Diffraction-Limited Infrared Imaging of M-Giants at Keck

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Abstract.
Preliminary results from a program of near-IR diffraction-limited interferometric imaging of late-type stars underway at the Keck Observatory are presented. M-giants are attractive targets as they exhibit bright extended emission in the IR which results from astrophysically interesting and poorly understood phenomena such as mass-loss and atmospheric extension. New images at unprecedented angular resolution have revealed the stellar photospheres and circumstellar environments in the near-IR. We report detection of anisotropic mass-loss in the inner regions of the dust shell where nucleation occurs.

1. Introduction

For astronomical sources, such as evolved giants and supergiants, numerous theoretical and experimental studies have underscored the dramatic gains in signal-to-noise ratio (SNR) to be obtained from the use of sparse apertures over more conventional full-pupil speckle interferometry (Roddier 1988, Haniff & Buscher 1992). By masking the pupil of the Keck telescope, we have verified these expected gains in SNR, enabling us to reconstruct complex images with the highest angular resolution in the near-infrared (IR) achieved to date.

With multi-wavelength images spanning the infrared J, H, K and L bands for a number of the brightest Mira variables and evolved supergiants, we have been able to address some of the most pressing questions in the field of late stellar evolution, such as stellar dynamics and mass-loss. Studies in the near-IR are particularly profitable due to the low dust opacity, low contamination from molecular lines, and high luminosity (stellar output peaks in the near-IR). Our measurements of stellar diameters and surface morphologies thus yield information on stellar properties such as pulsational modes, atmospheric structure, giant convective cells and overall photospheric symmetry.

2. Experiment and Observations

Masking of the telescope pupil was achieved by mounting custom-made plates in front of the secondary mirror. An example showing the hole-pattern of our 15-hole mask, as projected onto the Keck primary mirror, is given in Figure 2. There are many constraints in arriving at such pupil geometries, with the primary

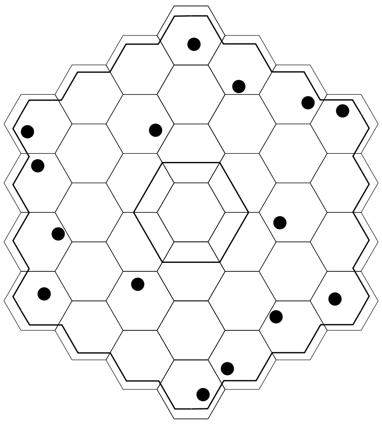

Figure 1. Example of a pupil geometry used for our Keck masking experiment. A 15-hole non-redundant array (dark spots) is shown superimposed over a scaled image of the Keck primary mirror.

concern being to sample the Fourier plane evenly and densely out to the cut-off of the telescope with a *non-redundant* array.

Light passing through the mask was bought to focus in the Near Infra-Red Camera (NIRC), a cryogenically cooled 256×256 pixel InSb array (Matthews & Soifer 1994). The optical configuration yielded an image scale of 20.57 mas/pixel – sufficient to Nyquist sample fringes on the longest baselines in K-band.

An example of a single 134 msec exposure is given in Figure 2. The pattern depicted results from the Airy disks of the small circular sub-apertures being crossed by numerous (105 in this case) fringe patterns arising from interference between each pair of holes. Contributions from each baseline can be separated and measured by taking the power spectrum, as shown to the right, where we have accumulated the mean spectrum over 100 separate interferograms.

Data reduction proceeded by extracting the visibilities and phases from each exposure. Such data are related to the brightness distribution of the science target by a Fourier transform (e.g. Born & Wolf 1964). Although the Fourier phases were corrupted by atmospheric fluctuations, an observable known as the *closure phase* – the sum of baseline phases around closed triangles – has been developed in radio astronomy to overcome this problem. These techniques are now well established at optical wavelengths (Haniff et al. 1987, Roddier 1988).

Raw visibilities were calibrated for the mean telescope–atmosphere transfer function by utilizing nearly contemporaneous observations of point-source stars. After such calibration, Fourier data were inverted to yield images with the help of reconstruction algorithms such as the "Maximum Entropy Method" (Gull & Skilling 1984, Sivia 1987) or CLEAN algorithm (Högbom 1974) – both of which have been used extensively in radio astronomy.

