HIGH-RESOLUTION IMAGING OF DUST SHELLS BY USING KECK APERTURE MASKING AND THE IOTA INTERFEROMETER

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ABSTRACT

We present first results of an experiment to combine data from Keck aperture masking and the Infrared-Optical Telescope Array to image the circumstellar environments of evolved stars with \( \sim 20 \) mas resolution. The unique combination of excellent Fourier coverage at short baselines and high-quality long-baseline fringe data allows us to determine the location and clumpiness of the innermost hot dust in the envelopes and to measure the diameters of the underlying stars themselves. We find evidence for large-scale inhomogeneities in some dust shells and also significant deviations from uniform brightness for the photospheres of the most evolved M stars. Deviations from spherically symmetric mass loss in the red supergiant NML Cyg could be related to recent evidence for dynamically important magnetic fields and/or stellar rotation. We point out that dust shell asymmetries, like those observed here, can qualitatively explain the difficulty recent workers have had in simultaneously fitting the broadband spectral energy distributions and high-resolution spatial information, without invoking unusual dust properties or multiple distinct shells (from hypothetical "superwinds"). This paper is the first to combine optical interferometry data from multiple facilities for imaging, and we discuss the challenges and potential for the future of this method, given current calibration and software limitations.

Subject headings: circumstellar matter — instrumentation: interferometers — stars: AGB and post-AGB — stars: atmospheres — techniques: interferometric

1. INTRODUCTION

Since the advent of infrared detectors, the classic tool for studying circumstellar dust shells has been fitting the spectral energy distributions (SEDs) by using radiative transfer models. This has been true for stars across the Hertzsprung-Russell diagram, for young stars still accreting material, as well as for evolved stars with their winds. The conclusions of these studies are only beginning to be tested rigorously through high-resolution imaging in the visible and infrared, using 8 m class telescopes and long-baseline interferometers.

In this paper, we focus mainly on dust shells around evolved stars. Almost all evolved star SEDs can be fitted well by using a simple physically realistic model including a star and a spherically symmetric, uniform-outflow model was successfully fitted to IRC +10216 have revealed inhomogeneities and asymmetries of this method, given current calibration and software limitations.

of a dense stellar atmosphere with a scale height larger than hydrostatic, maintained by shocks launched from photospheric pulsations (see recent reviews by Hearn 1990; Lafon & Berruyer 1991; Habing 1996). This theory makes definite predictions for what should be observed when high-resolution imaging can resolve these objects, in terms of both location and nature of the dust formation and the time evolution as clouds are accelerated away from the star by radiation pressure.

Although early speckle results of Dyck et al. (1984) found near-IR dust shell sizes consistent with expectations (given the limited spatial resolution), recent higher resolution imaging and interferometry have consistently found strong deviations from a simple mass-loss scenario. The Infrared Spatial Interferometer (ISI) found evidence for diverse dust shell properties in their survey of 13 stars (Danchi et al. 1994). More dramatically, recent speckle and aperture-masking images of the carbon star IRC +10216 have revealed inhomogeneities and asymmetries of stellar scales (Haniff & Buscher 1998; Weigelt et al. 1998; Tuthill et al. 2000a); only a few years earlier, a spherically symmetric, uniform-outflow model was successfully fitted to the SED (Ivezic & Elitzur 1996a). Virtually every recent published attempt to incorporate high-resolution spatial information into SED models has led to the conclusion that there are strong deviations from the simple mass-loss prescription of uniform outflow and spherical symmetry (e.g., Monnier et al. 1997, 1999b; Lopez et al. 1997; Hale et al. 1997; Wittkowski, Langer, & Weigelt 1998; Gauger et al. 1999; Blöcker et al. 1999; Hofmann et al. 2001), at least for the most evolved and dust-enshrouded sources.

While SED models are adequate for estimating some basic parameters about dust shells and mass-loss rates (average optical depth and temperatures), they cannot definitively answer some important questions regarding dust condensation conditions, grain properties, and the basic mass-loss mechanisms
masking and speckle interferometry. In this paper, we extend these questions by imaging dust as it forms and accelerates away from the star. This morphology and dynamical information is much better for constraining the wind and mass-loss theories. Current interferometer technology is beginning to provide this: “movies” of the expanding dust shell around IRC +10216 are already available (Tuthill et al. 2000a; Weigelt et al. 2002).

Until recently, high-resolution images of dust shells could be made only of the “biggest” sources by using aperture masking and speckle interferometry. In this paper, we extend the capability to ~20 mas scales by combining Keck aperture-masking data, which sample baselines up to 9 m, with Infrared-Optical Telescope Array (IOTA) interferometer data, which sample out to 38 m. By constraining the long-baseline visibility, we are able to make higher fidelity images of the inner dust shells. This allows us to measure the inner radius of dust condensation and to search for signs of dust shell asymmetry and clumpiness, information critical to validating (or falsifying) our current theories of mass loss.

Last, we want to connect our efforts to image evolved stars with beginning efforts to image disks around young stellar objects (YSOs). The history of YSO SED modeling is beginning to resemble the history for evolved stars recounted above. Interferometry results (Millan-Gabet et al. 1999; Akeson et al. 2000, 2002; Millan-Gabet, Schloerb, & Traub 2001; Tuthill et al. 2001, 2002; Monnier & Millan-Gabet 2002; Colavita et al. 2003) have found profound differences from the predictions of the “successful” disk models based on fitting to SEDs alone (Hillenbrand et al. 1992; Hartmann, Kenyon, & Calvet 1993; Chiang & Goldreich 1997). The new high-resolution imaging techniques developed here will soon be applied to imaging preplanetary disks around young stars by using new interferometer facilities, such as the Center for High Angular Resolution Array (CHARA).

The organization of this article is as follows. We begin by describing the nature of the observations and the facilities used to acquire the high-resolution data. Next, we describe the data analysis, including the results of extensive validation experiments using new observations of RT Vir, R Leo, R Hya, and W Hya (an Appendix details our novel calibration method). We then discuss the results on each of the “dust shell” targets: HD 62623, IRC +10420, VY CMa, NML Cyg, VX Sgr, and IK Tau. These analyses include diameter fitting, radiative transfer modeling, and image reconstructions. We also include a general discussion regarding the difficulties in imaging with new optical interferometers.

Future papers will take up the challenge of creating self-consistent two- or three-dimensional radiative transfer models of the individual sources. Considering the increased interest in this area recently, with this paper we provide an important and timely data set for other modelers of evolved stars and dust shells.

2. OBSERVATIONS

In this study, we combine data obtained by using aperture masking on the Keck I telescope (Tuthill et al. 2000b; Monnier 1999) and by using the Fiber Linked Unit for Optical Recombination (FLUOR) beam combiner (Coudé du Foresto et al. 1998) on the IOTA interferometer (Traub 1998). The circumstellar environments of evolved stars are known to change with time, both because of variable mass loss on the many-year timescale (e.g., Haniff & Buscher 1998; Monnier et al. 1997) and because of large-amplitude pulsations on shorter timescales (Danchi et al. 1994; Perrin et al. 1999). Thus, coordinated (near simultaneous) observations at both facilities were deemed critical to avoid possible changes in dust shell morphology between observations.

Here we report on all dust shell targets of this aperture synthesis effort except for the carbon star V Hya, the subject of a separate paper (R. Millan-Gabet 2004, in preparation), and Table 1 lists the target sources and their basic properties. Table 2 contains a full journal of our observations relevant to this paper, where it can be seen that Keck and IOTA measurements were typically made within 1 month of each other. In some cases (detailed later), we have also included data from other epochs for comparison. While all observations were done inside the astronomical K band (2.0–2.4 μm), the Keck data used narrowband filters, while the IOTA-FLUOR experiment used a broadband K’ filter; this and other factors lead to systematic errors, which are discussed fully in § 3.3.

2.1. Aperture Masking

Aperture-masking interferometry was performed by placing aluminum masks in front of the Keck I infrared secondary mirror. This technique converts the primary mirror into a VLA-style interferometric array, allowing the Fourier amplitudes and closure phases for a range of baselines to be recovered with minimal “redundancy” noise (e.g., Baldwin et al. 1986; Jennison 1958). For this work, we used both a

| Target Name     | R.A. (J2000.0) | Decl. (J2000.0) | V° (mag) | K° (mag) | Spectral Type | Type of Source |
|-----------------|---------------|----------------|----------|----------|---------------|----------------|
| IK Tau ..........| 03 53 28.84   | +11 24 22.6    | 11.9     | −1.1     | M10 III       | Dust-enshrouded Mira variable |
| VY CMa ..........| 07 22 58.33   | −25 46 03.2    | 8.0      | 0.1      | M3/4 I        | Dust-enshrouded red supergiant |
| HD 62623 .......| 07 43 48.47   | −28 57 17.4    | 4.0      | 2.3      | A3 Iab        | A supergiant with infrared excess |
| R Leo ...........| 09 47 33.49   | +11 25 43.6    | 6.0      | −2.2     | M8 III        | Mira variable |
| RT Vir ..........| 13 02 37.98   | +05 11 08.4    | 8.6      | −1.0     | M8 III        | Semiregular variable |
| R Hya ...........| 13 29 42.78   | −23 16 52.8    | 6.4      | −2.6     | M7 III        | Mira variable |
| W Hya ...........| 13 49 01.00   | −28 22 03.5    | 7.5      | −3.1     | M7 III        | Mira variable |
| VX Sgr ..........| 18 08 04.05   | −22 13 26.6    | 10.0     | 0.2      | M4–9.5 I      | Dust-enshrouded red supergiant |
| IRC +10420 ......| 19 26 48.03   | +11 21 16.7    | 8.5      | 3.6      | F8 I          | Rapidly evolving F supergiant |
| NML Cyg ..........| 20 46 25.46   | +40 06 59.6    | 16.6     | 0.6      | M6 I          | Dust-enshrouded red supergiant |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a Most of the targets are variable stars and these magnitudes are merely representative. See text for more recent photometry.

