MID-INFRARED SIZE SURVEY OF YOUNG STELLAR OBJECTS: DESCRIPTION OF KECK SEGMENT-TILTING EXPERIMENT AND BASIC RESULTS

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ABSTRACT

The mid-infrared properties of pre-planetary disks are sensitive to the temperature and flaring profiles of disks for the regions where planet formation is expected to occur. In order to constrain theories of planet formation, we have carried out a mid-infrared ($\lambda = 10.7$ $\mu$m) size survey of young stellar objects using the segmented Keck telescope in a novel configuration. We introduced a customized pattern of tilts to individual mirror segments to allow efficient sparse-aperture interferometry, allowing full aperture synthesis imaging with higher calibration precision than traditional imaging. In contrast to previous surveys on smaller telescopes and with poorer calibration precision, we find that most objects in our sample are partially resolved. Here, we present the main observational results of our survey of five embedded massive protostars, 25 Herbig Ae/Be stars, 3 T Tauri stars, 1 FU Ori system, and five emission-line objects of uncertain classification. The observed mid-infrared sizes do not obey the size–luminosity relation found at near-infrared wavelengths and a companion paper will provide further modeling analysis of this sample. In addition, we report imaging results for a few of the most resolved objects, including complex emission around embedded massive protostars, the photoevaporating circumbinary disk around MWC 361A, and the subarcsecond binaries T Tau, FU Ori, and MWC 1080.

Key words: accretion, accretion disks – circumstellar matter – instrumentation: interferometers – radiative transfer – stars: formation – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

Theories of planet formation rely on observational estimates of preplanetary disk initial conditions in order to make predictions. By connecting detailed and accurate disk initial conditions with the observed diversity of exoplanetary systems, these theories promise to explain how, when, and where exoplanets form under a wide range of circumstances. Unfortunately, direct measurements of the initial conditions are very uncertain since these regions remain largely unresolved by conventional observing techniques. Indeed, disk theory is still undergoing active revision and new measurements more often reveal puzzling surprises rather than build confidence in pre-existing models.

Pioneering near-infrared observations of young stellar objects (YSOs) using long-baseline interferometry (Millan-Gabet et al. 1999, 2001; Tuthill et al. 2001) found disk emission sizes that were much larger than expected from the conventional disk theory. This has been successfully interpreted in terms of an optically thin cavity surrounding the star, in contrast to previous assumptions of an optically thick disk extending to stellar surface (Monnier & Millan-Gabet 2002; Natta et al. 2001; Monnier et al. 2005). While most work has been done for the intermediate-mass Herbig Ae/Be stars, this general pattern is seen even for the young Sun analogs, the T Tauri stars (Akesson et al. 2005; Eisner et al. 2005; Millan-Gabet et al. 2007).

The introduction of this large inner cavity to explain the near-infrared sizes radically changed the inner disk structure in models of these systems, requiring a “puffed-up inner rim” and even a shadowed region behind the rim in some models (Dullemond et al. 2001). In order to probe the disk structure and surface temperatures at these larger radii, we need to observe at longer wavelengths. Mid-infrared size measurements using interferometric techniques promise to probe the terrestrial-planet forming zones around young stars, characterized by temperatures around 300 K. Until recently, most attempts to resolve YSO targets in the mid-IR have failed due to lack of angular resolution (e.g., Liu et al. 1996).

Hinz and collaborators have resolved a few targets using a novel nulling interferometer BLINC on a single 6.5 m aperture telescope (Hinz et al. 2001; Liu et al. 2005, 2007), although most targets were unresolved. Clearly, longer baselines will be needed to increase the angular resolution; the ISI interferometer was the first long-baseline interferometer to resolve thermal emission from a YSO (Lkha101; Tuthill et al. 2002).

A radical technological advance was recently made by the MIDI instrument on the VLTI interferometer, measuring seven mid-infrared sizes of Herbig Ae/Be stars (Leinert et al. 2004) and even taking a spatially resolved spectra across the silicate feature (van Boekel et al. 2004). With baselines ranging from 10 m to 200 m, the VLTI-MIDI system (and also the Keck Interferometer Nuller; Stark et al. 2009) is poised to revolutionize studies of YSO disks in the mid-infrared.

In this article, we describe an experiment employing one of the world’s largest single-aperture telescope, the Keck-1 telescope. We have optimized the calibration precision of our survey by programming the individual mirror segments of the Keck to create multiple nonredundant interferometric arrays. In this method, we allow precise calibration of changing atmospheric conditions while instantaneously sampling full two-dimensional sky angles, allowing the detection of disk elongations and asymmetries with unprecedented precision. Furthermore, we can also survey sources very quickly, allowing...
Figure 1. Left panel: this figure shows the 36 segments of the Keck telescope, color-coded by the tilt imposed using the Keck Active Control System (ACS) for "pattern 6" described in Section 2.1. Right panel: this figure shows the image plane locations associated with the tilts color-coded in left panel. The $10'' \times 10''$ array detector can simultaneously record fringe patterns of the bottom four image plane locations, while the top image is off the chip. (A color version of this figure is available in the online journal.)

a large sample to be observed in only a few nights. Our study complements longer-baseline observations since “short” baselines are needed to distinguish between large-scale disk emission and emission from the compact “puffed-up inner rim” (van Boekel et al. 2005; Tannirkulam et al. 2007). Here, we report the full results of our diffraction-limited size survey of bright YSOs, finding most of them to be resolved and a few to be elongated. In addition to our imaging results, we can investigate the mid-infrared size–luminosity relations for YSOs in detail for the first time. Unfortunately, the recent decommissioning of the only mid-infrared camera on the Keck telescope marks the end of this short-lived but exciting experiment.

