MULTIWAVELENGTH DIFFRACTION-LIMITED IMAGING OF THE EVOLVED
CARBON STAR IRC +10216. II.

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ABSTRACT

High angular resolution images of IRC +10216 taken at various bandpasses within the near-infrared H, K, and L bands are presented. The maps have the highest angular resolution yet recovered and were reconstructed from interferometric measurements obtained at the Keck I telescope in 1997 December and 1998 April, forming a subset of a seven-epoch monitoring program presented earlier by Tuthill and coworkers in Paper I. Systematic changes with observing wavelength are found and discussed in the context of present geometrical models for the circumstellar envelope. With these new high-resolution, multiwavelength data and contemporaneous photometry, we also revisit the hypothesis that the bright compact core of the nebula (component “A”) marks the location of the central carbon star. We find that directly measured properties of the core (angular size, flux density, color temperature) are consistent with a reddened carbon star photosphere (line-of-sight $\tau_{2.2} = 5.3$).

Subject headings: infrared: stars — stars: individual (IRC +10216) — stars: mass loss — techniques: high angular resolution — techniques: interferometric

1. INTRODUCTION

IRC +10216 (=CW Leo) is a dusty, embedded, carbon-rich long-period variable currently undergoing an episode of intense mass loss of up to $10^{-5} M_\odot$ yr$^{-1}$ (Mauron & Huggins 1999). It is the nearest object of its type (110–135 pc; Groenewegen 1997), brightest in the thermal IR, and is generally believed to be in transition between the latest stellar and the earliest planetary nebula phases. This fortuitous combination of factors has led to intensive study across the spectrum, resulting in an extensive and rich literature, making IRC +10216 the textbook example for studies now spanning some years, evolution of the material with apparent brightening, fading, and proper motion reveals considerable complexity in the immediate circumstellar environment. Here, we present the highest angular resolution images yet made, spanning the near-infrared H, K, and L bands.

2. OBSERVATIONS

Using the techniques of aperture-masking interferometry, images of IRC +10216 at a range of near-IR wavelengths were obtained from data taken at the 10 m Keck I telescope. These observations formed a somewhat distinct component of a program that also comprised the seven-epoch $K$-band imaging study presented in Paper I. This current paper is concerned with an intensive study of IRC +10216 made over only two observing runs, in 1997 December and 1998 April, during which images were made in five separate near-infrared wave bands. The bandpasses of the filters used are given in Table 1, while an observing log showing the dates, aperture masks, and filters can be found in Table 2.

In contrast to Paper I, which was concerned with changes of the morphology of the dust shell between the separate epochs, here we have averaged together data taken over two separate runs. This was done to enhance the signal-to-noise ratio (S/N) of some of the maps and to compensate for the fact that there was no single observing epoch that yielded high-quality maps at all the observing wavelengths of interest. Although the two epochs chosen were only 4 months apart, measurable changes in the relative locations of components in the inner dust shell were shown to occur in Paper I. However, the fastest moving component would be displaced only $\sim 8.5$ mas in this interval (see Paper I); averaging together maps with such small shifts should produce no great bias in the results.

The Golay and annulus aperture geometries from Table 2 are described in detail in Tuthill et al. (2000c), which contains a thorough description of the experimental methods. Although the two masks employed differed in performance for the various levels of source flux and seeing conditions encountered, comparisons proved that there were no systematic differences in the final maps produced, allowing them to be averaged together by observing wavelength alone. As absolute positional information is not recovered from our closure-phase-based techniques, maps to be averaged were registered with respect to each other by maximizing the cross-correlation before being summed.

3. RESULTS

This section presents the major observational findings of this paper. Diffraction-limited image reconstructions, visibility curves, and additional supporting data are presented and discussed.
3.1. K-band Images: A Comparison of Bandwidths

Reconstructed images of IRC +10216 from data taken in 1997 December through two different filters, kcont and ch4, are given in Figure 1. As is apparent from Table 1, the kcont and ch4 filters have similar central passbands, but their bandwidths differ by a factor of 3. The two images of Figure 1 do, however, exhibit a high degree of similarity to each other, with no significant departures beyond those to be expected at the lowest contours near the level of the noise. This is not surprising, given that the emission process we are concerned with is thermal radiation from warm dust, which exhibits a fairly featureless spectrum across the near-infrared. The findings from this comparison, and other maps presented later in the paper, confirm that rapid changes in morphology with wavelength were not seen.

