Recent Science Results from the Two-Telescope IOTA

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ABSTRACT

The IOTA (Infrared Optical Telescope Array) has been routinely operating with two-telescopes since 1994, a mode destined to become obsolete following its recent conversion to a three-telescope array.[1] In two-telescope mode, the IOTA has made numerous scientific and technical contributions, see e.g. our list of publications at *http://cfa-www.harvard.edu/cfa/oir/IOTA/PUBLI/publications.html.*

We present preliminary results on three different topics using recent data from the two-telescope IOTA: (1) measurements of Mira star diameters simultaneously in three different near-infrared spectral bands, (2) measurement of the characteristic size and shape of the source of near-infared emission in the x-ray binary system CI Cam, and (3) aperture synthesis of the Carbon star V Hydrae combining data from the IOTA and from aperture masking at the Keck-I telescope.

Keywords: IOTA, Interferometer, Mira stars, Carbon stars, X-ray binaries, CI Camelopardalis, CI Cam, V Hydrae

1. MULTICOLOR NEAR-INFRARED DIAMETERS OF MIRA STARS

Mira, or long period variable (LPV), stars are highly evolved cool (2000-3000 K) giants. They are very large - several hundred times the radius of the Sun, and very luminous - several thousand times the luminosity of the Sun. Miras pulsate with typical periods of about one year. As they expand, Miras become visually fainter, their spectrum shifts to later types, and the properties of molecule and dust formation in their extended cool atmospheres changes.

Despite much observational and theoretical work, many fundamental aspects of Mira atmosphere physics remain unknown. The determination of their sizes and shapes, and the variation of these quantities over time and wavelength are of fundamental importance, and can be directly measured with long baseline interferometers.

In an observing campaign between 1997-1999, the IOTA obtained interferometric measurements in the near-infrared of a large sample of Mira stars. The spectral coverage in the sample is important in order to constrain the atmospheric physics in these stars. Our preliminary results, in the form of stellar diameter estimates at each band are presented, for the subset of Miras which were measured at all three J, H and K' bands.

As shown in the representative spectra in Fig. 1 (top: maximum light, bottom: minimum light), the broad-band filters used encompass strong molecular bands of species such as H_2O, CO, TiO, VO and OH. This figure also illustrates how the amount of molecular absorption changes strongly as a function of pulsational phase. We have established the mean diameter ratios at these three bands, and measured a correlation with pulsational phase.

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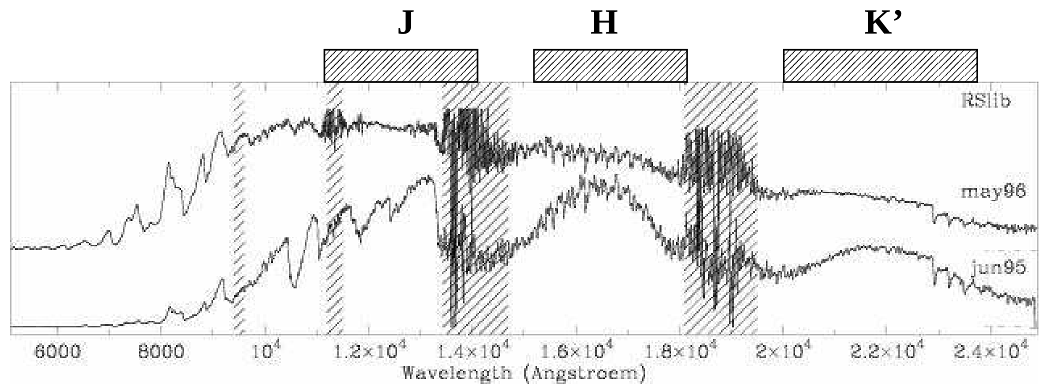


Figure 1. Representative Mira spectra, illustrating the location of our spectral filters with respect to molecular features, and the dramatic changes in spectrum with pulsational phase.