2. OBSERVATIONS

2.1. Description of Segment-Tilting Experiment

While mid-infrared imaging with 10 m class telescopes is often considered “diffraction-limited,” precise measurements of partially resolved objects are difficult due to changes in seeing between observing a target object and a point-spread function (PSF) calibrator. In order to circumvent these difficulties, we designed a novel interferometer experiment whereby individual segments of the 36 segment Keck telescope were reconfigured to form four interferometric arrays. Since each segment (1.8 m across) is much smaller than the typical coherence length of the atmosphere ($r_0 = 5–10$ m at $\lambda = 10$ $\mu$m) the results are more robust to variations in seeing conditions. The general approach of apodizing a telescope for interferometry is known as “aperture masking” and the technique has well established advantages over speckle interferometry and adaptive optics for bright targets. We refer the interested reader to the pioneering work of Haniff et al. (1987) and the more recent implementation on Keck for further discussion (Tuthill et al. 2000).

In this work, we formed five interferometric subarrays by tilting the Keck primary mirror segments in a customized pattern. Figure 1(a) shows the Keck segment map color-coded by the applied tilt in a pattern known as “pattern 6” (while other tilt patterns were available, only pattern 6 was used in this work). These tilts caused the stellar image to split into five separate images as illustrated in Figure 1(b). Four of the images (each with light from six segments) were arranged in a $5'' \times 5''$ square which fit perfectly on the $10'' \times 10''$ field of view of the Long Wavelength Spectrometer (LWS) camera on Keck-1, a $128 \times 128$ array with 0.83 platescale (Campbell & Jones 2004; Perrin 2006). The four images were used for science and were measured during data acquisition. The segments contributing to each of the four “science” arrays were arranged in a nonredundant pattern so that the fringe visibilities of all baseline pairs could be extracted using Fourier analysis (see the discussion of redundancy in aperture masking interferometry in Tuthill et al. 2000). Because not all segments could be incorporated into four nonredundant patterns, a fifth image was created using light from the 12 unused segments and this light was projected 15$''$ away from the detector. This approach to aperture masking has a few significant advantages over those employing opaque masks placed in the telescope pupil plane (as done for all previous aperture masking work). First, since light from 24 of the 36 segments are used for science, the collecting area of the Keck primary is efficiently used (compare to near-infrared Keck aperture masking which passes 1%–10% of the incident flux). Second, each of the four subarrays generally has different $(u, v)$ Fourier coverage, which is essential for high fidelity aperture synthesis imaging. Indeed, we have already presented high-resolution images of dusty
Figure 2. Left panel: this figure shows a single frame (90 ms exposure) of a calibrator source using the full pupil and after careful focusing. Although this image is "diffraction-limited," there are significant variations of this PSF with time and seeing conditions and the first Airy ring is usually distorted by phase aberrations. Middle panel: after applying the tilts and pistons for pattern 6 (see Figure 1), we see the light from the star is split into four patterns of overlapping fringes. This image was taken after correcting for the "focus mode" introduced when changing sensor gain setting (see the discussion in Section 2.2). Note the large residual tilt errors on some segments in the top of the image frame. Right panel: the tilt errors from the middle panel were analyzed at the beginning of the observing night and perturbative "optical tweaks" were applied to the segment actuators. The resulting image quality is much improved, showing four interference patterns with well aligned segments. The intensity patterns are all displayed with a linear scale. (A color version of this figure is available in the online journal.)

2.2. Segment-Tilting Procedure

The segments were tilted by sending offsets to the 108 actuators which support and control the Keck primary mirror. For all segments in a subarray, offsets were calculated so that incoming light was reflected to the desired off-axis location in the telescope image plane. Note that in addition to the tilts, a large piston offset was needed to be applied to the segments in order to preserve phase coherence at each of the four new pointing origins. In essence, this extra piston term was necessary so that each subset of segments conformed to a new parabolic surface. These piston offsets can amount to \( \sim 100 \, \mu \text{m} \), critical to correct so that interferometric fringes fall within the coherence envelope of the light (typical narrowband filters have \( \Delta \lambda / \lambda \sim 7 \)).

In normal Keck operation, offsets between mirror segments are continuously monitored and maintained by the Keck Active Control System (ACS), employing capacitive edge sensors. However, our experiment required the edge sensors to operate with a lower gain setting due to the much larger gaps between segment edges encountered here. Unfortunately, the sensor response was not well calibrated under these conditions, and so the actual tilts and pistons realized in practice only approximately the desired configuration (typical errors were \( 5'' \)). Fortunately, the introduced errors were found to be mostly corrected by employing the so-called "focus mode" to the primary. "Focus mode" approximates telescope focus by changing the overall curvature of the Keck primary mirror surface. It is a well-known characteristic of the Keck ACS system that changing sensor gain settings introduce focus-mode error (R. Cohen 2004, private communication).

After correcting focus-mode errors, there were still residual tilt mismatches that affected some segments greatly. Clearly, if the light patterns from individual segment do not overlap well, the fringe power will be reduced and become sensitive to small changes of mirror figure (say, as a function of elevation). In order to optimize beam overlap, we applied a final correction using "optical feedback." That is, we took a set of data at the beginning of each night using our best focus-mode alignment and analyzed the resulting fringe patterns to estimate correction terms for each segment. The algorithm we used employed phase slopes in the Fourier transform of the speckle patterns and would not have worked in the case of a redundant array of segments. We then applied these small corrections as a perturbation to the existing ACS offsets. This entire procedure took approximately 10 minutes and resulted in excellent alignment, with individual segments overlapping with \( \sim \frac{1}{10}'' \) precision, approximately 0.1 \( \lambda / D_{\text{segment}} \). See Figure 2 showing short-exposure fringe images before and after the final "optical tweaking."

It was found that the segment alignment could change by up to \( \sim 0.5'' \) as a function of telescope elevation and other operational variables (e.g., temperature), necessitating recalibration. In general, we solved this by having separate actuator calibration "snapshots" as a function of elevation and using calibrator stars near to each target in time and elevation angle. For bright objects one can use post-processing to measure the tilts of each segment after the fact (akin to the "optical tweak" algorithm discussed above) and apply correction factors. We did not use this extra calibration step in this paper since the correction is signal-to-noise dependent and many of the YSOs were too faint for robust implementation.