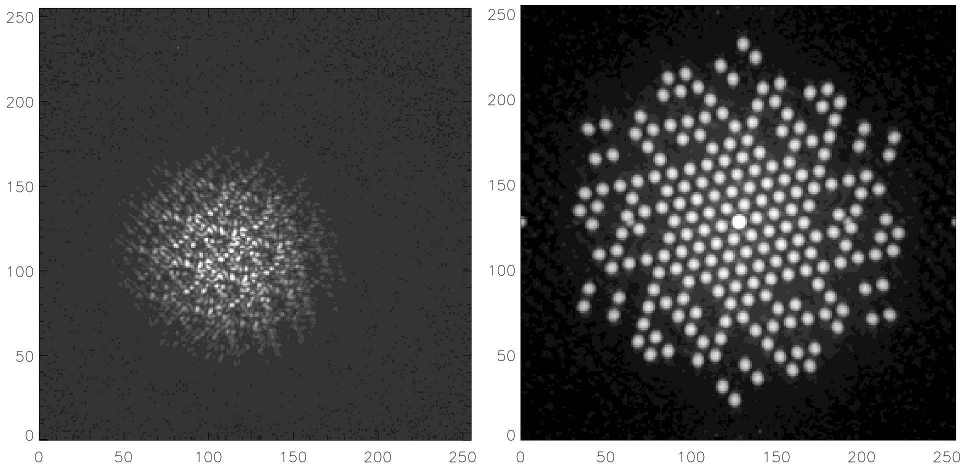

Figure 2. Interferogram of a point-source star taken at 2.2 μm (left). The 15-hole non-redundant mask depicted in Figure 1 generated this interference pattern. The power spectrum (right panel) is the result of accumulating the power spectra of 100 such raw data frames.

3. Results

Our diffraction-limited observations with the Keck telescope have enabled us to measure photospheric stellar diameters in a number of near-IR wavebands, as is illustrated in Figure 3. Such high-quality visibility data allows us to address a number of important topics in the study of evolved stars.

Firstly, data can be used for dynamical studies such as those of Haniff et al. (1995) to determine the pulsation mode and other fundamental dynamical properties. Secondly, quasi-monochromatic diameters at a range of wavelengths probe the atmospheric structure, helping to discriminate emission from the photosphere, molecular atmosphere and circumstellar dust, thereby providing valuable experimental testing of numerical model atmospheres. Thirdly, time-series measurements of stellar diameters through the pulsation cycle should be able to directly observe changes in photospheric radius. And finally, bright asymmetric features have been detected on the surfaces of late-type stars (Buscher et al. 1990, Tuthill et al. 1997), however other workers have reported elliptical distortions of the photosphere (Karovska et al. 1991, Quirrenbach et al. 1992). Our measurements provide images at the highest resolution yet in the near-IR, and can help to settle such questions of morphology.

Some of our target sources possess dusty circumstellar halos. At the diffraction limit of the Keck telescope, we were able to resolve these shells for some of the most well-studied, prototypical evolved stars. Spectacular images showing shells, clumps and outflows have been obtained for science targets IRC +10216, CIT 6, NML Cyg and VY CMa. To give a flavor of this work within the constraints of this report, we focus here on the enshrouded Mira IK Tau, and the red supergiant VY CMa.

Shell-like structures out beyond the 0.05-0.11$''$ dust condensation radius have been reported for IK Tau from studies mid-IR interferometry (Hale et al.