TABLE 1

Basic Properties of Targets
nonredundant “Golay” mask and a circular “Annulus” mask; this information, along with observing dates, filter bandpasses, and calibrator sources, is included in Table 2. Aperture mask specifications, implementation description, and detailed observing methodology can be found in Tuthill et al. (2000b) and Monnier (1999).

For these observations the Near Infrared Camera (NIRC; Matthews & Soifer 1994; Matthews et al. 1996) was used in a fast readout mode, adopting an integration time of 0.137 s per frame. Some of the data were corrupted by highly variable seeing and “windshake,” which blurs the fringes during the integration time and frustrates precise calibration. In situations where suspect calibration is indicated by our data pipeline (as opposed to the longest baseline, as measured by using three different IOTA configurations, with physical telescope separations between $B = 21$ m (north/south orientation) and 38 m (N-NE/S-SW orientation). For reference, the resolution corresponding to the longest baseline, as measured by the FWHM of the response to a point source, is $\lambda / 2B = 6$ mas at $K'$.

The IOTA observations reported here (2000 February, April, and June) were all carried out by using the FLUOR beam combiner (Coudé du Foresto et al. 1998), which uses single-mode fibers as spatial filters to achieve better precision in the measurement of fringe visibilities than achievable with bulk-optics combiners. A single-mode fiber essentially converts phase errors, caused by atmospheric turbulence and aberrated optics, into amplitude fluctuations that can be monitored and corrected (Shaklan & Roddier 1987; Shaklan 1989). In FLUOR, the light from each telescope is fed into a fluoride glass fiber and split into two parts. One part is directly sent to the detector as a monitor of the flux coupling efficiency (“photometric” signal), while the other is used for interference in a fiber coupler. By using the photometric signals, the fringe visibility can be precisely normalized for each measurement, thus calibrating effects of varying atmospheric turbulence. The fringes are modulated on the detector by a scanning piezo mirror placed in one leg of the interferometer, a fringe detection scheme referred to as temporal modulation.

A typical single observation consisted of 200 scans obtained in ~4 minutes, followed by calibration measurements of the background and single-telescope fluxes (important for characterizing the fiber coupler chromatic response).
Target observations are interleaved with an identical sequence obtained on an unresolved or partially resolved star, which serves to calibrate the interferometer’s instrumental response and the effect of atmospheric seeing on the visibility amplitudes. The target and calibrator sources are typically separated on the sky by $5^\circ - 10^\circ$ and are observed a few minutes apart; these conditions ensure that the calibrator observations provide a good estimate of the instrument’s transfer function. The high brightness of our targets necessitated using similarly bright calibrators, which were partially resolved on the longest baselines. Uncertainty in the sizes of these calibrators dominates the calibration error in most cases, and we have compiled a list of the adopted angular diameters and sizes in Table 3.

3. DATA REDUCTION

After briefly describing the basic data reduction procedures, we present the results of validation experiments.

3.1. Keck Aperture Masking

The analysis procedures for extracting the visibility amplitudes and closure phases are well documented in Tuthill et al. (2000b) and Monnier (1999). When performing image reconstructions, the maximum entropy method (MEM; Skilling & Bryan 1984; Gull & Skilling 1983) has been used to create diffraction-limited images from the interferometric data, as implemented in the VLBMEM package by Sivia (1987). Other engineering and performance details may be found in Tuthill et al. (2000b) and Monnier (1999), while other recent scientific applications of the data pipeline can be found in Monnier et al. (2002) and Tuthill et al. (2002).

3.2. IOTA-FLUOR

Reduction of the FLUOR data was carried out by using custom software developed using IDL, similar in its main principles to that described by Coude du Foresto, Ridgway, & Mariotti (1997). Significant efforts were made to validate the new data pipeline, and these are detailed in §3.4.

Here we briefly summarize the main steps in the data reduction procedure. We have included a more detailed description in the Appendix, including an explanation of our novel normalization scheme (§A2). Our data pipeline includes data inspection, determination of a $k$-matrix to characterize the transfer function of the fiber optics beam combiner, removal of photometric fluctuations, fringe amplitude normalization, power spectrum measurement, calibration of instrumental response by observing calibrator stars, and standard data quality checks. Most targets were observed multiple times, and the visibility measurements showed good internal consistency from night to night.

3.3. Systematic Errors

The most significant systematic errors in this experiment come from the aperture-masking data at Keck (i.e., not from IOTA-FLUOR). In order to have reasonably low read noise,

### Table 3: Calibrator Information

| Calibrator Name | Spectral Type | Adopted Uniform Disk Diameter$^a$ (mas) | Reference |
|-----------------|---------------|-----------------------------------------|-----------|
| 2 Cen           | M4.5 III      | 13.9 ± 1.4                              | Heras et al. (2002) |
| 14 Sgr          | K2 III        | 2.3 ± 1.8                               | GETCAL$^b$ |
| 54 Per          | G8 III        | 1.41 ± 0.13                             | CHARM$^e$ |
| α Cet           | M1.5 III      | 11.6 ± 0.4                              | CHARM |
| δ Vir           | M3 III        | 10.7 ± 1.0                              | Heras et al. (2002) |
| γ Hya*          | G8 III        | 3.4 ± 0.5                               | GETCAL |
| HD 47667        | K2 III        | 2.56 ± 0.04                             | CHARM |
| HD 63852*       | K5 III        | 2.3 ± 0.1                               | GETCAL |
| δ Tau*          | G6 III (SB)   | 2.7 ± 0.3                               | CHARM, CADARS$^d$ |
| π Hya*          | K2 III        | 3.7 ± 0.1                               | CHARM |
| π Leo*          | M2 III        | 4.85 ± 0.23                             | CHARM |
| SAO 49410*      | K5 lab        | 2.9 ± 0.5                               | van Belle et al. (1999)$^f$ |
| SAO 104467*     | K0 V          | 1.7 ± 0.3                               | GETCAL |
| SAO 104655      | G8 II –III    | 1.5 ± 0.2                               | GETCAL |
| SAO 105500      | M0 III        | 5.5 ± 0.5                               | CHARM |
| SAO 186681      | K3 III        | 6.9 ± 0.9                               | GETCAL |
| SAO 186841*     | K1 III        | 4.4 ± 0.2                               | CHARM |
| SW Vir          | M7 III        | 16.81 ± 0.12                            | CHARM |
| σ CMa*          | M0 lab        | 8.9 ± 1.2                               | GETCAL |
| σ Vir*          | M2 III        | 6.2 ± 1.0                               | GETCAL |
| ξ Cyg           | K4.5 I        | 6.0 ± 1.3                               | GETCAL, CHARM |

**Note.**—Asterisk indicates a calibrator of long-baseline IOTA interferometer data where accurate diameters are most critical.

$^a$ The diameter error quotations have not been validated independently. While adequate for our purposes here, workers who require precision calibration are warned to research their calibrators carefully and not rely too heavily on “catalogs” such as CHARM.

$^b$ GETCAL is maintained and distributed by the Michelson Science Center (http://msc.caltech.edu).

$^c$ CHARM is the Catalog of High Angular Resolution Measurements (Richichi & Percheron 2002).

$^d$ CADARS is the Catalog of Apparent Diameters and Absolute Radii of Stars (Pasinetti-Fracassini et al. 2001).

$^e$ The diameter recorded in this reference is in error; however, the reported $Y^2$ measurement is correct (G. T. van Belle 2003, private communication) and we have used this to calculate the uniform disk diameter found herein.
limitations of the NIRC camera electronics restrict the integration time of each “speckle” frame to \( \geq 0.137 \) s, many times longer than the typical atmospheric coherence time at 2.2 \( \mu \)m (\( \sim 40 \) ms). Even worse is windshake that occurs when one observes low-elevation sources into the wind, a common problem with large-aperture telescopes, which results in a blurring of the fringes. Most damagingly, this can induce asymmetric miscalibrations that must be carefully guarded against. Miscalibrations are usually identifiable in the raw data, thus allowing corrupted data to be flagged. In cases in which we suspect problems (due to obvious windshake before or after the target), we have included previous/subsequent epochs of data as a cross-check or have limited our analysis to the azimuthal averages of the visibility data.

Fortunately, fringe-blurring problems have virtually no effect on the measurements of the closure phases, which remain well calibrated and are crucial to the imaging process when the image is not centrosymmetric. In addition, the excellent Fourier coverage of the Keck masking allows hundreds of visibility points to be measured simultaneously, allowing averaging to recover high precision even when individual baselines show large fluctuations due to fringe blurring (when caused by statistical fluctuations of normal seeing—a systematic error occurs when windshake is present).