2.3. Data Collection Methodology

We employed standard chop-nod observing methods to minimize noise from fluctuating background. The secondary mirror was chopped at 5 Hz with a 10'' throw along the telescope azimuth direction. In general, each saved data frame had a total integration time of 90 ms and we collected approximately 350 individual chop-nod sets. We sometimes employed longer integrations and slower (2.5 Hz) chop cycles for faint targets, and also collected more chop-nod sets to improve signal-to-noise ratio. The 90 ms integration times were sufficient to evolved stars (Weiner et al. 2006; Ireland et al. 2007), Wolf-Rayet stars (Rajagopal et al. 2007), and one YSO (Monnier et al. 2008) with unprecedented angular resolution. Third, tilting segments is operationally straightforward and does not require any hardware modifications—we expect this technique to find application for the next generation of segmented telescopes, e.g., Gran Telescopio Canarias, Cornell Caltech Atacama Telescope, and the Thirty Meter Telescope.
The bulk of the data analysis processing was carried out by the same aperture masking code developed for the near-infrared version of the Keck masking experiment, which is best described in Monnier et al. (1999a) and Tuthill et al. (2000). The only major modification to the data pipeline was a change meant to address significant camera noise in the power spectra of our short exposure images. Here, we used the nod sequences (which did not have any starlight) to estimate a contemporaneous bias power spectrum. This bias subtraction proved necessary and key to extracting reliable results for the faintest targets in our sample.
The overall observing procedure was introduced in the first segment-tilting publications (Weiner et al. 2006; Rajagopal et al. 2007; Monnier et al. 2008). Essentially, each subarray pattern (field of view 3") was analyzed using Fourier techniques, resulting in fringe visibilities for each baseline and closure phases for all triangles. These values were calibrated using point-source reference stars. Some objects are very resolved and the shortest inter-segment spacing is approximately 2 m long, meaning we are missing a lot of short baselines. In order to make up for this, we also analyzed the same data frames using baselines shorter than 1.8 m, which correspond to sampling the many redundant baselines within a segment. These short baselines are useful when reconstructing a wide binary companion during apertures synthesis imaging and helps to constrain information on the percentage of the light coming from a large-scale “halo” for some targets.

The measurements from the four simultaneous (inter-segment) patterns and the results of the “short-baseline” (intra-segment) measurements are merged together and used in subsequent analysis. We used observations of the known binaries MWC 1080 and SVS 20 to validate our position angles and plate scale. The calibrated data are saved in the OI-FITS data format for optical interferometry (Pauls et al. 2005) and are available upon request.

2.5. Analysis of Systematic Errors

Since we expected some of our target samples to be “unresolved” it was critical to establish reliable upper limits in those cases. This required an extensive analysis of systematic errors, as was recently done for near-infrared aperture masking data (Monnier et al. 2007).

The best method for reliable error estimation is to obtain multiple independent data sets for each object. This requirement was a driving consideration in our observing strategy and we obtained multiple observations for all our targets as can be seen in Table 1. By analyzing the consistency between the multiple independent measurements we can provide robust error analysis.

Figure 3 shows a consistency plot for all the data of the Keck segment-tilting experiment using Pattern 6—this includes many objects not part of this YSO survey, but it is still useful for the analysis of systematic errors. Here, we graph the size measured for an object at one time against the size measured for the same target at another time (and nearly always using an independent calibrator sequence). To create this graph we removed known binaries (MWC 1080, T Tau, FU Ori) and the error bars were estimated by analyzing the four-subarrays of pattern 6 using bootstrap sampling techniques. Based on the variation in measured diameter as a function of mean diameter, we can quantitatively estimate our 2σ detection limit as full width at half-maximum (FWHM) 35 mas—our confidence limits as a function of mean diameter are also included in Figure 3.

As was found in Monnier et al. (2007), the calibration precision is nonlinear in the sense that the fractional error is very large for small sizes while being greatly reduced for larger sizes. Our final fitting results (both one-dimensional and two-dimensional) used bootstrap sampling of the different epochs and subarrays to capture calibration and systematic errors. In the case that two independent measurements disagreed dramatically, we removed this target from our sample. As can be seen in Figure 3, this rarely occurred and did not significantly impact our sample size.