Images such as those in Figure 1 also present a useful yardstick for measuring the fidelity of the image reconstructions. The level of agreement shown is typical for maps taken with different aperture masks and on different nights with varying seeing conditions. Such external consistency checks have allowed us to determine that structures above a certain level, in this case about 3% of the peak, are very well established experimentally.

3.2. A Descriptive Model of IRC +10216

A qualitative model of the appearance of the dust shell around IRC +10216 was given in Paper I. We repeat this description here, together with a cartoon that labels the features, given in Figure 2, which also uses the “A, B, C, D” nomenclature of Haniff & Buscher (1998). The brightest features in the maps of Figure 1, appearing as sharp spikes at the center of the maps, we denote as the core (“A”) in Figure 2. Surrounding the core is a roughly elliptical region of emission, elongated along a position angle of ~120°, which we call the southern component. The shorter north arm starts from a location 100 mas northwest of the core and extends approximately 150 mas to the north-northeast (“C”). Perpendicular to it runs the prominent northeast arm (“B”), running over 200 mas and forming the brightest structure outside the southern component. Displaced 150 mas from the core to the northeast is a region containing multiple weaker features, labeled the eastern complex. Within this region, the brightest feature, which consists of a roughly circular patch somewhat less than 100 mas across, has been tagged as cloud EC1 (“D”). For further clarification of these assignments, see Figure 2 of Paper I. The different nomenclature employed, compared to other workers, is necessitated by the higher angular resolution, so that the simple blobs reported in earlier work are resolved into clumpy or filamentary structures here.

3.3. Multispectral Near-Infrared Images

Maps of IRC +10216 spanning four near-infrared wavebands, representing a noise-weighted average of data collected over 1997 December and 1998 April, are given in Figure 3. Unfortunately, the S/N and image fidelity were never as high for maps outside the K band. For shorter wavelengths, a combination of lower intrinsic flux from the star, together with the greater role played by the atmospheric seeing, were probably to blame for this loss. For the observations at wavelengths greater than 3 μm, the intrinsically lower system angular resolution probably contributed to enhanced difficulties with the mapping, although it is likely that additional unidentified factors were also at play. For these reasons, the contour levels in Figure 3, chosen to be near or above the noise, are more conservative than those in Figure 1. Despite this precaution, it can be seen that for the map at 3.310 μm (pah filter) resulting from an average of only two somewhat noisy maps, the lowest contours do show the effects of noise.

When examining maps for systematic differences as a function of observing wavelength, the reader is cautioned to bear in mind that the four images in Figure 3 all have different angular resolutions and noise levels. Maps follow a similar basic shape, with the dominant features such as the core, north and northeast arms, and EC1 being identifiable at all wavelengths. However, it is apparent that changes in appearance do occur across the near-infrared.

In order to visualize these changes, Figure 4 shows color maps produced by differing the h – k and h – PAHCS images. As might be expected in a source with such complexities of morphology, in which opacity, temperature, and scattering all play varying roles, interpreting such maps is not straightforward. Of the bright high-S/N features, the core exhibits the bluest (hottest) spectrum in k – pahcs. However, in the h – k map, the core exhibits a flat spectrum, neither relatively blue nor red, although the bluest feature in the map does lie quite nearby, toward the dark lane. Even more puzzling is the behavior of the north/northeast arm and (to a lesser extent) EC1, which are among the reddest features in the h – k map yet appear markedly blue in k – pahcs. It is important to point out that among the many other physical properties that need to be modeled to understand these maps, there is also a strong molecular absorption feature due to HCN and C2H2 (Cernicharo et al. 1999), which coincides with the pahcs filter bandpass.