One common calibration difficulty encountered with the Keck aperture masking can be empirically corrected. When the coherence length \( r_0 \) or coherence time \( t_0 \) varies between observing the source and its calibrator, the overall ratio changes between the fringe power and the total flux on the detector. Fortunately for aperture-masking data, this change is nearly constant as a function of baseline, for baselines longer than the coherence length (\( \sim 0.5 \) m at \( K \) band). In practice, this means the observed visibility function will approach a non-unity visibility at short baselines (e.g., \( V_0 = 1.05 \)). As long as there is no significant flux coming from large scales (\( \sim 0.5' \), a reasonable assumption at these wavelengths, but not strictly true because of scattering by dust), we can renormalize the visibility and recover reasonable data quality (\( \leq 10\% \) visibility errors on the longest baselines).

We have applied an empirical correction (simple scaling) for each epoch of aperture-masking data before combining with IOTA data. An overall scaling of the visibility does not usually affect the image reconstruction process but can here because we are combining the Keck data with IOTA-FLUOR results. We have chosen to apply this “correction” to all the Keck data rather than be selective; usually this correction is only a few percent, but it is occasionally larger. Data are presented both with and without this correction. The calibration factor was arrived at by fitting a Gaussian to the visibility data for baselines shorter than 1.5 m and using the derived \( \gamma \)-intercept extrapolated to zero baseline.

In contrast to the relatively poor visibility calibration of the Keck aperture-masking data, the IOTA-FLUOR experiment can produce visibility measurements with precision of less than 1% under some circumstances (Perrin et al. 1999; Perrin 2003). Achieving this precision requires control of many possible systematic errors, including corrections for chromaticity, detector nonlinearities, and bandwidth smearing. However, this level of precision is not necessary in this experiment for many reasons. First, the Keck aperture-masking data typically suffer from greater (5%–10%) calibration errors because of the effects discussed above, which fundamentally limits our analysis. Second, our sources have relatively low visibility fringes, meaning our IOTA measurements are photon noise–limited (or limited by knowledge of the calibrator stellar sizes) and not limited by systematic errors in most cases. Third, high-resolution structures in the dust shells are expected at the \( \geq 1\% \) level but cannot be modeled/imagined without orders of magnitude more data; this acts as a kind of “noise” on the measurement that cannot be expected to be fitted by simple models.

As an aside, we expect it to be quite difficult to achieve 1% absolute precision for broadband fringe measurements when the source and calibrator have quite different spectra (as for dust-enshrouded targets); narrowband filters and/or low-resolution spectroscopy should always be used for precision visibility measurements. Hence, while we do not claim precision of less than 1% here, we do validate in the next section that our precision is \( \leq 3\% \) based on internal consistency checks and comparison with stars with previously measured diameters.

### 3.4. Validation

Tables 2 and 3 contain the observing and calibrator information for sources observed as part of our validation experiments, including RT Vir, R Leo, W Hya, and R Hya. Originally, the last three were observed to check the internal consistency of the data since the observations involved many configuration changes probing different resolutions. Figure 1 shows the \( u-v \) coverage and visibility data for RT Vir. Although in general we show averaged visibility data, here we present each individual visibility measurement (and error) in Figure 1 (middle). In this panel, we also show the expected calibration errors based on the uncertainty in the calibrator diameters. In rare cases in which the calibrator uncertainties are not significant, we have assumed a floor of 3% systematic error that might arise from unmodeled chromatic effects (based on software simulations of maximum miscalibrations possible from strong chromatic differences between source and calibrator using a model of the FLUOR coupler).

We have fitted uniform disk models to these data and have separately calculated the statistical and systematic errors. Perrin (2003) presented a sophisticated analytical method for handling this situation in interferometry data analysis. An alternate method, employing bootstrap (Efron & Tibshirani 1993) and Monte Carlo sampling, is used here. For determining the statistical error, random subsets of averaged data (from each facility) are generated and a best-fit diameter is calculated for each case. Variance in the fit parameters directly yields the statistical errors, and this method does not require assumptions concerning the noise distribution.

For the systematic errors, we have used a Monte Carlo method to vary the sizes of the calibrators used, given the uncertainties from Table 3. Usually systematic error slightly dominates random error in this experiment, although neither affects the estimated sizes dramatically because the targets are generally heavily resolved. Note that all averaging occurs by using the original \( F^2 \) and not the \( F \) in order to avoid bias for noisy data sets; however, we prefer to present our results using
V (which is fully equivalent, since the errors are small after averaging).

The fit to the RT Vir data acts as a “truth test” for our data analysis pipeline. The visibility data span a range of 0.2–0.7, allowing a robust test of calibration. Figure 1 (right) shows the result of fitting a uniform disk to the data set, allowing the visibility at the origin (V0) either to float or to be fixed to unity. For these two cases, we found the diameter to be 12.4 ± 0.1 ± 0.2 and 12.6 ± 1.0 ± 0.4 (the two error estimates are for statistical and systematic errors, respectively, following standard convention). Most importantly, the reduced χ² ≤ 1 indicates a high level of internal consistency to the data calibration. Our measurement is similar to the second of the two diameters reported by Perrin (1996): 13.06 ± 0.15 or 12.36 ± 0.27 mas, depending on data selection (see Perrin 1996 for more detailed discussion on this particular source).

When V0 is not fixed to unity, a slightly better fit is found with V0 = 0.96. This slight deviation from a perfect uniform disk could be due to many plausible mechanisms other than miscalibration, including changes in photospheric size between 2000 February and April, a non–uniform-disk photospheric profile for this late-type star (M8 III, semiregular pulsator), or a small amount of scattered light from the known circumstellar dust shell (Hron, Aringer, & Kerschbaum 1997). Regardless, we have shown an internal consistency of less than 3% for our data pipeline. While the true internal calibration might be better than this, the data quality starts to be become limited by systematic errors.

3.4.2. Comparing Keck Aperture Masking and IOTA-FLUOR Data

While most of our targets are complicated dust shell sources, a few “simple” sources can act to test the relative calibration between the Keck masking and IOTA-FLUOR data. This comparison is important since the interferometry methods employed are clearly very different: Keck masking used image plane combination with narrow bandpass filters, while IOTA used a fiber combiner over a broad wavelength band.

Figures 2, 3, and 4 contain the u-v coverage and two-dimensional visibility from Keck aperture masking for R Leo, R Hya, and W Hya. The low declination of the latter two sources causes the 21 m physical baseline at IOTA to be projected to ∼11 m, thus providing a near-overlap with the 9 m longest baselines employed at Keck. This overlap regime allows another good check of the relative calibration procedures. The Keck masking data reveal these sources to be fairly circular, as expected. A separate calibrator study has shown that we expect 10%–20% asymmetries from windshake and other systematic errors for sources of this size (N. Murphy 2003, private communication). Hence, any small residual asymmetries seen are likely to be miscalibrations and are not modeled here.

Figures 5, 6, and 7 show the azimuthally averaged data, both before and after applying the empirical Keck corrections described above in § 3.3. In addition, the results of the uniform disk fits are shown, following the same procedure described above for RT Vir. The final results of uniform disk diameter fits and relevant comments can be found in Table 4.

R Leo (Fig. 5) shows a surprisingly good agreement at long and short baselines, completely consistent with a uniform disk with diameter 30.2 ± 0.2 ± 0.3 mas. This is contrary to recent findings of Perrin et al. (1999), who found strong evidence for deviations from uniform brightness, possibly due to (time-variable) molecular opacity effects (e.g., Mennesson et al. 2002; Jacob & Scholz 2002).

The shortest IOTA baselines and the longest Keck baselines are similar for R Hya and W Hya (Figs. 6 and 7). Extrapolations
of the Keck visibility show good agreement, at the ~5%–10% level, consistent with expected calibration errors of Keck data themselves (additional data of HD 62623, VY CMa, and IRC +10420, presented in § 4, also contain baseline near-overlaps and confirm this result). We conclude that any systematic errors resulting from the use of different filters at Keck and IOTA are less than other known sources of error.

R Hya and W Hya each show systematic deviations from a uniform disk profile shown in Figures 6 and 7, evident from the large reduced $\chi^2$. While miscalibration could explain some of the changes, the presence of dust emission and/or molecular layers in the upper atmosphere could also explain the discrepancies. Our use of different filter bandpasses for Keck and IOTA affects our ability to study this effect, since molecular absorption dominates near the edges of the $K$ band (Thompson, Creech-Eakman, & van Belle 2002) and is not probed by the Keck narrowband filters. Our observations highlight the need for more systematic study of Mira photospheres using narrowband filters or spectroscopy.

Last, we consider a few miscellaneous effects that could affect the absolute data accuracy. For IOTA-FLUOR, calibration of the “effective” wavelength and corrections for bandwidth smearing can be important for sources observed at and beyond the first null of the visibility pattern. In order to estimate the size of this first effect, we considered a simple model of the $K'$ filter and a reasonable range of effective temperatures, finding that the effective wavelength can only shift by ~1%. Bandwidth smearing destroys any true nulls in a visibility curve because only a single wavelength experiences a null for a given projected baseline (thus, nonnulled wavelengths dominate signal when a broadband filter is used). For IOTA-FLUOR characteristics, the visibility minimum is $V \sim 2\%$ at the location of the “nulls” and the peaks are diminished by $\Delta V \sim 0.003$. This effect has been modeled for R Leo given the specific parameters of these new observations, and it was found not to significantly change the diameter estimation above.