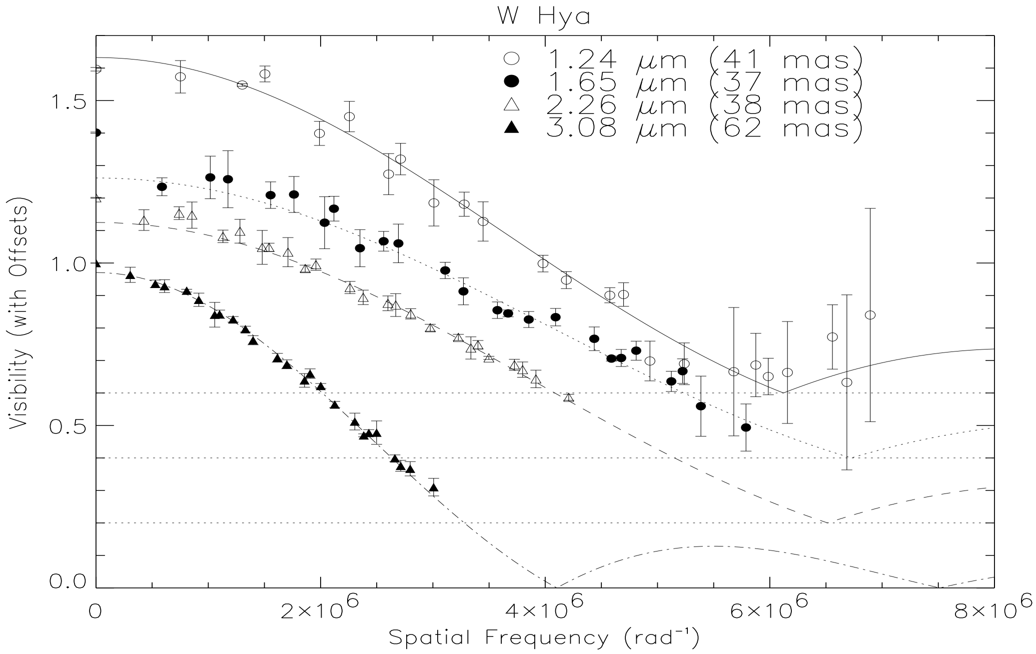

Figure 3. Azimuthally averaged visibility curves produced for W Hya from multi-wavelength speckle data. Diameters given correspond to the best-fit uniform-disk models, which can be seen to be well matched to the data. The larger apparent diameter recorded at 3.08 μm may be due to molecular or dust blanketing around the star.

1997). Our recent Keck image, shown in Figure 4, confirms the presence of significant circumstellar dust, and gives experimental support to the assumption that the outflow is spherically symmetric.

Although optical nebulosity around VY CMa has been known for most of this century, the dust formation zone close to the star is best viewed at infrared wavelengths due to the high scattering-induced optical depths in the visible. We present, in Figure 4, images of VY CMa's bright inner dust envelope at 2.2 μm. Such unprecedented resolution has revealed asymmetric, one-sided thermal emission to the south with a slight spiral structure. This emission is almost certainly a tracer for a dust clump or outflow whose proximity to the photosphere makes it hot enough to radiate in the near-IR.

Although there is evidence for asymmetries in the mass-loss process (e.g. polarization studies, molecular data and VLBI maser maps), direct observation has previously been hampered by the lack of sufficiently high resolution to image the inner stellar envelopes. Our program with the Keck has resolved the hot dust on small scales, revealing unambiguous signatures of anisotropic mass-loss close to the stellar surface. This raises intriguing questions as to why mass loss seems to be a fairly spherically symmetric in some stars yet not in others.

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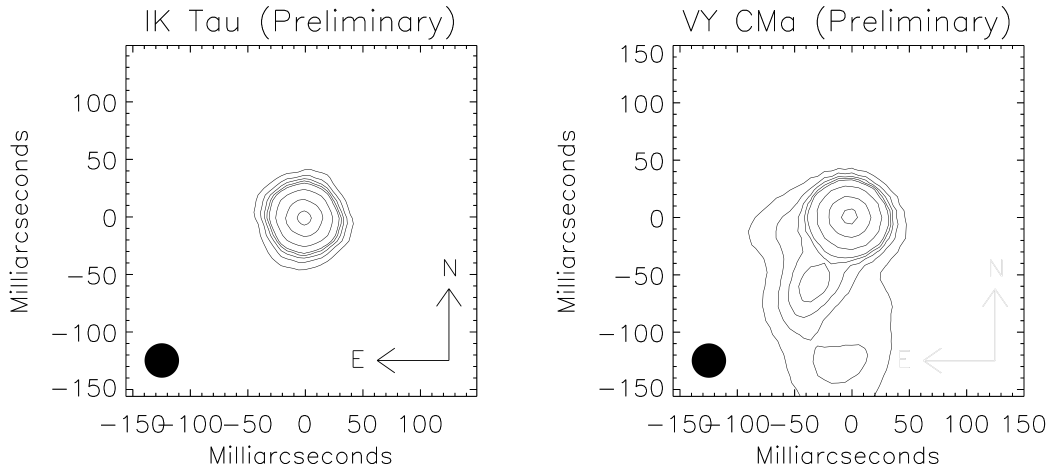

Figure 4. Maps of the Mira variable IK Tau (left) and the supergiant VY CMa (right) at 2.2 μm reconstructed from aperture synthesis imaging data. Contours are 2,4,6,8,10,20,50 and 90 % of the peak.

limited images. This work has been supported by grants from the National Science Foundation and the Office of Naval Research.

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