2.6. Aperture Synthesis Imaging

Aperture synthesis imaging can be carried out for the most resolved targets, useful for detecting faint diffuse emission and for detecting binary companions. We used the publicly available BSMEM image reconstruction software (Buscher 1994; Lawson et al. 2004, 2006) for aperture synthesis imaging. This program was discussed recently in Monnier et al. (2008) and was validated in more detail against the MACIM (Ireland et al. 2006) algorithm in Zhao et al. (2008). BSMEM uses the maximum entropy method (Gull & Skilling 1984; Narayan & Nityananda 1986) and is similar to the VLBMEM program (Sivia 1987) extensively used in the near-IR Keck masking project (e.g.,
| Name         | Coordinates | V^b | J  | H  | K  | IRAS12 | IRAS25 | Binary |
|--------------|-------------|-----|----|----|----|--------|--------|--------|
| AFGL 490     | 03 27 38.77 | +58 47 00.1 | ... | 10.9 | 8.1 | 5.7 | 58.3 ± 5.8 | 82.4 | 278.0 | N     |
| Mon R2 IRS 3 | 06 07 47.86 | −06 22 56.0 | ... | 13.2 | 9.8 | 6.6 | 109.9 ± 11.0 | 470.0 | 4100.0 | Y (1) |
| AFGL 2136    | 18 22 26.38 | −13 30 12.0 | ... | 15.0 | 12.7 | 7.3 | 37.1 ± 3.7 | 155.0 | 574.0 | N     |
| AFGL 2591    | 20 29 24.87 | +40 11 19.4 | ... | 14.3 | 10.8 | 6.6 | 127.7 ± 12.8 | 439.0 | 1110.0 | N     |
| S140 IRS1     | 22 19 18.28 | +63 18 45.8 | ... | 12.3 | 9.3 | 6.1 | 125.1 ± 12.5 | 308.0 | 1540.0 | N     |
| AB Aur       | HD 31293    | 04 55 45.83 | +30 33 04.4 | 7.1 | 5.9 | 5.1 | 28.3 ± 2.8 | 27.2 | 48.1 | N     |
| MWC 480      | HD 31648    | 04 58 46.26 | +29 50 37.1 | 7.7 | 6.9 | 6.3 | 5.5 | 15.4 ± 1.5 | 10.2 | 10.3 | N     |
| HD 142666    | v1026 Sco   | 15 56 40.02 | −22 01 40.0 | 8.8 | 7.4 | 6.7 | 6.1 | 5.9 ± 0.6 | 8.6 | 11.2 | N     |
| HD 142527    | 15 56 41.89 | −42 19 23.3 | ... | 8.3 | 6.5 | 5.7 | 5.0 | 11.1 ± 1.1 | 10.4 | 21.2 | N     |
| HD 144432    | 16 06 57.95 | −23 43 64.3 | ... | 8.2 | 7.1 | 6.5 | 5.9 | 9.8 ± 1.0 | 7.5 | 9.4 | Y (2) |
| MWC 863      | HD 150193   | 16 40 17.92 | −23 53 45.2 | 8.9 | 6.9 | 6.2 | 5.5 | 18.9 ± 3.8 | 17.6 | 18.1 | Y (3) |
| S1 Oph       | HD 158632   | 17 31 24.97 | −23 57 45.3 | 4.8 | 4.9 | 4.7 | 4.3 | 16.9 ± 1.7 | 15.7 | 10.2 | N     |
| MWC 275      | HD 163296   | 17 56 21.92 | −21 57 21.8 | 6.9 | 6.2 | 5.5 | 4.8 | 15.3 ± 1.5 | 18.2 | 21.0 | N     |
| R CrA        | 19 01 53.68 | −36 57 08.2 | ... | 11.5 | 6.9 | 5.0 | 2.9 | 110.8 ± 11.1 | 111.0 | 222.0 | N     |
| MWC 614      | HD 179218   | 19 11 11.24 | +15 47 15.6 | 7.2 | 7.0 | 6.6 | 6.0 | 20.6 ± 4.0 | 23.4 | 43.6 | N     |
| v1295 Aql     | HD 190073   | 20 03 02.51 | +05 44 16.7 | 7.8 | 7.2 | 6.6 | 5.9 | 6.8 ± 0.7 | 7.2 | 5.5 | N     |
| MWC 480      | HD 31648    | 04 58 46.26 | +29 50 37.1 | 7.7 | 6.9 | 6.3 | 5.5 | 15.4 ± 1.5 | 10.2 | 10.3 | N     |
| HD 142666    | v1026 Sco   | 15 56 40.02 | −22 01 40.0 | 8.8 | 7.4 | 6.7 | 6.1 | 5.9 ± 0.6 | 8.6 | 11.2 | N     |
| HD 142527    | 15 56 41.89 | −42 19 23.3 | ... | 8.3 | 6.5 | 5.7 | 5.0 | 11.1 ± 1.1 | 10.4 | 21.2 | N     |
| HD 144432    | 16 06 57.95 | −23 43 64.3 | ... | 8.2 | 7.1 | 6.5 | 5.9 | 9.8 ± 1.0 | 7.5 | 9.4 | Y (2) |
| MWC 863      | HD 150193   | 16 40 17.92 | −23 53 45.2 | 8.9 | 6.9 | 6.2 | 5.5 | 18.9 ± 3.8 | 17.6 | 18.1 | Y (3) |
| S1 Oph       | HD 158632   | 17 31 24.97 | −23 57 45.3 | 4.8 | 4.9 | 4.7 | 4.3 | 16.9 ± 1.7 | 15.7 | 10.2 | N     |
| MWC 275      | HD 163296   | 17 56 21.92 | −21 57 21.8 | 6.9 | 6.2 | 5.5 | 4.8 | 15.3 ± 1.5 | 18.2 | 21.0 | N     |
| R CrA        | 19 01 53.68 | −36 57 08.2 | ... | 11.5 | 6.9 | 5.0 | 2.9 | 110.8 ± 11.1 | 111.0 | 222.0 | N     |
| MWC 614      | HD 179218   | 19 11 11.24 | +15 47 15.6 | 7.2 | 7.0 | 6.6 | 6.0 | 20.6 ± 4.0 | 23.4 | 43.6 | N     |
| v1295 Aql     | HD 190073   | 20 03 02.51 | +05 44 16.7 | 7.8 | 7.2 | 6.6 | 5.9 | 6.8 ± 0.7 | 7.2 | 5.5 | N     |

**Notes.**

- Coordinates and JHK magnitudes are from Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006).
- V-band magnitudes from SIMBAD.
- IRAS12 and IRAS25 fluxes are from IRAS point source catalog (Joint IRAS Science Working Group 1988) using broadband filters from 8 to 15 μm and 15 to 30 μm.
- Binary references: (1) Koresko et al. 1993; (2) Carmona et al. 2007; (3) Corporet & Lagrange 1999; (4) Smith et al. 2005; (5) Tuthill et al. 2001; (6) Araya et al. 2007; (7) Thomas et al. 2007; (8) Millan-Gabet & Monnier 2002; (9) Cordero et al. 2006; (10) Cohen et al. 1985; (11) Monnier et al. 2006; (12) Leinert et al. 1997; (13) Dyck et al. 1982; (14) Mathieu et al. 1991; (15) Wang et al. 2004.

Monnier et al. 1999b; Tuthill et al. 1999, 2000). While most YSOs were only partially resolved here, a few sources were large enough (on the sky) to be imaged and are discussed in Section 3.3.
stars, 3 T Tauri stars, 1 FU Ori systems, and five emission-line objects of uncertain classification. We have also included other important characteristics of our sample, including \( V \), \( J \), \( H \), and \( K \) magnitudes, our measured 10.7 \( \mu m \) flux within an aperture of 2\arcsec diameter, the IRAS 12 and 25 \( \mu m \) flux, and notation regarding the presence of a close binary companion (based on the literature). Subsequent tables and figures maintain the groupings and target orderings as presented in Table 2.

