IC 4406: A RADIO-INFRARED VIEW

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ABSTRACT

IC 4406 is a large (about 100″ × 30″) southern bipolar planetary nebula composed of two elongated lobes extending from a bright central region where there is evidence for the presence of a large torus of gas and dust. We show new observations of this source performed with IRAC (Spitzer Space Telescope) and the Australia Telescope Compact Array. The radio maps show that the flux from the ionized gas is concentrated in the bright central region and originates in a clumpy structure previously observed in Hα, while in the infrared images filaments and clumps can be seen in the extended nebular envelope, the central region showing toroidal emission. Modeling of the infrared emission leads to the conclusion that several dust components are present in the nebula.

Subject headings: infrared: stars — planetary nebulae: individual (IC 4406) — radio continuum: stars

1. INTRODUCTION

IC 4406 is a well-studied southern planetary nebula. It has been imaged with several telescopes at different wavelengths. Near-infrared images show two H2 lobes (Storey 1984) orthogonal to the nebula’s major axis and ~25″ away from each other. These peaks are approximately coincident with the two blobs observed in Hα + [N ii] and [O iii] (Sahai et al. 1991), interpreted as indicative of the presence of a dense equatorial torus of dust. The optical images show a central ionized region about 32″ in diameter. CO maps show the presence of a collimated high-velocity outflow in the polar direction, with [CO]/[H2] ≈ 5 × 10⁻⁶ and a total molecular mass in the range 0.16−3.2 M☉ (Sahai et al. 1991). Hubble Space Telescope (HST) WFPC2 images in [N ii], Hα, and [O iii] have revealed the existence of an intricate system of dark lane features, which led to the name “Retina Nebula” for this object (O’Dell et al. 2002). The nebula appears to be chemically homogeneous, as Corradi et al. (1997) found no evidence of radial variation for He, O, N, Ne, and Ar. Cox et al. (1992) have detected several C-rich features at millimeter wavelengths, such as CN, HCO+, HCN, and HNC, which indicate the nebula is C-rich, although a C/O ratio of 0.6 is reported by Cohen & Barlow (2005).

IC 4406 is a relatively low electron density nebula. Values in the 400–2000 cm⁻³ range have been estimated using several different optical and infrared lines, with values derived by [S ii] and [O iii] doublets matching around 540 cm⁻³ (Liu et al. 2001; Wang et al. 2004). Its central star has a He ii Zanstra temperature of 96,800 K (Phillips 2003), and its distance is probably around 1.6 kpc (Sahai et al. 1991), although some authors claim it may be overestimated (O’Dell et al. 2002).

Gruenwald et al. (1997) have modeled IC 4406 with a three-dimensional photoionization code and fit many observed line intensities assuming there is a torus around the central star. They find as the best fit a central star temperature of 8 × 10⁴ K, luminosity of 400 L☉, torus density of 1500 cm⁻³, and nebular density of 100 cm⁻³.

In general, comparisons of infrared images of planetary nebulae, which trace the molecular gas and warm dust emission, to optical line images, which trace the ionized gas, have shown the presence of similar structures (Latter et al. 1995), leading to the conclusion that molecular and ionized gas spatially coexist in planetary nebulae, as well as dust grains, despite the different physical conditions these components are presumed to survive in. We have observed IC 4406 in the radio range to inspect the distribution of the ionized gas in its envelope and in the infrared to check for emission from the equatorial dust and molecular gas.

In § 2 we explain how we performed our observations and reduced the data. In § 3 we show our results and, in particular, in § 3.1 we explain how we modeled the emission in the radio and infrared ranges; § 3.2 compares our model results to the nebular parameter values obtained directly from the observational data. In § 4 we summarize our work.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Radio Observations