1.1. Observations and Analysis

The observations presented here were carried out at the IOTA interferometer over the period 1997-1999. In this experiment, the IOTA was operated in its two-telescope configuration, using two different baselines of approximate lengths 21 m and 38 m. Our full sample consists of 28 Mira stars, of which we present here preliminary results for a subsample of 13 stars that were measured at all three J ($\lambda_0 = 1.25\mu m, \Delta\lambda = 0.28\mu m$), H ($\lambda_0 = 1.65\mu m, \Delta\lambda = 0.30\mu m$) and K$'$ ($\lambda_0 = 2.16\mu m, \Delta\lambda = 0.32\mu m$) bands. For these observations, the two IOTA beams were combined in the pupil plane, at a bulk-optics beam splitter. We call this our "classical" beam combination scheme, to distinguish it from other beam combiners available available at the IOTA which employ single-mode fibers and couplers (FLUOR see e.g. Ref. 4, SMART see e.g. Ref. 7) or integrated optics components (IONIC see e.g. Ref 5). The instrumental setup and data reduction techniques have been previously described in Refs. 2, 3.

1.2. Results and Conclusions

The visibility data for the sample stars are shown in Fig. 2, where each panel contains data and uniform disk model fits, at the three bands, for a single star and epoch. The results are summarized in Table 1, which shows the uniform disk diameters found at each band. We note that although in reality Mira atmospheres are likely to not be well represented by a uniform disk model, this will not affect our results significantly given the relatively high visibilities measured by our baselines.

These results are the first measurements of Mira mean diameter ratios at those bands, and provide critical information for modelers of stellar atmospheres. For Miras in the narrow spectral range M6/M7, we find:

- On average: J Diameter $<$ H Diameter $<$ K Diameter
- J-band / H-band Diameter ratio $\simeq 0.95$
- H-band / K-band Diameter ratio $\simeq 0.86$

Moreover, it has been an elusive goal for optical interferometers to clearly establish that the near-infrared band diameters change coherently with the pulsational period (see however recent progress using narrow channels inside K-band from the Palomar Testbed Interferometer[8]). We see clear evidence for these phase-coherent size changes in our data, using diameter *ratios*, which are relatively insensitive to many sources of systematic error. Statistically, the diameter ratios are seen to vary with amplitudes of 12%, 15% and 12% for J/H, H/K$'$ and J/K$'$ respectively, as shown in Fig. 3 This variation suggests that the dominant molecular absorption features are located at different heights in the atmosphere and respond to the pulsation at different times.

In future work, we will analyze the complete set of H/K$'$ diameters measurements, to further probe the diameter ratio vs. pulsation phase relationship. We also have a programme to track the J, H, and K$'$ diameters for individual sources over their entire pulsation cycle. Finally, with better baseline coverage (provided by our new 3-telescope capability), we plan to measure how the limb-darkened profiles vary with pulsational phase, and by adding a low resolution spectrograph[9] to our infrared instrumentation, we will be able to make these measurements both in and out of spectral features.

In conclusion, infrared interferometry is providing a diverse set of multi-wavelength diameter measurements in the visible,[10,11] near-infrared (this work and e.g. Refs. 12, 13), and mid-infrared.[14] Current atmospheric models do not qualitatively agree with well-established results. It is therefore crucial to continue this work in collaboration with modelers[15] to invert these data in order to determine the molecular stratification of the stellar atmospheres, and ultimately improve the stellar atmosphere models and interferometry observing strategies.

Table 1. Uniform disk (UD) diameter results and errors for each star, at each band and epoch.

Target	Epoch	U.D. J	σ	U.D. H	σ	U.D. K	σ
R And	2450774.0	6.68	0.0	6.65	0.2	5.76	0.3
Z Cet	2451122.0	2.61	0.1	3.48	0.1	3.12	0.4
U Per	2450772.0	4.99	0.1	5.38	0.1	6.51	0.2
U Per	2451088.0	2.13	0.6	3.88	0.3	5.44	0.4
R Per	2451089.0	< 0.00	—	< 0.00	—	< 0.00	—
R Per	2451123.0	< 0.00	—	1.14	0.5	< 1.00	—
R Aur	2450734.0	11.06	0.1	10.49	0.2	16.18	0.2
X Aur	2450736.0	< 1.00	—	< 0.00	—	< 3.00	—
R Lmi	2450873.0	12.49	0.0	12.85	0.2	14.12	0.2
R Hya	2450873.0	18.84	0.1	20.13	0.3	25.41	0.2
R Hya	2450875.0	20.32	0.1	22.04	0.3	27.40	0.2
R Ser	2450875.0	7.50	0.1	8.40	0.7	10.39	0.4
S Crb	2450874.0	9.24	0.2	8.95	0.4	9.30	0.4
RS Lib	2450873.0	9.85	0.4	9.07	0.8	9.22	1.1
S Peg	2451087.0	4.09	0.1	5.07	0.3	4.87	0.5
R Aqr	2450739.0	17.69	0.2	17.78	0.1	20.80	0.2

