van den Bergh 1974, Kohoutek and Surdej 1980, Aspin and McLean 1984), with knots of emission in the nebula brightening or fading.

A number of factors point to its classification as a PPN. The central star type of B1 (Calvet and Cohen 1978) places it at the beginning of the sequence of nuclei of PN. The high density core and the unusual nebular shape also point toward an object evolving into a PN. Its highly variable structure and magnitude show that it is a rapidly evolving object. Finally, the strong infrared continuum observed is common to many objects considered to be PPN.

The IR emission from the nebula is mainly concentrated in the bright core. The near-IR spectral structure resembles that from a 800K blackbody (Allen and Swings 1972). Near-IR emission at J, H, and K was detected and imaged over the entire area of the optical nebula by Aspin, McLean, and Smith (1988). The emission in the lobes at J is similar to the optical, with bright knots visible.

2.8.1 Observations: M 2-9

The PN M 2-9 was observed at 8.8 and 9.8 µm on April 30 - May 4 1991 with MIRAC on the Steward Observatory 1.5 m telescope. For these observations, the long dimension of the array was oriented N-S, along the long axis of the nebula. Six channels were in operation, so a 6x32 section of the array was being sampled. The final image at each wavelength was constructed from 50-60 individual 20 sec. (on-source) integrations. The chop throw was 25" to the west, at 10 Hz, and the nod beam was 30" to the south.

2.8.2 Results and Discussion: M 2-9

Calibrated contour images are presented in Figure 2.43. The mid-IR emission from M 2-9 is in general very compact, with most of the flux coming from the core of the nebula near the central star. The total flux detected from the central source is consistent with previous large beam observations, indicating that there is not significant mid-IR flux coming from the lobes of the nebula. This is consistent with previous near-IR observations by Allen and Swings (1972), who determined that at least 90% of the 2 μm flux originates from within 3" of the core. Table 2.13 gives a summary of the photometry results from the MIRAC observations.

Table 2.13 Photometry of M 2-9

	Flux (Jy)		
Wavelength (μm)	These Observations	Previous Obs.[3]	1σ U.L. to lobe flux (Jy/arcsec^2)
8.8	31.2	35[1]	.029
9.8	36.0	37[2]	.011

[1] 8.6 μm, Cohen and Barlow 1974.
[2] 10.8 μm, Cohen and Barlow 1974.
[3] Fluxes adjusted for magnitudes of α Boo given in Table A6.1.

The agreement of the current flux measurements to previous results shown in the above table indicates that the IR flux from the core has not significantly changed since the earlier measurement. This is in contrast to the rapid changes in the optical appearance of the lobes above and below the central core.

2.8.2.1 Size and Shape of M 2-9

Evidence for extended emission of the core of M 2-9 at near-IR wavelengths has been previously reported from speckle interferometry (Dyck

1987). The source is reported to be partially resolved, with FWHM sizes of !2 and !09 at K and L at a PA of 90°, and a FWHM size of !13 at L and a PA of 0°.

The nebular images presented here show the source to be compact and centered on the bright optical condensation at the center of the nebula. However, the nebular images are significantly more extended than the point source α Boo. This can be seen more clearly from the source profiles, shown in Figure 2.44. A profile has been taken in the direction that shows the greatest extension in the M 2-9 images, at a PA of 62°, measured from a line passing through the center of the nebula S-N, 62° CCW (towards the east). The nebula is larger at both wavelengths, with source FWHM sizes of 3!2 and 2!6 for 8.8 and 9.8 µm, respectively, for M 2-9, compared to 2!0 and 2!2 for the 8.8 and 9.8 µm images of α Boo.

These source profiles show that the size of M 2-9 is larger at 8.8 µm than at 9.8 µm. If the emission is due to thermal emission from a single population of grains, one would expect that the size would increase with longer wavelength. The FWHM size of a point source should also be slightly larger at longer wavelengths, further increasing the size of the longer wavelength image. This effect is seen in the profiles of α Boo, which is slightly larger at 9.8 µm than at 8.8 µm.