3.1. Visibilities

Figure 4 shows the squared-visibility data for all our targets as a function of baseline in meters. In this figure, we have
performed \((u, v)\) averaging on scales of 0.45 m. This averaging is done in the \((u, v)\) plane so baselines are only merged when sharing similar lengths and position angles. Here, we did not average together results from the different independent observations, but rather overplotted each separate epoch detailed in Table 1. Thus, the observed scatter represents the combination of observing errors plus any position-angle dependency of the source structure. For instance, consider the visibilities of v892 Tau and MWC 349A which vary for the same baseline length outside the error bars—indeed, these two objects are extremely asymmetric. Also consider that MWC 1080 and T Tau are both well known subarcsecond binary stars—this is obvious in the scattered visibility data.

Figure 5 shows the squared-visibility as a two-dimensional function of \((u, v)\) coordinates, a useful presentation format for detecting elongations. For instance, the extreme asymmetry for MWC 349A and v892 Tau, inferred from the one-dimensional visibility curves, is quite evident here. Also, the large “halo” structure around MWC 361A, indicated by the sharp drop of visibilities as short baselines and then a plateau, can be easily spotted. The binary signatures in T Tau, FU Ori, and MWC 1080 are evident too, although it is difficult to interpret since the sinusoidal patterns are undersampled, requiring analysis through imaging or model-fitting to extract the binary component separation.

### 3.2. Fitting Results

We have characterized the emission sizes of all targets by fitting the visibility data with both a circularly symmetric (one-dimensional) Gaussian model and an elliptical (two-dimensional) Gaussian model. In both cases, we also allowed for a large-scale “halo” component, similar to the model used for near-infrared fitting of YSO visibilities in Monnier et al. (2006) which was motivated by earlier work (e.g., Leinert et al. 2001).

Table 3 contains the complete fitting results from our work. Error bars were estimated through bootstrap sampling of the multi-epoch data as well as from the different subarrays of “pattern 6.” For each fit (one-dimensional and two-dimensional) we also report the best-fit \(\chi^2\) normalized by degrees of freedom. Thus, if the \(\chi^2\) value is greater than \(\sim 1\) then we expect this model to be an incomplete description of the data. For instance, for MWC 349A, the \(\chi^2\) is 4.0 for the circular-symmetric fit but decreases to 1.1 for a two-dimensional Gaussian—we already discussed above that this object was clearly asymmetric. In most cases when the \(\chi^2\) is \(\lesssim 1\) for the one-dimensional fit, then the two-dimensional fit is only marginally better and that there is no statistically significant ellipticity detected. Some targets have high \(\chi^2\) even for the two-dimensional Gaussian model, indicating a more complicated object. This is true for all the embedded YSOs which are generally the most resolved—these objects are ideal targets for aperture synthesis imaging in the next section (Section 3.3).

### 3.3. Imaging

While most of the analysis in this work and the companion paper relies on the size-fitting results, we also report imaging results for the most resolved targets. We used the BSMEM image reconstruction program (see Section 2.6) on all targets and inspected the results. In Figure 6, we collected the images of all the objects that showed structures beyond a simple, partially resolved Gaussian profiles and/or were larger than 70 mas in size. Note there are residual imaging artifacts at the level of a few percent of the peak, especially evident for the binary sources MWC 1080, T Tau, and FU Ori. Notes on individual objects follow.

AFGL 490 has extension to south.

Mon R2 IRS 3 shows nebulosity along a N-NE to S-SW axis and a companion at \(\rho = 836\) mas, \(\theta = 16^\circ 7\), similar position to the companion first reported by McCarthy (1982) of separation 870 mas at PA 13:5.

AFGL 2136 has a slight extension to west-southwest that appears in two independent sets.

AFGL 2591 emission has slight extension to west.

S140 IRS1 shows significant nebulosity to the south.

AB Aur is a prototypical Herbig Ae star which has been claimed to be elongated nearly 2-to-1 along PA 30° by Liu et al. (2005). We rule out this large level of elongation (supported by four separate observations over three different observing nights), although we do find a slight extension along this position angle in our image. Overall the emission is circularly symmetric, consistent with a nearly face-on geometry and in agreement with the conclusions of Mariñas et al. (2006).
v892 Tau was resolved into a circumbinary disk and was discussed in Monnier et al. (2008). Here, we reproduce the image.

LkHα 101 shows a slight elongation along the north–south direction, similar to the reported asymmetry in the near-infrared (Tuthill et al. 2002). Note that we do not have fine enough angular resolution to resolve the dust-free cavity in the center reported by these authors.

R Mon is resolved approximately as much as AB Aur, showing mostly symmetrical emission.

Z CMa is a well known close binary (\(\sim 100 \text{ mas}\)) recently imaged by Millan-Gabet & Monnier (2002). Here, the mid-infrared emission appears extended toward position angle \(\sim 128^\circ\), which is the direction of the FU-Ori type companion. This extension could represent emission from a circumbinary disk or direct IR emission for the FU Orionis component to this system. Most likely, the bulk of the mid-IR emission is from the Herbig Be component of the system and not the FU Ori object.

MWC 349A is very elongated and the imaging shows a symmetric structure oriented along PA 95°, very similar to the PA 100° reported in the NIR (Danchi et al. 2001).

MWC 361A was found to have a large “halo” containing 45% of the flux at 10.7 \(\mu\)m. This halo was over-resolved on our shortest baselines. Our shortest baseline data suggested
that the halo was elongated north–south on arcsecond scales and this is confirmed by independent (standard full-aperture) LWS images taken at 11.6 μm (SiC filter) and 17.65 μm. These images are shown in Figure 7; a full description of these observations and the data reduction appears in Perrin (2006). Note the NS elongation of the extended emission matches the orientation of the binary orbit of MWC 361A measured by Monnier et al. (2006), strongly suggesting that this halo is the remnant of a circumbinary disk. It is remarkable that the mid-IR disk emission is >20 times bigger than the semimajor axis of the binary, indicating a huge disk gap in this system much larger than can be produced by disk clearing through dynamical interactions with the inner binary. Given the early spectral type of the primary star in this system, we suggest that photoevaporation of the circumbinary disk is well underway.