3.5. Data Quality Summary

Given that these results represent the first use of IOTA-FLUOR data by our group and the first combination of them with Keck data, we have detailed the statistical and systematic errors encountered in a number of validation experiments. We have shown that the IOTA-FLUOR data pipeline is self-consistent with less than 3% precision in visibility for the test...
observations of RT Vir. We find good agreement between visibilities measured at Keck and IOTA when using similar baselines on a common source, although detailed testing of this is currently limited by poor absolute calibration of Keck data at the longest baselines (~10%). These demonstrations are critical to give confidence in the fidelity of the results presented in the next section (and future papers that utilize these data), where challenges to data interpretation include large gaps in the baseline coverage and high uncertainties in the source models.

4. RESULTS AND DISCUSSION

In this section, we present the visibility data for six targets with resolved dust shells: HD 62623 (A3 Iab), IRC +10420 (F8 I), VY CMa (M3/4 I), NML Cyg (M6 I), VX Sgr (M4–9.5 I), and IK Tau (M10 III). The sources are at different states of stellar evolution and have a range of masses/luminosities. In this section, we discuss the data, modeling, and imaging results for each source individually. Detailed modeling will be pursued in future papers using more sophisticated techniques.

In some cases, simple radiative transfer models were used to interpret the visibility data and to compare with previous results. We consider only spherically symmetric models consisting of a central star (with radius $R_*$ and effective temperature $T_*$) surrounded by a dust shell with a power-law density profile (usually $\rho \propto r^{-2}$, uniform outflow). The dust is assumed to begin at $R_{\text{in}}$ and extend to $R_{\text{out}}$. The dust shell optical depth was parameterized in terms of $\tau_{2.2 \mu m}$. Additional details regarding the dust optical properties are given on a case-by-case basis below.

Figures 8 and 9 contain the $u$-$v$ coverage of our observations. Most targets were observed on at least two IOTA baselines, and all have extensive visibility data for baselines shorter than 9 m from Keck aperture masking. The IOTA baselines tend to be oriented mostly north-south because of the geometry of the array. Because of this, low-declination sources have relatively smaller $v$-components, reducing the attainable angular resolution.

4.1. “Peculiar” A2 I Supergiant HD 62623

The peculiar A2 I supergiant HD 62623 has a significant IR excess recently modeled as due to the presence of circumstellar dust (Plets, Waelkens, & Trams 1995; Bittar et al. 2001). Bittar et al. (2001) used multiwavelength Keck aperture-masking data to constrain radiative transfer models of the putative dust shell. Here we present additional Keck data and longer baseline IOTA data, which confirm that the dust shell is indeed partially resolved.
No definitive signs of asymmetry were found in the two-dimensional visibilities and closure phases of HD 62623 at 2.2 μm for three different epochs. If the dust in this system is arranged in a circumbinary disk around the short-period (≈137 days) binary in this system (binary separation is unresolved by the interferometer, major axis \( a \approx 0.1 \) AU \( \sim 0.14 \) mas at 700 pc; Plets et al. 1995), we conclude that the disk is viewed at a relatively low inclination (i.e., the disk is near face-on if the disk geometry is valid).

Figure 10 shows the azimuthally averaged Keck masking data along with the longer baseline data from IOTA. The IOTA data are consistent with the Keck data and confirm that the dust shell is partially resolved. In order to further explore the consequences of these observations, we have generated a simple radiative transfer model that can fit the visibility data (included on Fig. 10).

Our choice of stellar and dust shell parameters came mostly from the previous modeling work of Plets et al. (1995) and Bittar et al. (2001): \( R_* = 0.33 \) mas, \( T_* = 9000 \) K, \( R_{\text{in}} = 8.3 \) mas (\( T_{\text{in}} = 1500 \) K), \( R_{\text{out}} = 1000R_* \), \( \rho \propto r^{-1.5} \) (Plets et al. 1995), \( \tau_{2,2} = 0.16 \), and \( a = 0.75 \) μm. Note that at a distance of 700 pc, this inner radius corresponds to 5.8 AU, much larger than the binary separation (≈0.1 AU). For this modeling we used the publicly available radiative transfer code DUSTY (Ivezić, Nenkova, & Elitzur 1999), incorporating the (warm) silicate optical constants of Ossenkopf, Henning, & Mathis (1992).

We emphasize that a large grain size (\( a = 0.75 \) μm) was used in order to fit the visibility data (as found first by Bittar et al. 2001); otherwise, the dust would be heated in excess of the expected sublimation temperature \( T \sim 1500 \) K. While our model fits the visibility reasonably well, the dust does not produce enough infrared emission to match the observed SEDs (photometry extracted from Keck data yielded \( K \) magnitude \( 2.32 \pm 0.10 \), consistent with other recent IR photometry). Because the shell is optically thin, it is difficult to imagine a solution to this discrepancy, even if we abandon the assumption of spherical symmetry.

An alternate theory for the infrared excess was explored by Rovero & Ringleke (1994), who found that it could be explained by using only free-free/free-bound emission from a chromosphere without any dust. However, this model failed to explain the silicate feature seen in IRAS-LRS spectra (Plets et al. 1995). Further, the chromospheric models predict emission arising within a few stellar radii of the photosphere (e.g., Lamers & Waters 1984), so close as to be unresolved by our interferometer observations.

The presence of near-infrared chromospheric emission, however, could help explain the inability of dust shell models to simultaneously fit the SED and near-IR visibility data. This extra emission would not be resolved but would contribute flux to the SED. Future observations with \( \approx 10 \) times greater resolution, such as with the CHARA Interferometer, can directly test this by resolving any chromospheric emission itself.

4.2. Rapidly Evolving F Supergiant IRC+10420

IRC+10420 is an F supergiant, surrounded by a dust shell, thought to be caught in the short-lived phase of stellar evolution of evolving from a red supergiant into a Wolf-Rayet star (Oudmaijer et al. 1996; Blöcker et al. 1999; Humphreys, Davidson, & Smith 2002). The circumstellar envelope is
known to be complex on large and small scales (Humphreys et al. 1997; Blöcker et al. 1999).

Figure 11 shows IOTA data and the azimuthally averaged Keck visibility data. The emission from the dust shell (~38% of total K-band flux) is resolved out on short baselines (~2 m), and then there is a visibility plateau. As was the case for HD 62623, there are low-level asymmetries present in the Keck data (not shown), which we ascribe to residual mis-calibration (the same asymmetry is not present in independent observations). Our results are consistent with similar observations at this wavelength published by Blöcker et al. (1999) for baselines ~6 m. The IOTA visibilities are slightly higher than the long-baseline Keck data but consistent with our expected calibration (see § 3.4).

The IOTA data extend our angular resolution of this system by a factor of ~6 from previous observations. The fact that the visibility appears to remain constant from 9 m out to 36 m supports a model with an unresolved central source (diameter less than 3 mas) containing ~62% of the K-band flux; there is no evidence for a binary companion. We also note that photometry extracted from the Keck observations (K band: 3.63 ± 0.10 mag) is consistent with the trend of decreasing brightness documented by Oudmaijer et al. (1996).

Under normal circumstances, we would attempt to fit the visibility data with a simple radiative transfer model to estimate physical parameters of the dust shell. However, for this source, Blöcker et al. (1999) have convincingly shown that the short-baseline visibility data cannot be fitted by a simple dust-shell model. Furthermore, complicated dust shell features are present in Hubble Space Telescope scattered light images by Humphreys et al. (1997), who argue that we are viewing a bipolar outflow from a near-polar direction; thus, spherically symmetric modeling is difficult to justify for this thick dust shell.

Modeling this system at the required level of sophistication is beyond the scope of this paper. We attempted to produce images of IRC +10420 by using the aperture synthesis software (based on MEM). Unfortunately, miscalibration in the Keck data corrupted the short-baseline visibility (see § 3.3). Since these short baselines are critical for reconstructing the large-scale structure present in this source, imaging must await better calibrated data.

4.3. Red Supergiant VY CMa

VY CMa is a red supergiant with extreme mass loss and high luminosity greater than $10^5 L_\odot$, approaching its end as a Type II supernova (see Monnier et al. 1999b and references therein for a recent summary of the properties of this source). While the mid-infrared emission of the extensive dust shell around VY CMa can be fitted by a spherically symmetric outflow (Monnier et al. 2000a), the visible and near-infrared emission is dramatically asymmetric (Kastner & Weintraub 1998; Monnier et al. 1999b; Smith et al. 2001). Monnier et al. (1999b) used Keck aperture-masking data to image the dust
shell around this source at three infrared wavelengths. Here we improve on this work by incorporating the higher resolution IOTA data.

Figure 12 shows the two-dimensional visibility data of VY CMa for Keck masking observations of 1999 February and 2000 January. Both data sets show striking asymmetric structure consistent with previous epochs. These data are azimuthally averaged and included with the new IOTA data in Figure 13. The IOTA data allow the stellar component to be definitively separated from the dust component and further yield a direct measurement of VY CMa's diameter. First, we fit the diameter by using only the IOTA data (result included in Table 4): $18.7 \pm 0.3 \pm 0.4$ mas, which contributes $\sim 36\%$ of flux at $2.2 \mu m$. This is in reasonable agreement with a previous estimate of $\sim 20$ mas, assuming a $T_{\text{eff}} \sim 2700$ (Monnier et al. 2000a; Le Sidaner & Le Bertre 1996). We emphasize that we measure an apparent diameter at this wavelength, and relation to the true "photospheric" diameter relies on additional assumptions of limb darkening and other effects; late-type stars are known to have different apparent sizes between the visible, near-IR, and mid-IR (Weiner et al. 2000).