The mid-IR emission from M 2-9, however, is most likely not from a single population of grains. The *IRAS* Low Resolution Spectra (LRS) of M 2-9 shows that there is emission from UIR features at 7.7, 8.6, and 11.3 µm (Volk and Cohen 1990). Our 8.8 µm filter samples the emission from the 8.6 µm feature as well as from the broad wing of the 7.7 µm feature. The 9.8 µm filter samples the continuum emission between the UIR features at 8.6 and 11.3 µm. The larger image at 8.8 µm suggests that the UIR feature emission is more spatially extended than the mid-IR continuum emission. This is consistent with observations of other more evolved PN where the UIR emission has been seen to be more extended than the continuum emission, such as BD+30°3639 (this work) and NGC 7027 (Aitken and Roche 1983, Tresch-Fienberg 1985).

2.8.2.2 Structure of M 2-9

As in other BP nebulae, the structure of M 2-9 is thought to consist of a equatorial toroid that has confined the outflow into two opposing lobes (see discussion in the introduction of section 2.7). Evidence for the existence of this equatorial structure has been seen by Aspin, McLean, and Smith (1988) who detected a reddened structure in their near-IR images that was oriented roughly perpendicular to the major axis of the system.

The mid-IR emission seen here in M 2-9 may therefore be related to this inner disk that is confining the expansion of material into the bipolar lobes. The direction of largest extent of the 8.8 and 9.8 µm images presented here is roughly aligned with the equatorial plane of the system. Figure 2.45 shows an Hα image of M 2-9 from Balick (1987) with the overlaid contour lines of the 8.8 μm image, showing the alignment of the system.

2.8.3 Conclusions: M 2-9

1. Mid-IR imaging of the core of M 2-9 have shown the emission to be concentrated near the core of the nebula, consistent with previous observations. The images presented here show the source to be slightly extended in a direction roughly perpendicular to the major axis of the nebula.

2. The emission at 8.8, which samples UIR features present in the spectrum of M 2-9, is more spatially extended than the emission at 9.8 μm which samples the continuum emission. This is consistent with the UIR features being emitted by a second population of carriers that is spatially distinct from the population of grains responsible for the mid-IR continuum emission.

3. These observations of a structure extended in the equatorial plane of the system provide evidence for a circumstellar disk as predicted in models of bipolar nebula formation. This disk-like structure is much more compact than the structures detected previously in the near-IR.

2.9 Comparison of the Planetary Nebulae Properties

The planetary nebula observations presented here cover a wide range of nebular types, ages, and morphologies. The PN presented here have been grouped according to their IR properties. The four groups discussed are as follows:

1. The "IR-active" nebulae, including BD+30°3639 and J 900. These are carbon-rich nebulae, with a C/O>1. These PN are characterized by strong near- and mid-IR continuum emission in excess of that expected from the star and the nebular gas alone. The nebulae show strong UIR emission in all the usual UIR bands. The nebula NGC 7027 is also included in this category.
2. The moderately carbon-rich nebulae, including IC 418. The previously studied PN NGC 6572 is also in this class. These nebulae have a C/O≈1, and show weak UIR and continuum emission in the near- and mid-IR. These nebulae also have a spectral feature near 11 µm attributed to SiC emission.
3. The "IR-quiet" nebulae, including NGC 2392 and NGC 6543. These nebulae typically have C/O<1, and display little or no excess near- or mid-IR continuum emission. There is usually no evidence of UIR feature emission.
4. Protoplanetary nebulae, including AFGL 2688 and M 2-9. These PPN are bipolar nebulae with near- and mid-IR continuum emission attributed to

dust, as well as UIR feature emission. The nebulae have a bright mid-IR core of emission, with near-IR emission from the lobes. AFGL 2688 has little near-IR flux from the core region, whereas M 2-9 has strong near-IR emission from the core.

This grouping of nebulae is similar to that of Lenzuni, Natta, and Panagia (1989) whose classes of C2 = Carbon rich, C1 = Moderately carbon-rich, and O = Oxygen-rich correspond to the groups 1, 2, and 3 presented here.

2.9.1 BD+30°3639, J 900, and IC 418

These three nebulae are all classified as carbon-rich, young PN, with IR excess emission due to dust. They are also morphologically similar, having an overall circular or ellipsoidal appearance, with two symmetric lobes of emission superimposed on a ringlike structure. Also included in this class of objects are the well-studied PN NGC 7027 and NGC 6572.