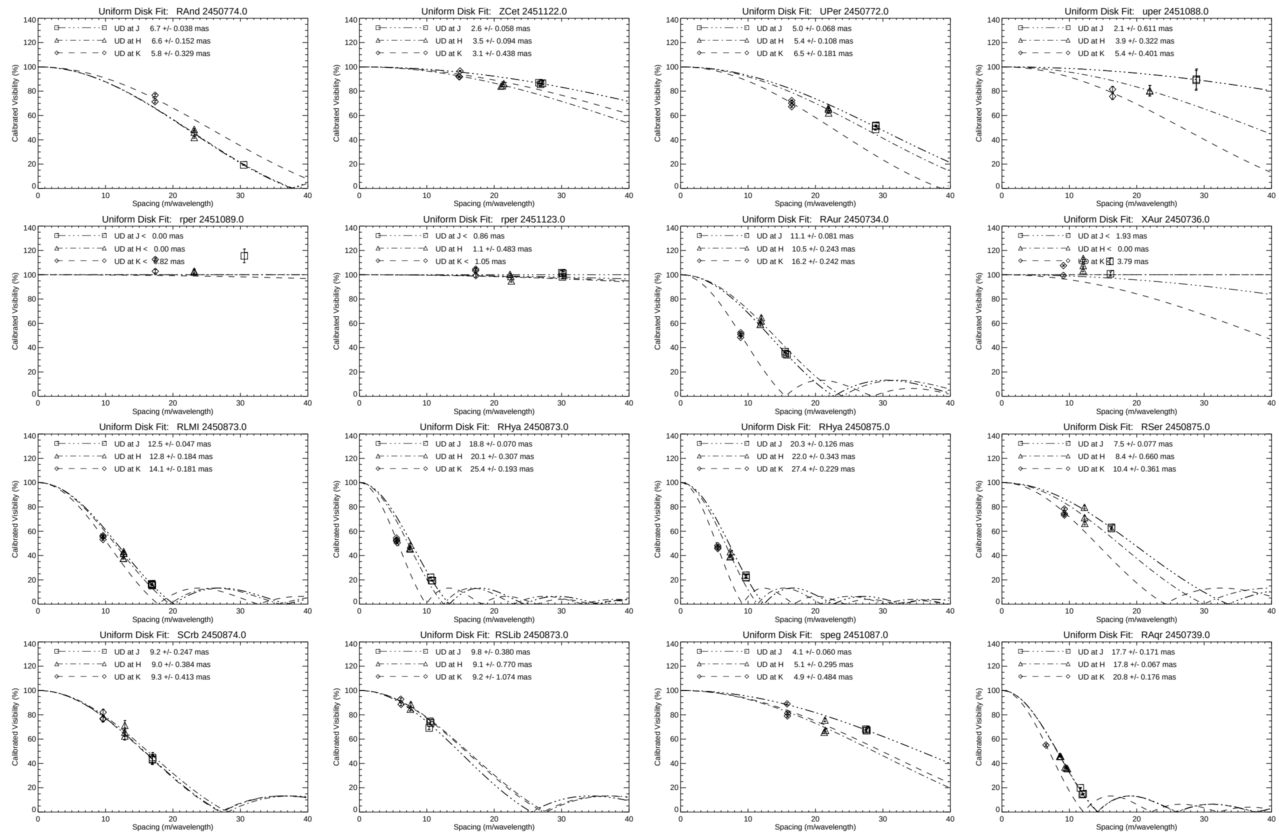


Figure 2. Visibility data as a function of projected baseline length for the 13-star sample. Each panel contains the data and uniform disk fit for one star and epoch at the 3 spectral bands.