MWC 1080 is binary with ρ = 764 mas, θ = −91:1, comparable to the result of Leinert et al. (1997) of ρ = 760 mas, θ = −93°.

The T Tau companion to the south (which is itself a close binary) is detected at ρ = 639 mas, θ = −170°:9. We attempted a more sophisticated analysis to look for evidence of the tertiary to this system. Indeed, we find that the visibility and closure phase data cannot be fit with a simple binary star (Skemer et al. 2008). However, there are calibration issues regarding field-of-view limitations caused by bandwidth smearing that we have not corrected here. This issue will be tackled in a future paper.

We detect a companion to FU Ori at separation 488 mas and PA of 163°:3 E of N, confirming the report by Wang et al. (2004) of a potential companion at separation 500 mas at PA 161°. As for T Tau, we cannot report a reliable flux ratio due to unresolved issues with bandwidth-smearing effects that have not yet been corrected.

3.4. Comparison to Literature

Our results are generally in agreement with results from the BLINC experiment by Hinz and collaborators (Hinz et al. 2001; Liu et al. 2005, 2007, excepting the elongation of AB Aur), although we note that most of these workers’ measurements were upper limits. We also compared our results to the long-baseline interferometry VLTI data of Leinert et al. (2004) and others (Quanz et al. 2006), finding that the Gaussian fits do not always agree between the two methods (our sizes typically larger). The size discrepancies can be understood if the long-baseline VLTI measurements are more sensitive to the properties of the hot inner wall while the short-baseline (single) Keck data can only probe the large-scale, outer flared disk (see discussion in van Boekel et al. 2005; Tannirkulam et al. 2007; Millan-Gabet et al. 2007). These observed differences appear to confirm the expectations from models that mid-infrared emission comes from (at least) two distinct spatial scales and we will need measurement from a wide range of scales in order to reconstruct the actual disk temperature profile.

4. ANALYSIS

4.1. Size–Luminosity Diagram

A very tight correlation has been found between the near-infrared size of a YSO disk and the luminosity of the host star for Herbig Ae and late Be stars (Monnier & Millan-Gabet 2002; Monnier et al. 2005; Millan-Gabet et al. 2007). This simple correlation arises because the NIR emission only comes from the hottest dust near the evaporation front and the location of the evaporation front is primarily sensitive to a single observable, the central luminosity.

The mid-infrared emission from young stars is expected to come from up to three regions: the hot inner wall located at the dust evaporation radius, a thin surface layer on the disk (e.g., van Boekel et al. 2005; Tannirkulam et al. 2008), and perhaps a circumstellar envelope (“halo”). Thus, the mid-infrared size and flux density will depend on multiple factors in addition to the central luminosity, depending most sensitively on the dust size distributions both vertically (setting temperature) and radially (controlling disk flaring). While it is beyond the scope of this paper to investigate these effects, we will discuss them generally in the context of the mid-IR size–luminosity diagram.

Figure 8 shows the mid-infrared size–luminosity diagram for the stars in our sample, constructed using the same procedure as in Monnier & Millan-Gabet (2002). Our sample represents a factor of 3 times increase in sample size over previous work and spans a large range of YSO luminosity. We used distances and luminosities from Acke & van den Ancker (2004) when available. In this diagram, we find a crude correlation of size with luminosity showing disk emission with characteristic temperatures of 250–900 K spanning about 5 orders of magnitude in luminosity. While the previously published near-infrared size–luminosity diagram shows only about a factor of 2 scatter at a given luminosity, this mid-infrared relation shows much larger
scatter, a factor of 5 or more. The origin(s) of the increased scatter and the breakdown in the size–luminosity relation will be the subject of a companion paper (A. Tannirkulam et al. 2009, in preparation). Here, we will only make general comments.

In Tannirkulam et al. (2008), the large mid-infrared size difference between two “twin” Herbig Ae stars (AB Aur and MWC 275) was explained through the influence of small grains in the AB Aur disk at radii of ~7 AU. These grains absorb stellar radiation effectively, heating up the disk and causing flaring. The origin of these small grains could be due to collisions between planetesimals or the release of small grains as ice-cemented dust agglomerates break apart at about ~10 AU. This example