Continuum emission from dust has been detected in all of these nebulae at both near- and mid-IR wavelengths. The near-IR emission and continuum mid-IR emission is in general confined to the ionized region of the nebulae, as defined by the optical and high-resolution radio continuum images of the nebulae. Detailed comparison between the images often shows small differences, however, which may indicate that the dust has a slightly different location. For example, in the images of IC 418 presented here, the emission is more extended at K than at J, with a different distribution in the lobes.

Emission from spectral features in the near- and mid-IR often show distinct differences from the continuum emission. This has been demonstrated before for other PN. In NGC 7027, Woodward *et al.* (1989) concluded that the UIR feature emission at 3.28 and 3.4 µm is spatially distinct from the continuum emission, being slightly more extended than the continuum. The UIR emission was also determined to extend beyond the ionized region of the nebula, as defined by the Br α flux at 4.052 µm. The UIR emission in the mid-IR is also spatially distinct and located on the outer edge of the ionized zone (Aitken and Roche 1983, Arens *et al.* 1984).

In BD+30°3639, there is evidence of the 3.28 µm UIR feature being spatially distinct from the ionized zone, as defined by the Br γ emission (Roche 1989). The UIR features at 7.7, 8.6, and 11.3 µm have also been found to be distinct from the dust continuum and ionized regions of the nebula (Bentley *et al.* 1984, Hora *et al.* 1990, this work). The distribution of the UIR emission is similar in the different UIR features at 3.3, 7.7, and 11.3, being in general more extended than the continuum and ionized regions.

The PN in group 2 also show spatial variations of the components of IR emission. Previous studies of the nebula NGC 6572 have shown distinct variations in its mid-IR flux as a function of wavelength, with evidence for extended emission in the UIR feature at 11.3 µm (Hora *et al.* 1990). The PN IC 418 and NGC 6572 both exhibit a feature in the mid-IR attributed to SiC emission. IC 418 is unique in that the emission from this feature seems to originate from *within* the ionized region, as defined by the optical and near-IR observations, with mid-IR emission detected from the position of the central star.

Cohen *et al.* (1986) found strong correlations between emission in each of the UIR bands, indicating a single class of chemical species is responsible for the emission. The studies of the spatial distribution of UIR emission have supported this. The similarities in the distribution of the UIR feature emission imply a common carrier, while the differences between the UIR features and the continuum IR emission suggest that a second population of emission species is responsible for the IR continuum.

The characteristics of the IR emission from these PN can be understood in terms of the varying carbon abundance in the nebulae, as indicated by the C/O ratio. In the study by Cohen *et al.* (1986), a strong correlation was found between the fraction of the nebular far-IR emission emitted in the 7.7 µm UIR feature and the C/O ratio. Their figure is reproduced here in Figure 2.46. Nebulae with high C/O ratios, such as NGC 7027, BD+30°3639, and J 900, have strong UIR features. Nebulae with low C/O ratios, such as IC 418 and NGC 6572, have much weaker UIR emission, and the mid-IR spectra contain features attributed to SiC.

This correlation can be understood as follows (Salpeter 1974, Frenklach, Carmer, and Feigelson 1989). The CO molecule is assumed to be stable in stellar atmospheres, and would contain all of the available atoms of the least abundant element. Therefore, for oxygen-rich nebulae, all the carbon will be locked up in CO and none would be available to condense out. For nebula with C/O>1, all the oxygen is locked into CO, and carbon would be available to condense into particles, the total amount depending on the size of the C/O ratio. Particles will form in the atmosphere and circumstellar region of an evolving AGB star when the temperature cools sufficiently, below approximately 3000K. SiC will be the first particles to form where there is sufficient Si abundance, and SiC may serve as nucleation sites for amorphous carbon particles and PAH formation. The PAH molecules will form at a much lower temperature, in the narrow temperature range of 900-1100K.

The correlation between C/O ratio and $f(7.7\mu m)$ seen in Figure 2.46 from Cohen *et al.* (1986) points to a carbonaceous origin for the UIR features, and implies that the formation of the UIR carriers is sensitive to the carbon abundance in the circumstellar region.

The spatially resolved observations of the IR emission support a model where the carriers of the UIR features are different than the source of the continuum dust emission, because of the different spatial distributions. In the nebulae studied here, the UIR emission is more extended than the continuum dust emission, although it is certainly overlapping the ionized zone and may be contained within it. The fact that the emission is more extended could be either because of the order of UIR carrier formation and expansion from the central star, or because of the destruction of the UIR carriers on the interior edge of the shell from absorption of UV flux from the central star.