Further discussion of the colors and sizes of features, particularly of the core, is given later; however, we prefer to do this based on simple models fit directly to the observed visibility data themselves. This is because the reconstruction of an image from a set of visibilities and closure phases is a complex and nonlinear process and can be subject to biases introduced by the deconvolution process. When possible, quantitative interpretation of the data is often best achieved by fitting to the

<table>
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<th>Table 1</th>
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<th>Journal of Interferometric Observations</th>
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Note.—For consistency with Paper I, we have preserved the nomenclature of the epochs from the larger seven-epoch set presented earlier, explaining why the epochs start at 2. See text and Table 1 for descriptions of the masks and the filters.

* Stellar phases from Monnier et al. (1998).
measurements rather than proceeding through the intermediate step of a reconstructed image.

3.4. Visibility Data

Simple quantitative brightness models were fitted directly to the calibrated visibilities. Figure 5 presents azimuthally averaged visibility data for IRC +10216 at four near-infrared wavelengths. At all wavelengths, the visibility curves exhibit a common, basic form. A rapid drop from high visibilities at the origin occurs over a spatial frequency range \( \lesssim 0.5 \times 10^6 \text{ rad}^{-1} \), denoting that most of the flux comes from well-resolved large-scale structure. This component has been modeled by fitting a circular Gaussian disk to the visibility data, the results of which are shown in Figure 5. Intermediate spatial frequencies (\(0.5 \lesssim 2 \times 10^6 \text{ rad}^{-1}\)) carry much of the signal that generates the asymmetric form of the maps. Owing to this known complexity, no attempts were made to fit to azimuthally averaged visibilities on these intermediate baselines. At high angular resolutions (\(2 \times 10^6 \text{ rad}^{-1}\)), visibilities for all wavelengths appear to follow a simple functional form corresponding to a partially resolved, circularly symmetric, compact component. A uniform disk model has been fitted to these data, and best fits are overplotted on the figure.

We proceed by identifying the uniform disk component fit to the long baselines as due to the core. However, this identification requires careful argument and justification. The idea that the core is responsible for the highest spatial frequency structure is to an extent confirmed by the appearance of the recovered images, which show this to be by far the dominant compact feature. Furthermore, based on the physical assumption that the core may indeed be the star, it is not unreasonable to expect that it is able to dominate the high angular frequency spectrum over flux coming from extended dust, which is less likely to have sharp structure on fine scales. In this case, mapping confirms the assumption to be reasonable; however, there may be some noncore contamination of visibilities at intermediate baselines, a difficulty which only higher angular resolution can cure. A second important caveat concerns the high-resolution asymmetry associated with the core (Paper I; Osterbart et al. 2000), which could cause difficulties in fitting to azimuthally averaged data (which assumes circular symmetry). The elongation was not as great at these epochs as it later became (Paper I), and tests
Fig. 3.—Image reconstructions of IRC +10216 from data taken at four different wavelengths in the near-infrared over the epochs 1997 December and 1998 January. Top left: Average of three maps taken with the h filter. Top right: Average of four maps taken with the ch4 filter. Bottom left: Average of eight maps taken with the pahcs filter. Bottom right: Average of two maps taken with the pah filter.
Fig. 4.—Color images with the h — ch4 filter (left) and the ch4 — pahs filter (right). In order to mitigate the effects of varying angular resolution for the different filters, images were smoothed to an effective beam size of 70 mas before subtraction. Data were also truncated at 3% of the peak brightness, giving rise to the blank areas at the edges. The overplotted contours show the structure from the smoothed ch4 map, indicating the locations of the core and dominant features. For the h — ch4 map, the reddest (lightest) areas correspond to 3.7 mag, and the bluest (d Darkest) to 1.8 mag. For the ch4 — pahs map, the reddest areas are 3.0 mag, and the bluest 1.4 mag. However, more extreme colors may occur over small regions but will be diluted by the smoothing mentioned above.