| Target | One-Dimensional Gaussiana | Two-Dimensional Gaussianb | Comments |
|-------|---------------------------|---------------------------|----------|
|       | FWHM Halo $\chi^2_\nu$ | FWHM (mas) PA Halo $\chi^2_\nu$ |          |
|       | (mas) (%) | Major Minor (deg) (%) |          |
| Embedded Young Stars (Class I Sources) | | | |
| AFGL 490 | 100 ± 5 11 ± 3 7.0 110 ± 4 81 ± 3 20 ± 2 12 ± 2 2.4 | | Faint extension to south |
| Mon R2 IRS 3 | 108 ± 16 39 ± 6 20.0 144 ± 6 88 ± 5 41 ± 2 35 ± 2 6.1 | | Nebulosity and binary at $\rho = 836$ mas, $\theta = 16:7$ |
| AFGL 2136 | 120 ± 3 20 ± 2 2.1 125 ± 5 115 ± 3 44 ± 14 19 ± 2 1.7 | | Faint extension to west-southwest |
| AFGL 2591 | 118 ± 3 9 ± 4 4.2 123 ± 3 111 ± 3 114 ± 7 9 ± 4 3.4 | | Nebulosity to west |
| S140 IRS1 | 134 ± 3 40 ± 1 5.5 136 ± 5 133 ± 4 117 ± 25 40 ± 2 5.6 | | Extensive nebulosity to south |
| Herbig Ae Stars | | | |
| AB Aur | 70 ± 3 11 ± 1 0.4 72 ± 3 68 ± 6 27 ± 25 11 ± 1 0.4 | | Slight extension PA≈30° but mostly symmetrical |
| MWC 480 | 16 ± 20 3 ± 2 0.8 29 ± 24 0 ± 17 29 ± 32 2 ± 2 0.8 | |          |
| HD 142666 | 33 ± 24 4 ± 2 0.6 65 ± 65 0 ± 40 173 ± 56 2 ± 4 0.5 | |          |
| HD 142527 | 50 ± 6 3 ± 1 0.4 55 ± 8 45 ± 4 60 ± 22 3 ± 1 0.4 | |          |
| HD 144432 | 39 ± 5 0 ± 1 1.0 49 ± 14 25 ± 25 103 ± 31 0 ± 1 0.9 | |          |
| MWC 865 | 21 ± 21 2 ± 2 1.0 33 ± 6 8 ± 14 12 ± 21 2 ± 1 0.9 | |          |
| 51 Oph | 0 ± 4 0 ± 1 0.3 0 ± 27 0 ± 1 93 ± 53 0 ± 1 0.3 | |          |
| MWC 275 | 17 ± 16 4 ± 3 1.2 24 ± 24 8 ± 9 60 ± 51 4 ± 3 1.2 | |          |
| R Cha | 69 ± 2 10 ± 1 0.9 77 ± 2 64 ± 2 78 ± 4 10 ± 1 0.6 | |          |
| MWC 614 | 68 ± 4 4 ± 1 0.7 80 ± 3 52 ± 8 17 ± 9 4 ± 1 0.3 | |          |
| v1295 Aql | 8 ± 15 0 ± 1 0.5 34 ± 34 0 ± 1 22 ± 49 0 ± 1 0.5 | |          |
| Herbig Be Stars | | | |
| v376 Cas | 37 ± 3 1 ± 2 0.5 40 ± 3 33 ± 5 134 ± 25 1 ± 2 0.5 | | Resolved circumbinary disk |
| v892 Tau | 210 ± 8 0 ± 3 21.6 244 ± 6 123 ± 7 49 ± 1 1 ± 0 2.1 | |          |
| LHα 101 | 70 ± 3 4 ± 2 0.8 73 ± 2 62 ± 7 180 ± 14 4 ± 2 0.6 | | Slight extension north–south |
| v883 Ori | 43 ± 4 6 ± 2 0.9 46 ± 4 37 ± 10 110 ± 31 7 ± 3 0.9 | |          |
| MWC 147 | 24 ± 14 3 ± 5 0.6 37 ± 14 0 ± 11 52 ± 31 3 ± 7 0.6 | |          |
| R Mon | 94 ± 2 8 ± 1 0.7 97 ± 4 91 ± 2 66 ± 23 8 ± 1 0.7 | | Mostly circularly symmetric |
| Z CMa | 61 ± 4 1 ± 1 2.4 68 ± 2 41 ± 6 137 ± 5 2 ± 1 0.6 | | Faint extension toward companion along PA≈128° |
| MWC 297 | 55 ± 6 2 ± 1 1.2 59 ± 9 50 ± 6 40 ± 21 2 ± 1 1.1 | | Symmetric elongation |
| v1685 Cyg | 29 ± 17 12 ± 6 0.6 56 ± 23 19 ± 19 112 ± 26 11 ± 6 0.5 | | Arcsec-scale halo elongated north–south. See Figure 7. |
| MWC 349 | 81 ± 6 8 ± 3 4.0 94 ± 7 26 ± 15 95 ± 6 8 ± 3 1.1 | |          |
| MWC 361 | 45 ± 17 45 ± 2 0.3 55 ± 14 39 ± 30 17 ± 26 45 ± 2 0.3 | |          |
| v645 Cyg | 46 ± 11 5 ± 4 1.0 55 ± 4 38 ± 19 34 ± 16 5 ± 4 0.9 | |          |
| LHα 234 | 27 ± 19 6 ± 1 0.2 42 ± 42 0 ± 44 91 ± 34 6 ± 2 0.2 | |          |
| MWC 1080 | 0 ± 10 17 ± 3 8.1 0 ± 44 0 ± 1 115 ± 49 17 ± 2 8.4 | | Binary: $\rho = 764$ mas, $\theta = -91:1$ |
| Emission-line Stars of Uncertain Classification (possible Herbigs, B[e] stars, or other) | | | |
| HD 41511 | 0 ± 6 0 ± 2 1.6 19 ± 26 9 ± 9 36 ± 90 0 ± 2 1.7 | |          |
| HD 45677 | 70 ± 3 12 ± 1 1.0 77 ± 3 66 ± 3 70 ± 5 12 ± 1 0.7 | |          |
| HD 50138 | 58 ± 6 1 ± 1 1.4 66 ± 4 46 ± 9 63 ± 6 1 ± 1 1.0 | |          |
| MWC 300 | 49 ± 3 1 ± 1 0.6 57 ± 4 44 ± 2 35 ± 14 0 ± 1 0.4 | |          |
| MWC 342 | 38 ± 22 6 ± 1 1.0 39 ± 11 37 ± 37 107 ± 90 6 ± 2 1.0 | |          |
| T Tauri Stars | | | |
| RY Tau | 49 ± 4 2 ± 1 0.9 59 ± 10 37 ± 25 12 ± 45 2 ± 3 0.8 | | Binary: $\rho = 639$ mas, $\theta = -170:9$ |
| T Tau | 0 ± 13 27 ± 2 3.5 29 ± 21 0 ± 1 1 ± 31 26 ± 2 3.6 | |          |
| GW Ori | 37 ± 20 0 ± 2 0.7 54 ± 7 25 ± 29 107 ± 10 0 ± 5 0.6 | |          |
| FU Orionis Objects | | | |
| FU Ori | 21 ± 22 10 ± 5 1.2 55 ± 27 0 ± 13 65 ± 35 8 ± 4 1.2 | | Binary: $\rho = 488$ mas, $\theta = 163:3$ |

Notes.

a Parameters of one-dimensional Gaussian fits: FWHM in milliarcseconds (mas), percentage of light coming from "halo" on scales larger than ~0.5.
b Parameters of two-dimensional Gaussian fits: FWHM along major and minor axes respectively, position angle (PA) of major axis in degrees east of north, percentage of light coming from extended “halo.”
Figure 6. This figure shows the aperture synthesis images of the most resolved targets in our sample. The intensity scale is logarithmic and is specified in the color bar. North is up and east is left in all figures.