We have modeled the dust shell by using a spherically symmetric radiative transfer model in order to illustrate how one can be misled by models when the true source structure is asymmetric and complex. Figure 13 (right) shows the visibility curve of a model with the following parameters: $R_e = 9.35$ mas, $T_e = 2600$ K, $R_m = 65$ mas ($T_m = 1050$ K), $R_{\text{out}} = 5000$ mas, $\rho \propto r^{-2}$ (uniform outflow), and $\tau_{2.2} = 2.18$. The effective temperature was found by fitting to the $K$-band magnitude of VY CMa on 2000 January 26 of $+0.1 \pm 0.1$, based on photometry extracted from Keck data themselves. Since we are using a simple blackbody function to estimate the stellar flux and because we are not fitting to the total luminosity, this temperature is not definitive (although the diameter measurement is direct). Assuming a distance of 1.5 kpc (Monnier et al. 1999b), the above angular quantities correspond to $R_e = 14$ AU and $R_m = 97.5$ AU.

For this source, and the ones that follow, we have used the Wolfire radiative transfer code (Wolfire & Cassinelli 1986) instead of DUSTY, which does not handle cases when the dust temperature is more than half the photospheric temperature, as is often appropriate for the most evolved red giants and supergiants. Here we used the warm silicate optical constants of Ossenkopf et al. (1992), with Mie scattering calculations based on Toon & Ackerman (1981), assuming MRN grain size distribution (Mathis, Rumpl, & Nordsieck 1977). Details on the use of this code have been given previously by Danchi et al. (1994) and Monnier et al. (1997).

As can be seen in Figure 13, the fit to the visibility data is reasonable at short and long baselines but poor at intermediate scales. This fit could be improved by changing the assumed dust properties or adding another dust shell in order to modify the visibility curve. However, in this case, unmistakable evidence in the closure phases and visibility amplitudes shows that the deviation here comes from the fact that the dust shell is highly asymmetric. To better visualize the dust distribution, we have incorporated the high-resolution IOTA data into the image reconstruction process, although current software limitations (see § 3.1) required an ad hoc approach. Figure 14
shows the image reconstruction results by using the 1999 February masking data, with and without IOTA information. The left panel shows the image using only Keck data, and this epoch looks very similar to previous ones published by Monnier et al. (1999b).

When only Keck data are used, the central source appears here to be slightly resolved and elongated (see Fig. 14, left). While it is not impossible that the central star of VY CMa is highly elongated, it is more likely an artifact of the MEM algorithm (Narayan & Nityananda 1986), which attempts to spread out the light as much as possible consistent with the maximum spatial resolution of the data. In Figure 13, which incorporates IOTA data, we have shown that the central star contributes ~36% of the K-band flux and is ~18 mas in size. We can include this high-resolution information in the MEM fit by using the MEM prior, which is the default map that MEM uses when the data cannot constrain the solution.

The technique of using the MEM prior to incorporate the presence of a compact central source known from either the SED or longer baseline data has already been explored by Monnier et al. (2003) and Tuthill et al. (2002); more discussion of this method can be found in these references.

### Table 4: Results of Uniform Disk Fits

| Source Name | Uniform Disk Diameter$^a$ (mas) | Comments |
|-------------|---------------------------------|----------|
| IK Tau      | 20.2 ± 0.2 ± 0.3                | Large deviation from uniform disk; see text for other provisos |
| NML Cyg     | 7.8 ± 0.4 ± 0.5                 | Unexpectedly small; large gap in baseline coverage |
| R Hya       | 23.7 ± 0.8 ± 0.6                | Some deviation from uniform disk ($\chi^2 \sim 2$) |
| R Leo       | 30.3 ± 0.2 ± 0.3                | Excellent fit to uniform disk |
| RT Vir      | 12.4 ± 0.1 ± 0.4                | Good fit |
| VX Sgr      | 8.7 ± 0.3 ± 0.1                 | Good fit (IOTA data only) |
| VY CMa      | 18.7 ± 0.3 ± 0.4                | Good fit; star contributes 36% of K-band flux |
| W Hya       | 42.5 ± 0.7 ± 0.4                | Poor fit ($\chi^2 \sim 5$) |

$^a$ The best-fit uniform disk diameter (for $\lambda = 2.16 \mu$m) is followed by estimates of the statistical error, then by an estimate of the systematic error (see text in § 3.4). The systematic error is usually dominated by uncertainty in the calibrator diameter. We emphasize that we measure an apparent diameter, and the relation to the true “photospheric” diameter relies on additional assumptions of limb darkening and other effects; some late-type stars are known to have different apparent sizes between the visible, near-IR, and mid-IR wavelengths (e.g., Weiner et al. 2000).
Fig. 8.—UV coverage of the new interferometric observations for (a) HD 62623, (b) IRC +10420, and (c) VY CMa

Fig. 9.—UV coverage of the new interferometric observations for (a) NML Cyg, (b) VX Sgr, and (c) IK Tau
Figure 14 (right) shows the image reconstruction by using a prior of an 18 mas star surrounded by asymmetric extended emission (based on previous imaging of Monnier et al. 1999b). While these two image reconstructions are very similar to each other (indeed, both fit the data with a reduced $\chi^2$), there are some details in the new image that are important. The dust distribution forms more of an arc to the south of the star and is less "clumpy." Without sufficient long-baseline $u$-$v$ coverage, the MEM (or any other) method by itself cannot precisely image dust very close to the stellar photosphere without the additional information of the stellar size and flux contribution.

Interpretation of this dust shell is complicated by its high optical depth. These new results confirm previous indications by Kastner & Weintraub (1998) and Monnier et al. (1999b) of bipolar dust distribution (the dusty "disk" is oriented roughly east-west). The $K$-band light arises predominantly from the southern "pole" of the dust envelope, where the relatively low optical depth allows hot dust emission near the star to be seen directly and also allows scattered light to escape into our line of sight. With high-fidelity images of this complicated dust shell, we can begin proper-motion studies, as has already been demonstrated for IRC +10216 (Tuthill et al. 2000a). We hope to image new dust production episodes as they happen and to deduce the physics of mass loss by following the time evolution of the circumstellar environment.

4.4. Red Supergiant NML Cyg

NML Cyg is an extreme red supergiant surrounded by an optically thick dust envelope. Mid-infrared interferometry uncovered strong evidence for multiple shells of dust (Monnier et al. 1997). This basic result was confirmed and explored further by new near-infrared speckle measurements of Blöcker et al. (2001). Our new observations allow this dust shell to be imaged with unprecedented fidelity by separating the dust emission from the stellar emission.

Figure 15 shows three separate Keck masking observations of NML Cyg. As was the case for VY CMa, the strong asymmetry is repeated in each independent measurement and thus can be reliably associated with source structure and not miscalibration. NML Cyg does not show large closure phases, indicating that the emission is largely centrosymmetric (Monnier 2000), in marked contrast to VY CMa, which showed large closure phases resulting from the highly asymmetric nebula (see Fig. 14). Photometry from Keck found an NML Cyg $K$ magnitude of $+0.55 \pm 0.10$ at this epoch.

Figure 16 shows the azimuthally averaged Keck data along with limited IOTA measurements. The large gap between the two baseline ranges makes interpolation uncertain. A uniform disk was fitted to the longest baseline Keck data and IOTA visibilities, and the result (diameter $7.8 \pm 0.4 \pm 0.5$ mas) is shown in Figure 16 (right); this diameter estimate should be considered an upper limit until more extensive data fully characterize the "knee" or "break" in the visibility curve between circumstellar and photospheric emission. Since the bolometric luminosity is well constrained by the SED ($\sim 3.5 \times 10^5 L_\odot$ at 1.8 kpc; Monnier et al. 1997), this diameter implies $T_{\text{eff}} \sim 3650$ K, somewhat hotter than expected for an M6 supergiant (e.g., $\sim 3375$ K; van Belle et al. 1999).

Given the recent extensive efforts to model this dust shell, an overly simplistic treatment here would serve little purpose. Instead, we present aperture synthesis images of the dust shell, which allow us to discover asymmetries and clumpiness in a model-independent way.

We present image reconstructions following the strategy adopted in the last subsection for VY CMa. Figure 17 shows image reconstruction both with Keck masking data alone...
and by using a MEM prior to introduce the presence of an unresolved central source (with 59% of flux, based on IOTA data). In this case (unlike VY CMa earlier) the additional prior information has made a dramatic difference between these images. In Figure 17 (left), without the MEM prior containing the central source, the algorithm has created an image with a very elongated central source to fit the asymmetric visibility data. The size and shape of this central source is not physically plausible (i.e., a red supergiant photosphere is not expected to be this large and elongated), and thus we use a MEM prior to incorporate a priori information (derived from IOTA data) concerning the size and shape of the central source.

This example serves as a potent reminder that MEM imaging of extended dust shells around unresolved “point” sources depends greatly on the resolution of the interferometer in the case in which the dust shell is marginally resolved. In this case, there is simply not enough information in the Keck data alone to constrain the large number of images consistent with the visibility data and closure phases. Indeed, both of these images fit the Keck data with a reduced $\chi^2 \sim 1$; it is the addition of a priori information regarding the nature of the stellar component that allows a higher fidelity image reconstruction.