Radio observations were performed simultaneously at 4.8 and 8.6 GHz at the Australia Telescope Compact Array (ATCA) on 2005 November 24 (17:00:00–08:00:00 UT) and December 11 (15:30:00–02:00:00 UT). The November run was performed with the array in the 1.5C configuration, while for the December run the configuration was 6.0A. The adopted configurations are both linear but with different antenna positions, giving maximum baselines of 4500 m (1.5C) and 5939 m (6.0A) and minimum baselines of 77 m (1.5C) and 337 m (6.0A). The precalibration of the array was performed using 0823−500, while the absolute flux calibrator was 1934−638. Another target was also observed during our two runs, and the total on-target time was about 7 hr for each of the two. The phase calibrator chosen for IC 4406 was 1431+134 away from the target. The data were reduced with MIRIAD, following a standard reduction procedure as recommended in the MIRIAD User’s Guide. The data from the two runs were combined.
into one data set, obtaining \( \nu - \nu \) coverage from 0.9 to 96 k\( \lambda \) at 4.8 GHz and from 1.5 to 172 k\( \lambda \) at 8.6 GHz. These correspond to an angular resolution of 2.2\( '' \) at 4.8 GHz and 1.2\( '' \) at 8.6 GHz, while the largest observable structures (largest angular scale) are 230\( '' \) and 140\( '' \), respectively. Such a setup suits the need to collect all the radiation from the target, whose maximum size, as previously mentioned, is about 100\( '' \).

After combining the data sets from the two runs, we created a dirty map from the \( \nu - \nu \) data set with the task INVERT. The image size was set to 1024 pixels in the X band (8.6 GHz), but a larger size (2048 pixels) was necessary for the C band (4.8 GHz) in order to include a secondary source in the field and allow subsequent proper cleaning of the map. The cell size was set to 0.7\( '' \) at 4.8 GHz and 0.4\( '' \) at 8.6 GHz so that the beam would be extended over approximately three cells. We set the INVERT parameter options to double. This allows us to obtain a map from the multifrequency data set without averaging in frequency and to create a beam image with a size twice as large as the map, thus improving the performance of the cleaning algorithm. To combine sensitivity to extended emission with sidelobe suppression, we used Briggs’s weights, leaving the parameter sum unset and ROBUST = 1. In our maps, smaller values of the ROBUST parameter determine a worse signal-to-noise ratio. This setting gave a beam of 4.122\( '' \) \times 3.089\( '' \) at 4.8 GHz and 2.669\( '' \) \times 2.060\( '' \) at 8.6 GHz.

We then used the task CLEAN to deconvolve the dirty map from the synthetic beam. We set a gain of 0.1 and minpatch of 257 for each CLEAN cycle, letting the task choose the proper algorithm, which at both frequencies was the CLARK one. We performed 3000 CLEAN iterations to reach the theoretical rms noise, as given in the output by INVERT.

As at both frequencies our target appears to be quite resolved, the estimate of its flux has been performed on naturally weighted maps obtained using tapering (INVERT: fwhm = 15 for both frequency bands). This results in larger weights for the visibility points corresponding to short baselines, then limits the chance to miss extended flux in the final map, although it possibly produces higher noise. Since the error in our measurement is primarily determined by the error in the absolute flux calibration, tapering is not an issue.

With such a procedure we measure 103.3 \pm 0.3 mJy at 4.8 GHz and 92.5 \pm 0.4 mJy at 8.6 GHz, which, taking into account a typical 5\% error in the absolute calibration, gives us the following final measurements: 103 \pm 5 mJy at 4.8 GHz and 92 \pm 5 mJy at 8.6 GHz.\(^2\) These values agree with the previous measurements in Milne & Aller (1975), performed with single-dish telescopes, and therefore we can conclude that no flux is missing.

\(^2\) The final error has been estimated as \( \sigma = [\text{rms}^2 + (\sigma_{\text{cal}}F)^2]^{1/2} \), where \( \sigma_{\text{cal}} \) is the 5\% relative error in absolute calibration and \( F \) is the measured flux density.
direction; at 10% of the peak level, the size of the emitting region is restricted to $32'' \times 32''$. At 8.6 GHz, 10% of the peak level gives a size of $36'' \times 40''$, in agreement with its $3\sigma$ level size. The maps do not show any north-south blobs of emission. What is seen is a clumpy emitting region that resembles what is observed by HST in Hγ (O’Dell et al. 2002). Using the fluxes that we estimate at the two frequencies, we can calculate a spectral index $\alpha = -0.19 \pm 0.09$, which matches the expected value of $-0.1$ for an optically thin radio shell.