All the characteristics described above are consistent with the UIR emission being from a mixture of PAH molecules. They have characteristic bands in each of the UIR feature emission regions, and although no one PAH has been observed to match the spectrum of an astronomical source, the most likely case is that a mixture of PAHs, at various temperatures, molecule sizes, and states of hydrogenation are responsible for the emission in each object. Frenklach and Feigelson (1989) have shown in modelling the conditions in carbon-rich circumstellar envelopes that PAH molecules can form under the expected conditions. The PAH molecules will be susceptible to dissociation by absorption of UV photons (Duley 1987), with smaller molecules being easiest to dissociate. This may explain why the UIR emission is located on the outer edge of PN -- they may be destroyed by UV flux on the inner side of the PN shell. There is other evidence of an anticorrelation of UIR emission to objects with high UV flux (Roche 1987, Puget and Léger 1989).

2.9.2 NGC 2392 and NGC 6543

These two nebulae are grouped together because of their similar near-IR emission characteristics, since in other respects they are quite different. NGC 6543 is a type "peculiar" PN, simply because it is a morphologically unique object that does not fall easily into any of the categories containing highly symmetric nebulae. NGC 2392 has a simpler shape, roughly elliptical, although it also has its complexities, having a double shell, surrounded by filaments of emission and enclosed in a larger halo.

The two nebulae are similar in their near-IR emission in that no IR excess is detected at K in broad-beam measurements (Willner, Becklin, and Visvanathan 1972, Cohen and Barlow 1974). The observed emission could be accounted for by recombination emission from the ionized region of the nebula and flux from the central star. In addition, no evidence of warm dust emission in the mid-IR is detected. The *IRAS* LRS data presented by Volk and Cohen (1990) show little continuum emission from dust, and no UIR feature emission. NGC 6543 does show several forbidden line transitions, such as the [S IV] line at 10.5 µm, and the [ArIII] line at 9.0 µm. The lack of UIR features is consistent with C/O ratios for NGC 2392 and NGC 6543 of .58 and 1.0 (Pottasch 1983), respectively.

One of the most unusual characteristics of the IR emission is shown in the data presented here, that the near-IR emission in these nebulae, instead of being distributed roughly the same as the optical and radio continuum emission, is highly concentrated in a particular area of the nebula, compared to the nebular recombination emission. The amount of excess near-IR emission in these regions is small compared to the total flux in the nebula, so if this is a sign of excess emission from dust, this could easily have been missed in broad-beam photometry of the PN at these wavelengths. This unexpected concentration of the near-IR flux was seen in both H and K bands in both of these nebulae. If this is emission due to hot dust, its distribution is quite different from that of the gas in the nebula.

2.9.3 AFGL 2688 and M 2-9

The two bipolar nebulae, M 2-9 and AFGL 2688, are morphologically very similar. Both nebulae have been postulated to be approximately 1 kpc distant (although estimates vary widely) and are roughly the same angular size, so it would seem that they are possibly at a similar point in their evolution. However, the objects have quite different characteristics in other respects. For example, the optical spectrum of AFGL 2688 shows Na I D lines in emission, and strong [S II] emission is detected. Bands of SiC_2 are seen in absorption, which have been observed in carbon stars of high carbon abundance (Humphreys *et al.* 1975, Cohen and Kuhi 1977). The spectrum has been characterized as a F5 Ia supergiant, with some anomalous features superimposed.

At wavelengths longward of 4100 Å, the continuum of AFGL 2688 is depressed and strong anomalous absorption is seen, comparable to what has been yseen previously in the spectra of carbon stars (Crampton *et al.* 1975). The absorption is attributed to bands of C_3, and the Swan bands of C_2 are seen in emission. The observed light from both lobes is highly polarized (50% or larger in the optical), indicating that the lobes are reflection nebula illuminated by the obscured source (Ney *et al.* 1975). The lobes are fairly featureless, with no distinct filaments or small clumps of emission. The source has shown variability, increasing in brightness between 1920 and 1977 by approximately 2 magnitudes, and has increased in size by ~ 1" (Gottlieb and Liller 1976).