The new image significantly advances our understanding of the NML Cyg dust shell by establishing that the inner circumstellar shell is not spherically symmetric. Astrophysically, the “Keck + IOTA” image can be understood in the context of the H$_2$O maser data of Richards, Yates, & Cohen (1996), who had already found evidence for a bipolar outflow along the

![Figure 11](image1.png)

**Fig. 11.**—Same as Fig. 10, except for IRC +10420 data

![Figure 12](image2.png)

**Fig. 12.**—Visibility data for Keck aperture-masking observations of VY CMa: 1999 February (left), 2000 January (middle), and averaged and smoothed (right). Each solid contour line represents 0.10 in visibility.
Fig. 13.—Same as Fig. 10, except for VY CMa data. The solid line shows the visibility prediction from a simple radiative transfer model (see § 4.3).

Fig. 14.—Maximum entropy image reconstructions of the VY CMa circumstellar environment. The left panel shows an image reconstruction using Keck masking data only and a uniform prior. The right panel shows an image reconstruction using a MEM prior incorporating a 18 mas disk in the center of the asymmetric nebula (see text for further details); the star is shown here actual size. The lowest contour level in each figure represents a 2 $\sigma$ noise level above the background; the subsequent contours are logarithmically spaced, increasing by a factor of 2 for each level. For reference, the 1 $\sigma$ noise limits are 0.09% and 0.026% of the peak for the left and right panels, respectively, a scaling due to the difference in the compactness of the central source.
northwest-southeast axis. We interpret our data as the first definitive detection of the dust asymmetry, showing an equatorial enhancement along the northwest-southeast axis, perpendicular to the maser outflow. This identification could not have been made without combining the Keck with the IOTA data. The SiO maser data of Boboltz & Marvel (2000) have been interpreted as a sign of rotation about a northwest-southeast axis: it is interesting to speculate that the increased dust density seen in our image may be due to stellar rotation.

Bipolar outflows and the associated dust shell asymmetries are not reliably modeled with a spherically symmetric radiative transfer code when the dust shell is optically thick. This can help explain the strong difficulty in fitting the near-IR visibility data at the same time as the SED and mid-IR visibility data (Monnier et al. 1997; Bloécker et al. 2001). The near-IR visibility is strongly affected by the fact that the average dust shell optical depth (which controls the total near-IR emission) is different from the line-of-sight optical depth (which affects the stellar contribution due to extinction). Assuming a different stellar fraction ($\neq 59\%$) causes the reconstructed dust shell to change somewhat in scale but not general morphology; additional data with resolution intermediate between Keck and these IOTA data will allow both the stellar diameter and fractional flux to be precisely measured. Until then, current conclusions should remain qualitative.

4.5. Red Supergiant VX Sgr

VX Sgr is a bright infrared source with strong maser emission, a red supergiant experiencing heavy mass loss. There has been no high-resolution near-IR data published since early speckle results of Dyck et al. (1984), when the dust shell was only partially resolved. Our new data have $\sim 5$ times greater resolution, and the dust shell is easily resolved at short baselines ($\sim 3$ m), allowing the dust and stellar components to be distinguished even without long-baseline IOTA data. The two-dimensional visibility data from Keck show some evidence for asymmetry (i.e., deviations from circularity); however, since the dust contributes only $\sim 20\%$ of the $K$-band flux, we cannot place strong limits on possible asymmetries, given our calibration uncertainties. As was the case for NML Cyg previously, the closure phases for VX Sgr are all small ($\leq 3\arcsec$), indicating that the dust shell is centrosymmetric.

Figure 18 shows the azimuthal averages of the Keck data, along with extensive IOTA data allowing a diameter measurement of the underlying star. The most precise measurement comes by fitting to the IOTA data alone, which have sufficient baseline coverage to constrain the diameter to $8.7 \pm 0.3 \pm 0.1$ mas; this fit can be found in the figure. Also shown is a fit that includes the longest baseline Keck data: $9.5 \pm 0.2 \pm 1.0$ mas. The latter estimate has a large systematic error due to known systematic errors in the Keck calibration at long baselines; however, the two fits are statistically consistent. We conclude that there is a 5% calibration difference between the IOTA and Keck data sets, although we cannot determine the cause (e.g., atmospheric miscalibration, filter bandpass differences).

Despite the calibration difficulties with the aperture masking, which hampers measurements of asymmetries, the azimuthal averages of the three different masking data sets shown in Figure 18 are quite consistent with each other and motivate us to pursue radiative transfer modeling. Because the Keck data resolve the dust shell completely, we have performed modeling using this data set alone (without IOTA data explicitly, but using the angular diameter derived above), also incorporating the
results of Keck photometry, a $K$-band of $-0.2 \pm 0.1$ mag. Figure 19 shows the reasonable fit for a simple model: $R_s = 4.35$ mas, $T_s = 3200$ K, $R_m = 60$ mas ($T_m = 940$ K), $R_out = 5000$ mas, $\rho \propto r^{-2}$ (uniform outflow), $\tau_{2.2} = 0.17$, and with dust properties and grain size distribution the same as described previously for VY CMa.

![Image](image1.png)

**Fig. 16.**—Same as Fig. 10, except for NML Cyg data. The solid line shows a uniform disk fit to the longest baseline visibility data.

The diameter of VX Sgr found here is dramatically smaller than assumed in a recent modeling paper of Greenhill et al. (1995). In this paper, mid-IR interferometry from the ISI was used to constrain a radiative transfer model with a stellar diameter of 26 mas (3 times larger than found here!). It is not clear why this previous model assumed such a large diameter of VX Sgr.

![Image](image2.png)

**Fig. 17.**—Maximum entropy image reconstructions of the NML Cyg circumstellar environment. The left panel shows image reconstruction Keck masking data only, using a uniform prior. The right panel shows an image reconstruction using a MEM prior with 59% of the flux in a single 7 mas pixel (the star is shown here actual size). This image reconstruction allows a high-fidelity dust shell image to be created by constraining the size and amount of compact stellar emission (based on IOTA data). The logarithmic contour levels each represent a factor of 2 in surface brightness compared to the peak. For the left panel, we have 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, and 64 percent, respectively; for the right panel, we have 0.03125, 0.0625, 0.125, 0.25, 0.5, 1, 2, and 4 percent, respectively.
photosphere (and correspondingly low effective temperature) since the 10 \( \mu \text{m} \) visibility data did not have enough resolution to directly constrain the diameter as we do here. The SiO masers at \( \sim 16.9 \) mas can now be interpreted to lie at 3.9 \( R_\odot \) (instead of 1.3 \( R_\odot \))—a significant difference, showing that SiO masers do form well above the photosphere. We note that the dust shell parameters (which were constrained by the ISI mid-IR measurements) of Greenhill et al. (1995) are quite consistent with our current modeling of the near-IR Keck visibility data.

VX Sgr is a good source for future study, since the dust shell is fairly large and the high signal-to-noise ratio (S/N) closure phases from Keck show it to be centrosymmetric (recall that disk structures possess centrosymmetry; thus, closure phases cannot help in distinguishing circular dust shells from disks). In \( \S \) 4.7, we discuss some lessons learned regarding imaging dust shells around bright sources, such as VX Sgr.

4.6. O-rich Mira IK Tau

IK Tau is an evolved Mira variable star with an optically thick, silicate-rich dust envelope. Here we report the first high-resolution near-IR results since Dyck et al. (1984), extending full \( u-v \) coverage by a factor of \( \sim 3 \).

The Keck masking closure phases are small (close to zero); thus, the dust shell appears centrosymmetric at this resolution (scales \( \lesssim 50 \) mas). As for VX Sgr discussed earlier, the two-dimensional visibility data from masking show signs of asymmetries, which could not be confirmed because of poor data quality. Future observations will focus on the two-dimensional visibilities, while we consider here only the azimuthally averaged visibility in the context of model fitting.

Figure 20 shows the azimuthally averaged Keck data along with longer baseline IOTA data. This combination allows the diameter of IK Tau to be measured for the first time. However, the large gap in baseline coverage between the longest Keck baselines and the IOTA baselines leaves some ambiguity about what data to use. One possibility is to fit a uniform disk to the IOTA data alone, which results in a diameter of...
12.4 ± 0.4 ± 0.1 mas. There are two major problems with this result. First, this small size would require an effective temperature \( T_{\text{eff}} \approx 3000 \text{ K} \) in order to have sufficient luminosity to match observed flux (on the basis of Keck photometry, the \( K \)-band magnitude of IK Tau on 2000 January 26 was \(-1.05 \pm 0.1 \)). This is unlikely considering the strong CO and \( \text{H}_2\text{O} \) bands in the near-IR spectrum (Hyland et al. 1972), which suggest a \( T_{\text{eff}} \approx 2000 \text{ K} \) appropriate for a star with spectral type M10 III. Furthermore, a simple radiative transfer model fit (not shown) with this small stellar component requires a dust shell inner radius of \( R_{\text{in}} \approx 10 \text{ mas} \), so close to the star that the dust would be heated to the unrealistically high temperature of 2300 K.