Figure 3 shows the IRAC images of the nebula. To properly view the central equatorial area, the images were plotted with a logarithmic scale with the peak flux and $3\sigma$ of the image as thresholds. Channel 1 and especially channel 3 resemble the H$_2$ emission image in Storey (1984), probably because the $v = 0-0$ S(7) line at 5.51 $\mu$m falls within the 5.8 $\mu$m band and several H$_2$ lines may contribute to the 3.6 $\mu$m image (Hora et al. 2004). Channel 4 clearly shows emission from the torus of dust surrounding the central star. Its size is about $28'' \times 20''$, elongated in the north-south direction, and the angular distance between its peaks is about $14''$ (the north peak is found at R.A. = $14^h22^m26.05^s$, decl. = $-44^\circ08'54.64''$, and the south peak is at R.A. = $14^h22^m26.31^s$, decl. = $-44^\circ09'08.14''$, with a position angle of 168.7$^\circ$). The overall size of the torus matches the approximate size of the nebula in the north-south direction ($\sim 30''$), although its peaks are much closer to the center than the H$_2$ blobs reported by Storey (1984), whose separation can be roughly estimated as $\sim 25''$. This indicates that the torus is partly shielding the molecular gas from the UV radiation from the central star.
Figure 4 is a combination of IRAC channels plotted with linear scale. Despite the lower resolution compared to HST images, IRAC is able to detect the faint emission from the neutral components in the envelope and reveals the structure of the elongated lobes. The IRAC images show filaments at different distances and inclinations from the central star connected to the mass-loss history of the nebula. The filaments that are closer in projected separation to the central star show relatively stronger blue (3.6 μm) emission, which may imply a higher temperature, being intrinsically closer to the central object. The overall structure observed in the envelope corresponds to the assumption that the central torus is the main collimating agent, as confirmed by the superposition of the 8.6 GHz and 8 μm images in Figure 5.

The scaled WFPC2 images match our radio maps at 6 and 3 cm reasonably well. Following Lee & Kwok (2005), we also calculated the expected Hα image from our 8.6 GHz radio map and then an optical depth map (Fig. 6). The optical depth map confirms the clumpy nature of the central region, and it also points to a larger absorption toward the very core of the region, implying that dust can be present even in “close proximity” to the central star.

3.1. The Spectral Energy Distribution of IC 4406

To inspect the dust properties of our target we have collected literature data that, along with our observations, enable us to build the SED. We have retrieved 2MASS (Skrutskie et al. 2006) images (J, H, and Ks) from the 2MASS archive to measure our target’s flux in such bands; the values in the Point Source Catalog neglect the emission from the extended envelope. To estimate the flux and its error, a procedure analogous to that used for IRAC data was applied. In each image four areas were boxed with a polygon, then the mean emission in each polygon was calculated and averaged to obtain the background and its standard deviation was taken as the flux density error for the selected image. The nebula itself was boxed with a polygon around its contour equal to 3σ above the background. The 2MASS fluxes were then converted into UKIRT system J, H, and K magnitudes, so that color correction according to Schlegel et al. (1998) could be performed, adopting $E(B-V) = 0.19$ (Gathier & Pottasch 1988). The IRAS color-corrected data were taken from Sahai et al. 1991. In our modeling we have assumed a central star temperature of 96,800 K (Phillips 2003), a distance of 1.6 kpc, and a luminosity of 170 $L_\odot$ (Sahai et al. 1991).

We have modeled the SED separately for the radio (ATCA and single-dish literature data) and infrared (IRAS, IRAC, and 2MASS) emission. The radio data collected from the literature are listed in Table 2 with their references. For the former we have solved the radiation transfer equation in a spherical shell. The density distribution profile in the shell was determined by fitting the density profile found in Corradi et al. (1997), which gave us a radial variation of $r^{-1.252}$. We introduced this density radial variation in our model shell, and we found as a best fit to the data a density at the inner radius of 730 cm$^{-3}$, an inner radius of 18,000, and an outer radius of 24”, with a fixed distance of 1.6 kpc and an electron temperature of $10^4$ K. This gives us an optically thin spectrum down to 800 MHz, which confirms the status of our target as a fairly evolved object, and it also provides us with an estimate of the ionized gas mass of about 0.22 $M_\odot$. To estimate the free-free contribution from radio to near-infrared wavelengths, in our model we have calculated the Gaunt factor according to Karzas & Latter (1961).