On the other hand, the optical spectrum of M 2-9 is characterized by numerous FeII, [FeII], and [FeIII] emission lines. Strong emission lines of [OIII], [OI], He I and the Balmer series are seen in the core, along with weaker emission from lines of [NeIII], [SIII], [SII], SiII, and [NiII] (Walsh 1981). The central star has been tentatively identified as B1 (Calvet and Cohen 1978). Distinct knots of emission are present, which have been seen to change on timescales of 2 to 20 years, implying large velocities and rapid evolution (Allen and Swings 1972, van den Berg 1974, Kohoutek and Surdej 1980, Aspin and McLean 1984). The polarization of the optical emission is lower, approximately 16% for permitted lines and continuum, and 2% for forbidden lines, implying that ~ 60% of the continuum and permitted line emission and ~ 10% of the forbidden line emission from the lobes is scattered emission from the core (Schmidt and Cohen 1981, Aspin and McLean 1984).

No continuum 5 GHz emission has been detected from AFGL 2688, implying the absence of an ionized region (Ney *et al.* 1975). However, radio continuum emission has been detected at several wavelengths from the compact core of M 2-9, and from the lobes at 20 cm (Kwok *et al.* 1985). The 20 cm emission was essentially coincident with the core and the bright knots of emission seen in the optical images of the lobes. Molecular line radiation has been detected in both nebulae. Kawabe *et al.* (1987) have mapped the CO J = 1 - 0 emission from AFGL 2688 and found three structures: a central compact core elongated in the equatorial plane of the system and centered on the IR core, spurs of emission from the outer edge of the northern optical lobe, and blueshifted emission along the polar axis of the system. Structures perpendicular to the polar axis in the equatorial plane have also been detected in NH_3, HC_7N, and HCN (Nguyen-Q.-Rieu, Winnberg, and Bujarrabal 1986, Bieging and Nguyen-Q.-Rieu 1988). CO J = 1 - 0 and J = 2 - 1 emission has been detected in M 2-9 (Bachiller *et al.* 1988, Bachiller, Martin-Pintado, and Bujarrabal 1990). The emission is concentrated in the core, and the J = 2 - 1 emission is unresolved in a 13" beam.

Both of the BPN presented here show strong IR emission. The nebula AFGL 2688 emits most of the near-IR emission from the lobes, with no detectable emission from the central source. The lobe emission is 20% polarized, indicating a significant contribution from scattered light from the central star (Ney *et al.*1975). In M 2-9, however, the core emits strongly in the near-IR, with the emission from the lobes not detected until the IR camera observations of Aspin, McLean, and Smith (1988). The mid-IR emission is centrally concentrated in both sources, with the emission in M 2-9 extended primarily perpendicular to the equatorial plane, and the emission in AFGL 2688 extended slightly in both the polar and equatorial directions (Deutsch 1990).

The mid-IR emission in both objects shows at least two different components: thermal continuum emission and UIR feature emission. In M 2-9, the sizes of the images presented here give evidence of a different spatial distribution of the UIR emission, with the UIR emission more spatially extended than the continuum emission.

The morphologies of these nebulae are perhaps a result of a similar mechanism, where a fast stellar wind has been confined by a circumstellar disk to flow primarily along the polar axis of the system, and has created roughly symmetric lobes of emission. This does not suggest, however, that these nebulae are necessarily at a similar point in an evolutionary sequence. The differences seen between these nebulae and other BPN are in part due to the differences in the central star and its mass loss history and current rate.

Many of the observational differences between M 2-9 and AFGL 2688 can be understood considering the central stars of the nebulae. The hotter star in M 2-9 results in the high excitation emission observed, both emitted from the nebula and scattered from the central star. The star in M 2-9 is also responsible for the radio continuum emission detected from the ionized gas (Kwok *et al.* 1985). The excitation of optical emission lines near the source causes the central emission in M 2-9, whereas in AFGL 2688 there is no optical emission centered between the lobes.

Another nebula in this class is NGC 6302, a bipolar PN which has two bright lobes of emission on opposite sides of the central star, similar to AFGL 2688 and M 2-9. NGC 6302 is considered to be at a later stage of evolution than AFGL 2688, since it is larger, less dense, and more highly ionized. Lester and Dinerstein (1984) mapped the source at 2.2 and 10.2 μm and found that most of the emission is concentrated between the two optical lobes, with the emission more extended in the equatorial plane of the system. They conclude that the observed IR disk is not the structure responsible for confining the flow, since the estimated density is not high enough to keep it from being disrupted by the stellar wind at the expected velocity and mass loss rate. Instead, they suggest that the observed disk is either the expanded remnant of the toroid that confined the outflow, or it is the material remaining after the biconical wind has blown out the material in the direction of the flow.