Instead, we base our uniform disk fit on the baselines longer than 7 m and shorter than 21 m (ignoring the longest baseline IOTA data at 27 m); the result of this fit appears in Figure 20. The fitted diameter, \( 20.2 \pm 0.2 \pm 0.3 \) mas, is more consistent with expectations, corresponding to an effective temperature of \( \approx 2300 \text{ K} \). One major difficulty with this fit is that the prediction at the longest IOTA baseline (\( \approx 27 \text{ m} \)) is not consistent with the measured data. Having dismissed the small 12.4 mas diameter that would be needed to fit both sets of IOTA data, we are left to explain this major discrepancy.

Our preferred explanation for the high visibility at the longest IOTA baselines is that the IK Tau photosphere has strong departures from uniform brightness, due either to hot spots (e.g., Tuthill, Haniff, & Baldwin 1999a) or extended molecular emission (e.g., Tsuji et al. 1997; Matsuura et al. 2002; Jacob & Scholz 2002). Similar effects have already been seen around other late-type O-rich Mira variables (Perrin et al. 1999; Thompson et al. 2002). Given the extreme molecular band structures of M10 III stars, this explanation takes on greater credence. Longer baseline data (preferable with closure phases) will be required to confirm this and also to rule out the presence of a binary companion.

A radiative transfer model has been fitted to the visibility data by using the 20.2 mas photospheric diameter, and satisfactory results were obtained. Figure 21 shows the predicted visibility curve at 2.2 \( \mu \text{m} \) for a model with the following parameters: \( R_s = 10.1 \text{ mas}, \ T_s = 2300 \text{ K}, \ R_{\text{in}} = 35 \text{ mas} \) \( (T_{\text{in}} = 1100 \text{ K}), \ R_{\text{out}} = 5000 \text{ mas}, \rho \propto r^{-2} \) (uniform outflow), and \( \tau_{2.2} = 0.32 \). We used the same dust properties as described previously for VY CMa. Assuming a distance of 200 pc (Le Sidaner & Le Bertre 1996), then \( R_s = 2.0 \text{ AU} \) and \( R_{\text{in}} = 7 \text{ AU} \).

The longest baseline Keck data may not be fully resolving the dust shell, resulting in ambiguity over the fractional flux of the dust shell relative to the star. In order to explore the effects of this, we generated models with successively smaller stellar diameters. In order to maintain a reasonable fit, decreasing the stellar size requires increasing the dust contribution and decreasing the dust shell inner radius. Eventually, the inner radius becomes so small that an unphysical dust temperature is reached. In Figure 21, we have included the visibility curve for the most extreme model with plausible dust temperatures \( (T_{\text{in}} = 1500 \text{ K}), \ R_s = 9.3 \text{ mas}, \ T_s = 2500 \text{ K}, \ R_{\text{in}} = 22 \text{ mas}, \) and \( \tau_{2.2} = 0.27 \) (other parameters the same). This gives a
asymmetric, possessing large nonzero closure phases. We now flux), and (2) most of the previous dust shells were very shell dominated the flux (the central source contributed little these previously published sources and the sources presented imaging problems encountered in this paper, imaging these sources [Tuthill et al. 2000a; Danchi, Tuthill, & Monnier et al. 2000b], and young stars LkH dusty pinwheel nebulae around Wolf-Rayet stars (Tuthill, Monnier, & Danchi 1999b; Monnier, Tuthill, & Danchi 1999a), carbon stars IRC +10216 and CIT 6 (Tuthill et al. 2000a; Monnier et al. 2000b), and young stars LkH 101 and MWC 349 (Tuthill et al. 2000a; Danchi, Tuthill, & Monnier 2001). Despite suffering from the same miscalibration problems encountered in this paper, imaging these sources was rather straightforward. Two major differences between these previously published sources and the sources presented here account for the differing ease of imaging: (1) the dust shell dominated the flux (the central source contributed little flux), and (2) most of the previous dust shells were very asymmetric, possessing large nonzero closure phases. We now discuss the importance of each of these characteristics for imaging.

Consider a highly resolved dust shell with little or no contribution from an unresolved central source: the visibility might be, say, 8% at some long baseline. Miscalibrations are typically multiplicative, and hence a 10% error corresponds to \( \Delta V = 0.008 \) at this baseline, a small fraction of the total dust shell contribution (fraction \( \sim 1.0 \)). However, consider the case in which the dust shell contributes only 20% of the flux (as was the case for VX Sgr in this paper). This means that long-baseline visibility data (when the dust is mostly resolved and only the visibility from the central unresolved star is left) will be quite high, \( V \sim 80\% \). Hence, a 10% error translates to \( \Delta V = 0.08 \), quite a significant effect considering that the dust shell signal is at most only \( \Delta V_{\text{dust}} = 0.20 \). Since the model for the central (point) source is well known, this has the effect of essentially transferring all of the visibility error onto the remaining component, the dust shell.

From the examples above, one can see that for the same size dust shell, the S/Ns of the dust shell visibilities \( \Delta V_{\text{dust}}/\Delta V_{\text{error}} \) go from 1.0/0.008 \( \sim 125 \) with no point-source contribution to only 0.20/0.08 \( \sim 2.5 \) with an 80% point source, considering just multiplicative miscalibrations. Miscalibrations thus have a compounding effect when the central star dominates the flux (both the absolute level of miscalibration increases and the proportional effect compared with the dust shell signal increases). We remark that A. Michelson, in the first interferometry experiments at Mount Wilson (Michelson & Pease 1921), cleverly measured stellar diameters by finding the visibility null \( (V = 0) \), which is zero no matter what the visibility miscalibration might be!

The second reason that imaging was easier with previous sources is because many are very asymmetric. The strong deviations from centrosymmetry meant that much of the morphology information was encoded in the Fourier phases and not just the visibility amplitudes. This effect is enhanced for sources with strong central sources that dilute the closure phase signal of the dust shell. As discussed earlier in this work, the Keck masking experiment (and most interferometers) can measure closure phases quite accurately because atmospheric changes do not bias the measurement (e.g., Monnier 2000). In general, any image reconstruction procedure that incorporates a \( \chi^2 \)-type statistic to measure goodness of fit is most constrained by high-S/N data. Hence, the algorithm implicitly relies heavily on the high-S/N phase information when making images and would be more immune to the miscalibrations in the visibility amplitudes. This is the main reason why imaging of VY CMa (Fig. 14) showed fewer changes than NML Cyg (Fig. 17) when long-baseline IOTA data were incorporated.

While the above problems affect optical interferometers more than radio interferometers, a third difficulty encountered for a few sources here is common to all interferometers: the Fourier coverage of the interferometer must match the angular size of the source being observed. For IRC +10420, the dust shell is nearly too large for the Keck masking experiment (overresolved on short baselines); for HD 62623, the baselines were not long enough to fully resolve the dust shell structures.

In summary, imaging faint centrosymmetric dust shells around bright stars is difficult for reasons both obvious and subtle. All of the effects described above contributed to the problems encountered in this paper. The dust shells for most of the sources presented here contributed less than 50% of the flux and showed closure phase with only small departures.

![Fig. 21.—Results of two fits to the IK Tau 2.2 \( \mu \)m visibility data using simple radiative transfer models. The fit to the short-baseline data is noticeably better using a stellar diameter of 20.2 mas than 18.6 mas; diameters smaller than this range require dust temperature \( \geq 1500 \) K. The disagreement between models and the data at the longest baselines may be due to deviations from uniform brightness across the photosphere of this highly evolved giant star (M10 III).](image-url)
from zero (the only major exception was VY CMa). Imaging these sources will remain challenging until excellent Fourier coverage and excellent visibility calibration (~3% error) can be achieved at the same time.

An interesting consequence of the above difficulties is that there is a tendency to successfully image "strange-looking" dust shells (e.g., VY CMa, CIT 6, and IRC +10216) but to fail to easily image circularly symmetric ones. This is consistent with the fact that the successfully imaged sources (thus far) are not "normal" mass-losing stars but rather are extreme cases that were most suitable for early interferometric imaging. Although current evidence suggests that large-scale dust shell asymmetries are common to mass-losing stars, too few dust shells have been imaged to say this with confidence. As the spatial resolution and sensitivity of interferometers improves, we should be able to image more "normal" evolved stars and begin to know whether strange dust shells are the exception or the rule.

5. CONCLUSIONS

Major results here fall into two categories: stellar diameters and circumstellar dust shells. We were able to measure 2.2 μm stellar sizes of a number of dust-obscured sources for the first time. The VX Sgr diameter was found to be about 3 times smaller than previous modeling, with important repercussions for understanding the SiO maser distribution. The IK Tau and NML Cyg data suggest either photospheric profiles that strongly deviate from a uniform disk or the presence of an extra component to the system that is not being modeled here (e.g., a binary companion). Long-baseline (>20 m) data with closure-phase arrays are needed to understand this better.

These diameter measurements allowed the stellar and dust contributions to be separated in most cases. By increasing the angular resolution in the near-IR by 3–10 times over best current literature measurements, our new data offer strong
constraints for new radiative transfer modeling. In addition, the dust shells for a few sources were imaged by using the maximum entropy method. When assisted by a MEM prior incorporating the long-baseline IOTA data, dust shell asymmetries and clumpiness are unambiguously identified and separated from photospheric light. Unfortunately, we were able to confidently make images for only a subset of these sources, because of problems with calibration of the atmospheric transfer function in the aperture-masking experiment and incomplete sampling at longer baselines; however, these limited results have proved enlightening. Most importantly, we have found a bipolar dust shell geometry for NML Cyg, as earlier suggested by OH, H$_2$O, and SiO masers, giving credence to some alternative mass-loss mechanisms (e.g., involving magnetic fields and/or rotation).