For the infrared range we have used the code DUSTY (Ivezić et al. 1999) to solve the radiation transfer, assuming once again that the nebula is spherical. This simple assumption can provide reasonable constraints on the main properties of the envelope, since asymmetries in the density distribution would mostly affect the...
optical part of the SED, not the mid-infrared/far-infrared region that we are modeling (Sánchez Contreras et al. 2007). DUSTY does not allow the simultaneous treatment of more than one shell, yet its output can be used as input in a second run, thus mimicking the shell structure of the nebula.

One constraint on our model is the optical depth at a specified wavelength, which we can calculate as

$$\tau_{\nu} = 2.03 \times 10^{10} \frac{F_{\nu}}{\theta^2 B_{\nu}(T_d)}, \quad (1)$$

where $T_d$ is the dust temperature, $\theta$ is the angular radius of the nebula in arcseconds, $F_{\nu}$ is the flux density at the frequency $\nu$ in erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$, and $B_{\nu}(T_d)$ is the Planck function at the temperature $T_d$ in erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ (Gathier et al. 1986).

The first attempts to fit the data were done with a standard Mathis et al. (1977) size distribution of the grains, with $a_{\min} = 0.005$, $a_{\max} = 0.26$, $n(a) \propto a^q$, $q = -3.5$, density distribution in the shell as $r^{-3}$ (where $r$ is the shell radius), a chemical composition of amorphous C only, and 0.1 as the optical depth at 0.55 $\mu$m. The choice of an amorphous C-only chemistry is due to the detection of several C-rich features mentioned in § 1.

By a first inspection of the observed data points, it was evident that the data could not be matched by a single dust component. In order to fit several components, we performed our fit in steps, first fitting the lower wavelength data in a DUSTY run reproducing a hot inner shell, then giving the output of this run as input to a second run of DUSTY. We were able to reproduce the observed data assuming the dust envelope is made up of three shells containing hot, warm, and cold dust. The temperature of the cold component thus obtained was used in equation (1) to calculate $\tau$ at 60 $\mu$m. We chose this wavelength because all the flux seems to be due to one emitting component and cirrus contribution is negligible, which is not necessarily true at 100 $\mu$m. Having calculated the optical depth at 60 $\mu$m with equation (1), we checked whether this value matched the one given by DUSTY in its output. This was not the case. Then we used the $\tau_{60}$ to estimate an input optical depth in DUSTY. This led to a mismatch with all the longer wavelength data points. We started changing the cold dust temperature, looking for a combination of $T_d$ and $\tau_{60}$ that would allow a match to the data. We found that it was not possible to reach such a match with the specified set of input parameters, the DUSTY fluxes at larger wavelengths being larger than the observed ones. We then tried to change the density distribution dependence on the radius; exponents such as $-3$, $-1$, and $-0.5$ were tested, but none resulted in a good match to the observations. Our second attempt was to change the grain size; we noted that the presence of larger grains in the model (up to 6.5 $\mu$m) could effectively modify the reproduced data.

Since DUSTY makes use of spherical geometry, we assumed an effective radius of 45”, corresponding to the radius of a circle with the same area as the dust ellipse observed in our IRAC images. The shell relative thickness parameter in DUSTY was calculated to reproduce this angular size. The final set of parameters for our best fit is reported in Table 3. Figure 7 shows the fit components to the observational data points and the combination of the infrared and radio fits.

We note that if in our free-free model we had used the usual radio approximation of the Gaunt factor, around 2 $\mu$m the model would predict a lower level of emission than observed (as can be seen in Fig. 7, where the single emitting components are plotted), which might be interpreted as due to a fourth hotter component of dust missing in the model. Our proper estimate of the Gaunt factor shows how the free-free contribution in the near-infrared is actually nonnegligible and allows us to achieve a good fit to the data points in this range. The larger flux measured in the $K$ band can be explained when we consider that $H_\gamma$ emission has been detected in IC 4406 (Storey 1984) and several lines may fall within the $K$-band filters, along with ionized gas lines such as Br$\gamma$. In fact,
Phillips & Ramos-Larios (2005) and Ramos-Larios et al. (2006) have explained the excess in the $K_s$ band in terms of H$_2$ emission; in particular, the latter show how the $K_s$-band 2MASS image matches the H$_2$ image in Storey (1984).