(A color version of this figure is available in the online journal.)

Figure 7. This figure shows imaging of MWC 361A at 11.6 \( \mu \text{m} \) and 17.65 \( \mu \text{m} \) using the LWS camera on the Keck telescope without segment-tilting (first presented in Perrin 2006). We see an arcsecond-scale north–south extension which follows the orientation of the underlying subarcsecond binary in this system (Monnier et al. 2006). This is a remarkable structure suggesting that the circumbinary disk is in an advanced stage of photoevaporation. The intensity scale is logarithmic and is specified in the color bar. North is up and east is left in all figures.

(A color version of this figure is available in the online journal.)

illustrates how variations between targets in the radial dust size distributions can explain some of the scatter in this diagram. Other modifications to the dust distribution, such as dust growth and settling, can also cause significant changes in mid-infrared spectral energy distribution (SED; Dullemond & Dominik 2004; D’Alessio et al. 2006).

Another source of scatter is the presence of binaries. We have indicated close binaries in Table 2 and in Figure 8. For instance, the emission from v892 Tau was recently imaged to be from a circumbinary disk (Monnier et al. 2008) and we see in Figure 8 that v892 Tau is indeed oversized for its luminosity.
We also note that the embedded YSOs all cluster near the top-right of the diagram at high luminosities and low temperatures. This is expected since the high optical depths toward these Class I objects mean their infalling envelopes are still optically thick and we do not expect to be able to see into the warmer inner regions surrounding these protostars. Note that these regions all show complicated, often bipolar, structures (see Figure 6) and that the sizes in this diagram refer only to the central core of emission.

4.2. Size Versus IRAS Color

Leinert et al. (2004) found some evidence that the physical emission scale for the mid-infrared emission (in Herbig Ae stars) was correlated with the IRAS 12–25 μm color, defined as $-2.5 \log F_\nu(12 \, \mu m)/F_\nu(25 \, \mu m)$. This is sensible since redder colors indicate cooler dust temperatures which naturally arise farther from the central star. Unfortunately, this diagram is difficult to use when your target sample spans a large luminosity range. This is because the radius for dust at given temperature depends on the root of central luminosity (see the size–luminosity diagram above). Neither size–luminosity nor the size–color diagram can simultaneously take into account both of these effects. Liu et al. (2007) also explored mid-IR size differences as a function of some SED parameters but his work also suffers from these same limitations.

Despite these drawbacks, we have produced a similar diagram as a way to present our basic results. Figure 9(a) shows our measured Gaussian FWHM size (in milliarcseconds) versus the IRAS 12–25 color. We chose to use the distance-independent angular size instead of the physical size here, just so that our quantities did not depend on the uncertain distance estimates. Within each grouping, we do see some correlations. The Herbig Ae stars do show a correlation, with the striking result that nearly all the objects with colors bluer than 0.25 were unresolved by our survey. The embedded objects also might show a weak correlation. Just as the diagram in Leinert et al. (2004), this size–color diagram does not conserve a target’s position if you take the same disk temperature profile and change the luminosity. We only present this data to illustrate some trends within the sample, but caution against further use of this sort of diagram in subsequent work.

In order to overcome the luminosity and distance dependencies for this sort of diagram, we introduce a new diagram in Figure 9(b). Here, plot the luminosity-normalized ring radius versus IRAS 12–25 color. This is defined as the physical ring radius (AU) divided by the square-root of luminosity (in solar luminosities). This quantity is both independent of distance and also naturally accounts for the expected scaling of emission scale with luminosity (for similar disk temperature profiles). Again, we see a significant correlation for the Herbig Ae stars, although other objects appear to scatter in this diagram. The location of each YSO system in this diagram is diagnostic of the disk flaring and temperature profiles and this diagram will prove useful for future work.

In the next paper in this series, we will be carrying out a radiative transfer study of YSO disks in order to understand the scatter in the size–luminosity diagram and how the deviations correlate with observables such as stellar luminosity and the [12]–[25] μm color. This new work will motivate improved diagrams to be used for plotting basic observational data and will explore the potential for using luminosity-normalized sizes (radius AU/sqrt luminosity) and surface brightness relations.

5. SUMMARY

We have presented a large survey of mid-infrared sizes of YSOs using the Keck telescope. We can reliably resolve disks with size scales down to 35 mas (5 AU at 140 pc), roughly 8x smaller than the formal diffraction limit. We have overcome the traditional calibration problems that have plagued previous
surveys by reconfiguring the Keck segments into multiple nonredundant interferometric arrays.

We have presented a detailed description of the experimental methodology and validated our calibration precision. We have measured the characteristic sizes of all our targets using a Gaussian + Halo model and have presented aperture synthesis imaging when possible. Our atlas of diffraction-limited imaging has revealed the complicated emissions around a sample of Class-I embedded YSOs and also discovered the remarkable photoevaporating circumbinary disk around MWC 361A.

Lastly, we have presented the most complete size–luminosity diagram for YSOs in the mid-infrared. Notably, we found that the mid-IR size–luminosity relation shows a factor of 5–10 scatter for a given luminosity, much larger than the tight correlation seen in the near-infrared. This large scatter can partially be understood in terms of the influence of small dust grains that can be created in collisions between planetesimals in these young planet-forming disks (Tannirkulam et al. 2008). Disk clearing by binary companions and emission from remnant dust envelopes may also contribute to this scatter. With the help of a large grid of radiative transfer models, we will be fully exploring how the mid-infrared sizes correlate with disk properties in the next paper in the series.

While this particular experiment can no longer be carried out due to the absence of mid-IR instrumentation on the single Keck telescopes, we hope our method can be applied on current and future proposed segmented telescopes, such as the Gran Telescopio Canarias, the Cornell Caltech Atacama Telescope, and the Thirty Meter Telescope.

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Facility: Keck: I (LWS)

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