The near-IR structures observed in M 2-9 and AFGL 2688 are similar to that observed in NGC 6302, since they are much larger than the expected size of the confining toroid. In AFGL 2688, the equatorial emission is well separated from the central region, implying that it is no longer responsible for confining the outflow. The mid-IR structures, however, are centrally concentrated and barely resolved in both objects, so it is possible that the mid-IR emission is directly from the structure that is confining the outflow into bipolar lobes.

It should be mentioned that the identification of these objects as proto-planetary nebulae is not yet completely established. Balick (1989) has suggested that M 2-9 shares more similarities with objects such as Eta Car, or the nova RR Tel, some symbiotic stars, or the P Cyg star AG Car. The observational characteristics of AFGL 2688 have also been compared to some Herbig Haro objects, although its classification as a protoplanetary is now fairly well established.

2.10 Conclusion

The first part of this dissertation provides a description of MIRAC capabilities and performance. The camera is a significant advance over the previous generation of mid-IR array cameras in sensitivity, format, and ease of use, and its performance is on the same level as similar state-of-the-art detector cameras currently being operated. MIRAC is an extremely versatile instrument that has a wide range of possible applications, from the study of star formation regions, planetary nebulae, and circumstellar disks to the investigation of extragalactic nuclei and star formation in galaxies.

The observations presented here have shown that infrared imaging of PN can be a very useful technique in gaining understanding of these objects. Data on PN and PPN of vastly different morphological types and evolutionary stages have been presented here, showing a wide range of IR characteristics. Important information has been revealed by this study of the dust distribution within the nebula.

The observations of BD+30°3639 presented here have confirmed the results of previous investigations that have shown the images taken in the UIR feature wavelengths to be slightly more spatially extended than the continuum emission. This has been the case in other PN where the spatial distribution of the UIR emission has been studied, such as NGC 7027, and J 900 in this study. The location of the UIR features on the outer edge of the ionized zone indicates that the UIR emission carriers may be destroyed on the inner edge of the nebular shell.

In IC 418, the near-IR structure, although similar to the optical images, shows a trend of larger source size with increasing wavelength, due to the contribution of dust emission. The H and K images show evidence of emission from an extended halo around IC 418 of approximately 40". The spatial distribution of the mid-IR emission is significantly different from the distribution of the near-IR or optical images. The 11.7 µm emission peaks within the ring of the nebula as defined by the near-IR images, showing that the flux is coming from within the ionized zone. A central peak of emission is seen, in excess of what is expected from the central star or outer nebula shell, indicating emission from near the central star.

Both of the PN NGC 6543 and NGC 2392 have a small IR excess in the near-IR, but the spatial distribution has been seen in the images presented here to be very non-uniform. Both have emission excesses at particular locations in the nebular shells. These locations are at the intersection points of the multiple shells of the nebulae, which suggests some density enhancement in these regions. Further study of these nebulae must be done to determine if the source of the excess emission regions is due to continuum emission from hot dust, or from line emission from the ionized gas.

In the bipolar nebulae AFGL 2688 and M 2-9, evidence for structures in the equatorial planes of the systems have been detected in the near- and mid-IR. These structures are thought to be responsible for directing the outflow from the central star to be primarily in opposing directions, along the poles of the system. In AFGL 2688, the equatorial emission is seen in the K and Br γ filters. In M 2-9, the mid-IR flux shows a bright central core which is extended in the equatorial direction. The image taken in the filter which samples the UIR feature emission is larger in spatial extent, consistent with the behavior of UIR emission in the other PN studied here. The detection of the equatorial structures in both of these nebula have confirmed an important element in the models of bipolar nebula formation.

In summary, infrared cameras such as MIRAC and the Hg:Cd:Te systems available at Steward Observatory have proved to be very effective in studying the infrared emission from planetary nebulae. In the observations presented here, the images have revealed important information on the spatial distribution of dust and ionized gas in the nebulae. Using MIRAC, we will be able to extend this study to many other nebulae, as well as a wide variety of other astronomical applications.