### 3.2. Nebular Parameters

Our models enable us to estimate such nebular parameters as electron density, ionized gas mass, and dust mass. The dust mass can be calculated from the DUSTY output following Sarkar & Sahai (2006) as

$$M_d = 4\pi R^2 Y \frac{\tau_{100}}{k_{100}}, \tag{2}$$

where $R$ is the inner radius of the emitting shell in cm, $Y$ is the thickness of the shell relative to $R$, and $\tau_{100}$ and $k_{100}$ are the optical depth and absorption coefficient at 100 $\mu$m. We can now use our DUSTY output for $R$ and $\tau_{100}$, which, for the 57 K more external shell, are estimated as $3.6 \times 10^{16}$ cm and $2.34 \times 10^{-5}$; $Y$ is 30 and $k_{100} = 92$ cm$^2$ g$^{-1}$, calculated following Jura (1986). We thus obtain a dust mass of $6 \times 10^{-5} M_\odot$. Our radio model instead gives an electron density of $730$ cm$^{-3}$ and an ionized mass of $0.22 M_\odot$, as mentioned in the previous section.

These values can be compared to those derived by equations that directly use the observed fluxes. From our radio observations it is possible to derive the H$\beta$ flux and electron density, which can then be used to estimate the ionized mass of the nebula:

$$H\beta = \frac{S_{4.8\text{ GHz}}}{(2.83 \times 10^9) \tau^{0.53}[1 + (1 - x)y + 3.7xy]} \text{ erg cm}^{-2} \text{ s}^{-1}, \tag{3}$$

$$n_e = 2.74 \times 10^4 \sqrt{\frac{y^{0.88} H\beta}{e^0.3 t d}} \text{ cm}^{-3}, \tag{4}$$

$$M_{ion} = \frac{11.06d^2 y^{0.88}}{n_e} H\beta \text{ M}_\odot. \tag{5}$$

In equation (5) H$\beta$ is the H$\beta$ line flux in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$, $n_e$ is the electron density in cm$^{-3}$, $t$ is the electron gas temperature in units of $10^4$ K, and $d$ is the distance to the star in kpc.

#### Table 2

| $\nu$ (GHz) | $S_\nu$ (mJy) |
|-------------|---------------|
| 0.843       | 104 $\pm$ 3$^a$ |
| 2.7         | 150 $\pm$ 60$^b$ |
| 5           | 110 $\pm$ 15$^c$ |
| 14.7        | 84 $\pm$ 8$^d$ |

$^a$ Mauch et al. (2003).
$^b$ Milne & Webster (1979).
$^c$ Milne & Aller (1975).
$^d$ Milne & Aller (1982).
In equation (4) \( H_\beta \) is the same as in the previous equation, \( \theta \) is the ionized gas radius as deduced from the 4.8 GHz radio map (we have used a value of 24") in arcseconds, \( \epsilon \) is the filling factor (for which we have used an average value of 0.6), and \( t \) is the same as before. In equation (3) \( S_{4.8 \text{ GHz}} \) is the 4.8 GHz flux density in Jy, 60 is the same as before, \( x \) is He\(^+\)/He = 0.121, and \( y \) is He/\( \sum \) = 0.132, calculated from the abundances in Corradi et al. (1997). Equations (3)–(5) are from Pottasch (1984). We find 0.21 \( M_\odot \), 418 cm\(^{-3}\), and \( 3.09 \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1} \) for the ionized mass, electron density, and \( H_\beta \) flux, respectively, which closely match our radio model’s results.

The dust mass can be estimated according to Pottasch et al. (1984) as

\[
M_{\text{dust}} = \frac{4}{3} \frac{a \rho}{Q_{\nu}} \frac{d^2 F_{\nu}}{B(\nu, T_{\text{dust}})} \text{g.} \tag{6}
\]

Following Jura (1986), we consider 1.1 to be a representative value of the power-law distribution of the emissivity of carbon grains in the infrared. We can thus calculate the dust emissivity at 60 \( \mu \text{m} \) assuming an average grain radius \( a = 10^{-5} \text{ cm} \) and a density \( \rho = 3 \text{ g cm}^{-3} \), which results in \( Q_{60} = 1.107 \times 10^{-3} \). Considering the flux at 60 \( \mu \text{m} \) to be due only to the cold component at 57 K in our best fit, we calculate a dust mass of about \( 2.8 \times 10^{-4} M_\odot \). We also calculate the dust mass of the other emitting components in our fit, but they are negligible when compared to the cold dust; we find \( 5 \times 10^{-11} M_\odot \) (calculated using the 4.5 \( \mu \text{m} \) flux) for the 700 K component and \( 4 \times 10^{-8} M_\odot \) (using the 12 \( \mu \text{m} \) flux) for the 200 K component. The dust-to-gas mass ratio can be estimated as \( M_{\text{d}}/M_\odot = 1.3 \times 10^{-3} \). See Table 4 for a summary of the parameters we have derived.