While it lies beyond the scope of this paper, future detailed modeling of the data presented here will dramatically improve our knowledge of these sources, and our results point the way toward new classes of dust shell models. It has lately been fashionable to extend spherically symmetric radiative transfer modeling up to (or beyond) the range of applicability, by incorporating multiple dust shells and unusal dust properties to fit multiwavelength dust shell observations. When viewed together with other recent aperture-masking results (see Fig. 22), the new images presented here strengthen the argument that clumpiness and global asymmetry should be considered more seriously as the main explanation for the observed deviations from simple uniform-outflow models. We suggest that global dust shell properties are best derived from mid-IR observations where dust emission dominates stellar and the effects of clumpiness are better “averaged out” by the intrinsically larger emission volume in the mid-IR. Presumably, the larger emission volume will encompass many such “clumps,” as well as a longer span of mass-loss history, and should represent average dust shell properties more faithfully.

We have also shown examples of how MEM imaging of interferometry data can yield very different dust shell images, depending on the MEM prior being used, and have discussed the difficulties in imaging faint dust shells around bright stars. We recognize and emphasize that optical interferometry is still at an early stage of development, and recent image reconstructions cannot be interpreted as straightforwardly as those derived from the Very Large Array (VLA) or other radio interferometers. The use of a priori information is critical for accurately interpreting data from marginally resolved sources, and new imaging software is needed to facilitate this (the method used here was admittedly ad hoc). All the visibility data here (Keck masking and IOTA) have been converted to the new FITS format for optical interferometry data (OI-FITS) and are available upon request.

Results from the IOTA interferometer would not have been possible without continued support from the Smithsonian Astrophysical Observatory. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and NASA’s Astrophysics Data System Abstract Service. Some data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Keck Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The GETCAL program is a product of the Michelson Science Center (IPAC, Caltech).

APPENDIX

IOTA-FLUOR DATA REDUCTION DETAILS

A1. BASIC PROCEDURES

Reduction of the FLUOR data was carried out by using custom software developed using IDL, similar in its main principles to that described by Coude´ du Foresto et al. (1997).

The major steps of the data reductions are as follows:

1. **Data inspection**.—The raw fringe data are background subtracted and inspected. Cosmic-ray hits and other detector anomalies are automatically detected and removed. Visual inspection of the power spectra allows for flagging of data corrupted by instrumental problems, in particular delay line vibrations. Although troublesome, these problems are easily identified and removed from the data stream.

2. **M-matrix**.—Coude´ du Foresto et al. (1997) described the use of the M-matrix for removal of photometric fluctuations and normalization of the fringe amplitudes. The M-matrix is chromatic and thus must be measured separately for each source and calibrator. The stability of the M-matrix during the night is a useful diagnostic of data quality.

3. **Removal of photometric fluctuations**.—During poor seeing, rapid coupling fluctuations will contain high-frequency power that mimics real fringes. The interferometric channels have the incoherent part of the flux removed by using the photometric signals and the M-matrix, which eliminates scintillation and coupling fluctuations (a strong effect).

4. **Fringe normalization**.—In each scan, the expected fringe envelope for 100% coherent light (unity visibility) is calculated from the photometric and M-measurements (e.g., Coude´ du Foresto et al. 1997), which allows for precise calibration of the observed fringe visibility independent of the atmosphere. Coude´ du Foresto et al. (1997) advocate dividing the fringe data by the envelope at this stage; however, we have pursued a different strategy, which is more robust for low light levels and is described in the next section of this appendix.

5. **Power spectrum measurement**.—Next the power spectra are calculated for each scan. Noise sources cause a bias in the power spectrum that must be removed. The contribution from read noise is estimated from calibration measurements of dark sky, while the remaining bias (from photon noise and uncorrected scintillation) is estimated by measuring the power at frequencies both above and below the fringe frequency and interpolating for the intermediate (fringe) frequencies; this bias term is subtracted for each scan. For

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11 See http://www.mrao.cam.ac.uk/~jsy1001/exchange.
the classical FLUOR analysis from Coudé du Foresto et al. (1997), this “power” is directly proportional to the $V^2$ (squared visibility) and can be averaged. In our method, we combine this measurement with the normalization factor appropriate for that scan and make a weighted average of the normalized scans by using bootstrap sampling (Efron & Tibshirani 1993).

6. **Instrumental response.**—The above procedure is repeated for the target and calibrator stars. After correction for finite size effects, the calibrator $V^2$ are used to monitor the instrumental transfer function as a function of time. Using simple linear interpolation to estimate the transfer function at the times the target observations were made, we divide the target $V^2$ by the interpolated calibrator $V^2$ to yield a final calibrated measurement of $V^2$.

7. **Standard data quality checks.**—We always analyze the two interferometric channels independently and also apply both the classical FLUOR method and our new normalization scheme in parallel. Our results from the two methods, and for both fringe outputs, are statistically and internally consistent for bright sources.

**A2. NORMALIZATION SCHEME**

Here we describe more quantitatively the novel normalization procedure used in the IOTA-FLUOR data reduction. The method of dividing by the fringe envelope, as described in detail by Coudé du Foresto et al. (1997), does correct for the varying photometric signal strengths but amplifies noise when the signals are small. For bright sources, signals are never small, and thus this limitation poses no problem; in fact, dividing by the envelope (sample by sample) maximizes the precision of observations when limited by the calibration of coupling fluctuations (i.e., when one is not limited by detector read noise or photon noise). However, in the experiment reported here, we observed low-visibility sources that had an S/N (in a single scan) that was sometimes below the threshold used by traditional FLUOR analysis (S/N ~ 3).

In our method, we measure an average normalization for each scan based on the photometric signal. Hence, rather than treating each scan equally when taking the power spectrum, we have assigned a normalization that both weights the average power spectrum and also allows the weighting to be done in a statistical way that is free of bias. Here we briefly describe the method (see Coudé du Foresto et al. 1997; Monnier 2001 for more background on the notation and related methods).

As already mentioned, the incoherent flux that appears on the interferometric channels $(I_1, I_2)$ is a linear combination of the signals that appear on the photometric channels $(P_1, P_2)$; the $\kappa$-matrix can be used then to “predict” $(I_1, I_2)$ given $(P_1, P_2)$. In addition, we can use the components of the $\kappa$-matrix to predict the maximum amplitude of the coherent part of the interferometric channels. This can written as

$$I_1 = \kappa(P_1, I_1)P_1 + \kappa(P_2, I_1)P_2 + 2\sqrt{\kappa(P_1, I_1)\kappa(P_2, I_1)\kappa^2(t)} \gamma(t).$$

(A1)

Here $\gamma(t)$ is the mutual coherence function and encodes the fringe visibility, the quantity we wish to measure. Usually $\gamma$ is temporally modulated by adjusting the relative path lengths in the two arms of the interferometer. An equation for $I_2$ follows from the above. Hence, for perfect coherence $\|\gamma\| = 1$, the maximum measured fringe amplitude would be *not normalized by mean flux*

$$I_1^{\text{envelope}} = 2\sqrt{\kappa(P_1, I_1)\kappa(P_2, I_1)P_2}.$$  

(A2)

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**Fig. 23.**—Normalization scheme illustrating the new calibration method being employed for analyzing IOTA-FLUOR data. The (bias-corrected) fringe power observed in each fringe scan (of 200) is plotted against a “normalization” factor estimated from the photometric channels of FLUOR. The $V^2$ is simply proportional to the slope of this relation, which is plotted here along with its uncertainty. For this single data set, the formal uncertainty in the slope is 1.3% in $V^2$, which is only 0.65% for the visibility.
In the power spectrum method, the \( V^2 \) is measured because it is free of bias from read noise and photon noise. By applying Parseval’s theorem to the coherent part of the fringe interferogram, we can understand this integration of the fringe “power” in the Fourier (frequency) space as equivalent to the integration of the square of the fringe envelope in time. Hence, we intend to normalize the measured fringe “power” by the average of

\[
(P_{envelope}^2) = 4\kappa(p_1, t_1)\kappa(p_2, t_2)P_1P_2.
\]

Figure 23 shows an example of this method applied to one interferometric output of a single observation set of a bright source (\( \sigma \) CMa). This figure shows that the (bias-corrected) fringe power varies by a large amount because of coupling fluctuations but that our “normalization” factor, calculated from the photometric channels, faithfully tracks this variation. We can also see that the fringe power is very linear with normalization and a simple weighted mean is used to estimate the slope of the relation, a value proportional to \( V^2 \). In this example, the error was calculated by using a bootstrap method and the 1.3% uncertainty in the slope is reflected in the plot.

Typically, one might worry that Poisson and read noise would bias the above normalization. However, one can see that this quantity is not biased as long as \( P_1 \) and \( P_2 \) are uncorrelated on the timescale of a single scan (\( \ll \) s), a reasonable assumption for a long-baseline interferometer where the atmospheric distortion above an aperture is independent of the others. Note that this useful statistical property implies that one could also average \( P_1 \) and \( P_2 \) separately, as pointed out by Shaklan, Colavita, & Shao (1992), and still have a good bias-free estimate of the fringe amplitude normalization.

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