Fig. 5.—Azimuthally averaged visibility data for IRC +10216 at four different wavelengths. Top left: h filter. Top right: ch4 filter. Bottom left: pahs filter. Bottom right: pah filter. Two separate models (solid lines) have been fitted to data over different spatial frequency ranges. The rapid falloff in visibility at low resolution (spatial frequencies less than $2 \times 10^5 \text{ rad}^{-1}$ was used for the model) has been fitted with a circular Gaussian disk model, with FWHM given in the figure. The gradual decline at high spatial frequencies (greater than $2 \times 10^5 \text{ rad}^{-1}$ was used for the model), which implies the presence of a bright, partially resolved component, has been fitted with a uniform disk model with the diameter as given. Errors were computed from the spread of values among separate fits to a number of independent data sets at each wavelength. The best-fitting model parameters and their errors, together with the model visibility curves themselves, are all plotted in the figure.
were performed in which data were grouped in sectors according to the orientation of the baseline. The spread of values found for these core diameter fits was incorporated into the error term for the final diameters given in Figure 5.

4. DISCUSSION AND ConClUSIONS

The purported location of the stellar photosphere within the IRC +10216 nebula has been discussed in various studies, starting with Kastner & Weintraub (1994). However, the complexities of the dust shell and the absence of an unambiguously distinct bright compact component have caused continuing uncertainty over identifying which, if any, feature corresponds to the star itself. This has led to fundamental uncertainties over the structure of the dust shell, and determining the location of the star is essential to further progress. In Paper I we argued that the core of the southern component (A) consisted of emission from the stellar photosphere, with the possible addition of some flux from hot dust on the inner wall of a cavity or torus, tilted into the line of sight in the south. While this bright core, with an angular diameter of 50 mas, was the prime candidate to be the stellar photosphere, the possibility that the star itself lay completely obscured behind the central dark dust lane was also advanced.

Osterbart et al. (2000) suggested an alternate interpretation: that the star itself lies within the bright knot at the end of the northeast arm (component B). Evidence supporting this view came from color maps, from observations of changes in shape of the core, and particularly from attempts to trace the point of origin of the polarization field. An ambitious series of papers built on this interpretation, including detailed radiative transfer modeling (Men'shchikov et al. 2001, 2002) and the results of a further observational campaign (Weigelt et al. 2002). Detailed models interpreting the southern component as a cavity in a bipolar structure (A) with the star at the location of the northeast arm (B) were produced, which gave reasonable fits both to the spectral energy distribution and the high-resolution imaging. However, these models were quite complex, incorporating >20 free parameters describing many different shells of varying symmetry and density profile. Based on this analysis, the authors rule out the possibility that the star can be either at the southern core or completely hidden behind the dust (Men’shchikov et al. 2001).

Despite this, there remain a number of simple arguments against the view that the star is located in the northeast arm. At the higher resolutions afforded by the Keck imaging, the northeast arm is shown to be a linear structure with almost uniform brightness along a ridge with no dominant compact knot. Furthermore, the northeast arm was found to be elongating and fading with time (Paper I), and in the most recent Keck observations (P. G. Tuthill et al. 2005, in preparation), it is almost entirely absent. Similar findings of the disappearance of the feature they previously identified as the star were explained by Men’shchikov et al. (2002), who invoke a recent and dramatic increase in mass-loss rate, which has had the effect of burying the photosphere beneath a thickening dust shell. However, our higher angular resolution Keck observations show that the northeast arm is fading, lengthening, and separating from the southern component. The observed proper motion, with tentative acceleration detection (Tuthill et al. 2000a; Weigelt et al. 2002), would not be expected from the identification of Men’shchikov et al. (2001) of these two components as parts of the circumstellar torus and the stellar photosphere.

Recent lunar occultation measurements (Chandrasekhar & Mondal 2001; Richichi et al. 2003) have been able to shed some light on this question, with extremely high angular resolutions (0.8 mas) attained in one-dimensional profiles. The core of the southern component was found to be well fitted by a compact Gaussian profile, with FWHM 35 mas contributing 6% of the total flux in the \( K \) band. The close agreement with the expected angular size of the photosphere for the star, as well as the finding of a component of similar size and position in the \( H \)-band profile, led these authors to identify the southern core (A) as the stellar disk, although not with sufficient confidence to rule out alternative hypotheses.