We note that the cold dust mass value we estimated with DUSTY is 1 order of magnitude smaller than that calculated with equation (6). This could perhaps be due to the approximations intrinsic to both the DUSTY modeling and the derivation of equation (6) (i.e., spherical shape, single-component chemistry, and physical knowledge of dust opacity). For example, Sarkar & Sahai (2006) noted how in general the DUSTY SEDs are not very sensitive to cooler dust at large radii, as demonstrated by the fact that large differences in shell relative thickness values do not determine drastically different SEDs. Therefore, it is possible that the code itself is underestimating the amount of dust.

Another issue concerning the use of DUSTY is the assumed spherical symmetry. As previously mentioned, one-dimensional models have been used in the literature for modeling the mid- and far-infrared SEDs in planetary nebulae, since asymmetries in the distribution and orientation have less of an effect than in the optical part of the SED (Sánchez Contreras et al. 2007).

Using more realistic geometries with other codes would be expected to provide more accurate results, but assumptions must usually be made on the three-dimensional geometry. The advantages of a better match to the geometry of the nebula given by these codes can be heavily affected by such assumptions, so a careful exploration of parameter space consistent with the observations must be performed in order to guide and interpret the modeling results. The use of one-dimensional codes such as DUSTY is therefore still valid in determining the mean properties of an envelope, within the intrinsic errors of any modeling process.

### 4. SUMMARY

We have observed IC 4406 in the centimeter and 3–10 \( \mu \text{m} \) ranges. Our radio observations have confirmed the presence of the complicated maze of lanes already observed in H\( \alpha \) in the central region of the nebula and enabled us to calculate several

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**TABLE 3**

| Parameter                        | Value                              |
|----------------------------------|------------------------------------|
| Chemistry                        | 100% amorphous carbon              |
| Central source                   | Blackbody at 96,800 K              |
| Density distribution             | \( \propto r^{-2} \)               |
| Grain size distribution          | \( a_{\text{min}} = 0.005 \mu m, a_{\text{max}} = 6.5 \mu m \) |
| Hot component                    | \( T_d = 700 \text{ K}, \tau_{60} = 4.5 \times 10^{-4}, R_{\text{in}} = 7.17 \times 10^{15} \text{ cm}, Y = 14790 \) |
| Warm component                   | \( T_d = 200 \text{ K}, \tau_{60} = 1.0 \times 10^{-4}, R_{\text{in}} = 1.40 \times 10^{15} \text{ cm}, Y = 750 \) |
| Cold component                   | \( T_d = 57 \text{ K}, \tau_{60} = 6.8 \times 10^{-5}, R_{\text{in}} = 3.62 \times 10^{16} \text{ cm}, Y = 30 \) |

**Notes.**—\( Y \) is the shell thickness relative to the inner radius, which is determined by the code as the layer with temperature \( T_d \); \( R_{\text{in}} \) is the distance to the central star of the layer with temperature \( T_d \); and \( \tau_{60} \) is the optical depth at 60 \( \mu \text{m} \).

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**TABLE 4**

| Parameter                        | Empirical | Models |
|----------------------------------|-----------|--------|
| \( M_{\text{ion}} (M_\odot) \)   | 0.21      | 0.22   |
| \( M_{\text{dust}} (10^{-4} M_\odot) \) | 2.8      | 0.6    |
| \( M_{\text{dust}}/M_{\text{ion}} (10^{-4}) \) | 13      | 3      |
| Gas density (cm\(^{-3}\))       | 418       | 730    |

**Notes.**—“Empirical” refers to values calculated with the equations in § 3.2; “Models” refers to values deduced from the modeling explained in § 3.1. The model gas density is the value at the inner radius.
nebular parameters whose values match the classification of this target as an evolved planetary nebula, in particular its low dust-to-gas mass ratio and density. IRAC imaging has revealed the presence of filaments in the nebula that were not detected in previous observations.