By fitting only the longest baselines, as shown in Figure 5, we were able to discriminate between the compact core and the well-resolved nebula, revealing a partially resolved component giving measurable visibility signal at even the longest baselines. For the four different bandpasses depicted (1.65, 2.26, 3.08, and 3.31 \( \mu \)m), uniform disk fits yielded diameters of 40, 52, 60, and 65 mas with relative flux contributions of 10%, 10%, 7%, and 6% of the total, respectively. Our \( K \)-band uniform disk diameter of 52 mas is in close agreement with the lunar occultation measurements of Richichi et al. (2003), whose 35 mas FWHM Gaussian model would correspond, in the partially resolved case here, to a uniform disk diameter of 56 mas. The observed variation in angular diameter with wavelength across the near-IR is not necessarily strong evidence that the feature is a dust clump. Rather, it has become apparent that opacity changes due to various molecular and atomic species in the atmospheres of evolved stars lead to precisely such large, apparent diameter variations, at least for M stars (Tuthill et al. 2000a; Mennesson et al. 2002).

We turn now to examination of the apparent color of the compact core. From the uniform disk fits above, the same relative contribution from the core was found in \( H \) and \( K \) band (both 10%), but significantly less was found at the longer wavelengths (7% and 6% at 3.08 and 3.31 \( \mu \)m, respectively). This finding is in good accord with the color maps presented in Figure 4, which found the core to be neutral in \( h - k \) and blue in \( k - pahc \). If the core is indeed the star, the simplest expectation is that the hottest effective temperature component of the system should present the bluest colors. The evidence here is somewhat equivocal: the core is blue in \( k - pahc \) and adjacent to the bluest part of the \( h - k \) map, but clearly there are more complicated effects going on. To understand the color maps further, the complexities of scattering and reddening in an inhomogeneous environment must be more carefully modeled.

Finally, we subject the hypothesis that the core is the stellar photosphere to a quantitative test. Assuming the \( K \)-band 52 mas core is the stellar size, and if we adopt a reasonable effective temperature of 2000 K, the unreddened stellar flux density can be calculated. This flux density can be reddened by amorphous carbon dust (Rouleau & Martin 1991), and the resulting spectral energy distribution (SED) can be compared to the photometry of the core derived from the Keck aperture-masking frames (calibrated using the contemporaneous interferometric calibrator and the visibility decomposition from Fig. 5). Figure 6 shows the results of reddening the stellar spectrum with MRN dust (Mathis et al. 1977), using the standard dust size range \((0.005 \mu m < a < 0.25 \mu m)\), as calculated using DUSTY code.\(^4\) The \( K \)-band flux density of the core is well fitted using \( \tau_{22} = 5.3 \), although the reddened spectrum is too red to fit the \( H \)-band and \( L \)-band core photometry. By including

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somewhat larger grains (0.005 \( \mu m < a < 0.75 \mu m \)), all the near-IR photometry of the core is well fitted (also, \( \tau_{22} = 5.3 \)). This result is not sensitive to the adopted stellar effective temperature.

This simple test does not prove that the core is the star; however, the hypothesis does gain credence. Furthermore, our results that \( \tau_{22} = 5.3 \) and the finding that the photosphere contributes 10% of \( K \)-band emission is remarkably close to the estimate of Keady et al. (1988), who found \( \tau_{22} = 5.4 \) from SED modeling and a photospheric contribution of \( 75\% \) to the IR photometry of the core. This stellar spectrum was reddened by standard monochromatic extinction laws.

In conclusion, although complicated models in which the star is obscured and eventually buried in the northern regions cannot be ruled out, the simple alternate hypothesis that core component A is highly reddened, direct photospheric light can naturally explain the observed properties of the compact core, including: (1) its angular size, (2) its \( K \)-band flux density, (3) its color temperature, (4) its persistence over multiple epochs, (5) the observed dilution of near-IR photospheric absorption lines, (6) the general level of mid-infrared emission, and (7) the magnitude of proper motion between the core and the northeast arm (A and B). We encourage detailed radiative transfer modeling constrained by the latest multiwavelength imaging to explore the physical structure of this fascinating source.

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