Our IRAC measurements, combined with literature data at longer and shorter wavelengths, have enabled us to study the SED of the planetary nebula IC 4406 and reproduce it with DUSTY. This has revealed that three different dust components are needed to model the data, with temperatures ranging from 57 to 700 K. It has also been necessary to include in the model slightly larger grains than in the standard Mathis et al. (1977) composition (up to 6.5 \mu m) to account for the calculated 60 \mu m optical depth. The main limits of our modeled curve are the spherical geometry assumed in DUSTY and the lack of data in the millimeter and submillimeter ranges, which give a constraint on the slope of the curve. As we have observed during our trials with DUSTY, the slope of the SED in the submillimeter range changes with the maximum size of the grains included in the model. Unfortunately, in this range observations are available only for a few stars so far, with none for our target.

We can speculate that in a diversified dust environment such as we find in IC 4406, more low-temperature components may exist and future high-sensitivity, high angular resolution observations will provide a fundamental contribution to understanding the physics of circumstellar envelopes in planetary nebulae.

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Facilities: ATCA, Spitzer (IRAC)

REFERENCES

Cohen, M., & Barlow, M. J. 2005, MNRAS, 362, 1199
Corradi, R. L. M, Perinotto, M., Schwarz, H. E., & Claeskens, J.-F. 1997, A&A, 322, 975
Cox, P., Omont, A., Huggins, P. J., Bachiller, R., & Forveille, T. 1992, A&A, 266, 420
Fazio, G., et al. 2004, ApJS, 154, 10
Gathier, G. A., & Pottasch, S. 1988, A&A, 197, 266
Gathier, G. A., Pottasch, S. R., & Pel, J. W. 1986, A&A, 157, 171
Gruenwald, R., Viega, S. M., & Broggiere, D. 1997, ApJ, 480, 283
Hora, J. L., Latter, W. B., Allen, L. E., Marengo, M., Deutsch, L. K., & Pipher, J. L. 2004, ApJS, 154, 296
Ivezić, Z., Nenova, M., & Elitzur, M. 1999, User Manual for DUSTY (Lexington: Univ. Kentucky), http://www.pa.uky.edu/~moshe/dusty
Jura, M. 1986, ApJ, 303, 327
Karzas, W. J., & Latter, R. 1961, ApJS, 6, 167
Latter, W. B., Kelly, D. M., Hora, J. L., & Deutsch, L. K. 1995, ApJS, 100, 159
Lee, T.-H., & Kwok, S. 2005, ApJ, 632, 340
Liu, X.-W., et al. 2001, MNRAS, 323, 343
Mathis, J. S., Rumpl, W., & Nordsieck, K. H. 1977, ApJ, 217, 425
Mauch, T., Murphy, T., Buttery, H. J., Curran, J., Hunstead, R. W., Pietrzyński, B., Robertson, J. G., & Sadler, E. M. 2003, MNRAS, 342, 1117
Milne, D. K., & Aller, L. H. 1975, A&A, 38, 183
———. 1982, A&AS, 50, 209
Milne, D. K., & Webster, B. L. 1979, A&AS, 36, 169
O’Dell, C. R., Balick, B., Hajian, A. R., Henney, W. J., & Burkert, A. 2002, AJ, 123, 3329
Phillips, J. P. 2003, MNRAS, 344, 501
Phillips, J. P., & Ramos-Larios, G. 2005, MNRAS, 364, 849
Pottasch, S. 1984, Planetary Nebulae: A Study of Late Stages of Stellar Evolution (Dordrecht: Riedel)
Pottasch, S. R., et al. 1984, A&A, 138, 10
Ramos-Larios, G., Kemp, S. N., & Phillips, J. P. 2006, Rev. Mex. AA, 42, 131
Sahai, R., Wooten, A., Schwarz, H. E., & Clegg, R. E. S. 1991, A&A, 251, 560
Sánchez Contreras, C., Le Mignant, D., Sahai, R., Gil de Paz, A., & Morris, M. 2007, ApJ, 656, 1150
Sarkar, G., & Sahai, R. 2006, ApJ, 644, 1171
Schlegel, D., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schuster, M. T., Marengo, M., & Patten, B. 2006, Proc. SPIE, 6270, 65
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Storey, J. W. V. 1984, MNRAS, 206, 521
Wang, W., Liu, X.-W., Zhang, Y., & Barlow, M. J. 2004, A&A, 427, 873