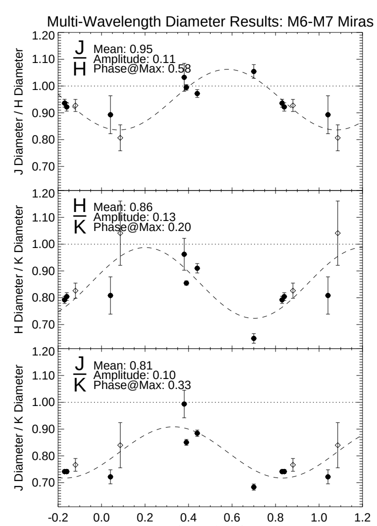


Figure 3. Mean diameter ratios as a function of pulsational phase. Each point corresponds to a single Mira (of spectral type M6/M7) in our sample, in order to mimic the behaviour of a representative single star.

2. DUST EMISSION IN THE X-RAY BINARY CI CAM

CI Camelopardalis (CI Cam) is an unusual star with a weak blue visible continuum (possibly a very hot star), a very strong near infrared continuum (possibly a dust shell around the star), and strong visible and infrared allowed and forbidden spectral lines (possibly excited and ionized gas close to the star). In April 1998 its x-ray flux rose from zero to a peak and back to nearly zero again in a few days. At the distance (1-2 kpc) of CI Cam, the strength of the x-ray outburst is suggestive of material falling from the central star onto an orbiting neutron star or a black hole. Soon after the x-ray burst, radio observations with the VLA were made, and it was thought that a pair of relativistic jets had been seen.

2.1. Observations and Analysis

We observed CI Cam in September to November 1998 using the IOTA interferometer at H and K′ bands. The instrumental setup and data reduction methods were as described in Section 1. We observed this source over a wide range of position angles, from -15 to +45 degrees, in an effort to see a jet signature. As shown in Fig. 4, we found the visibilities to be constant over this range of angles, giving no evidence for an infrared jet signature. Later it turned out that the radio identification of a jet was a data-processing artifact, in agreement with our lack of any infrared indication. Our measured visibilities are about 0.65 ± 0.03 for both bands, at projected baselines in the range 32-36 m. A formal fit to a circular uniform disk source give diameters of 5.6 ± 0.4 mas and 7.4 ± 0.4 mas at H and K′ bands respectively. Additional observations of CI Cam were made in September 2001 with an aperture mask at K-band at Keck, giving a visibility of greater than 0.90 at about 8 m baseline, consistent with the IOTA results.

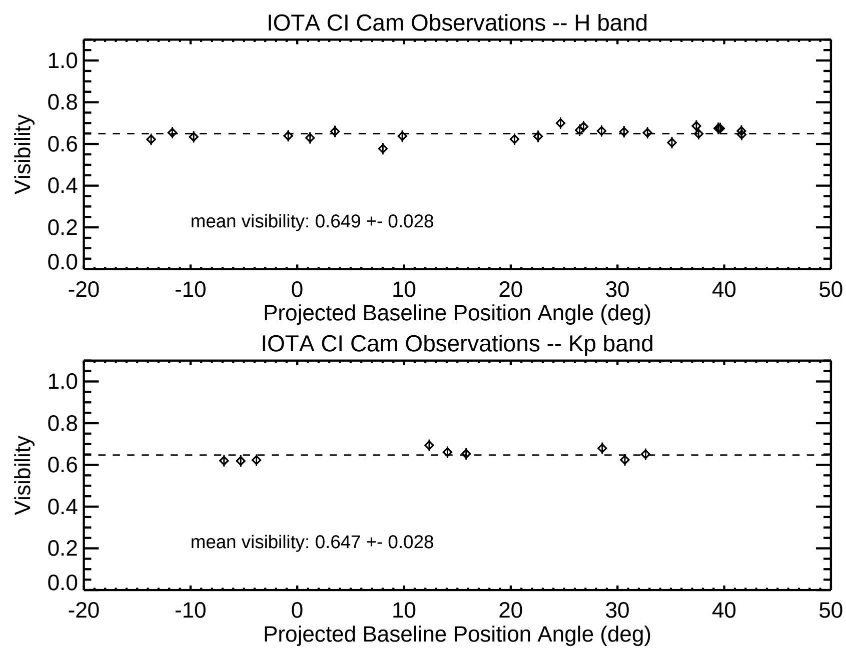


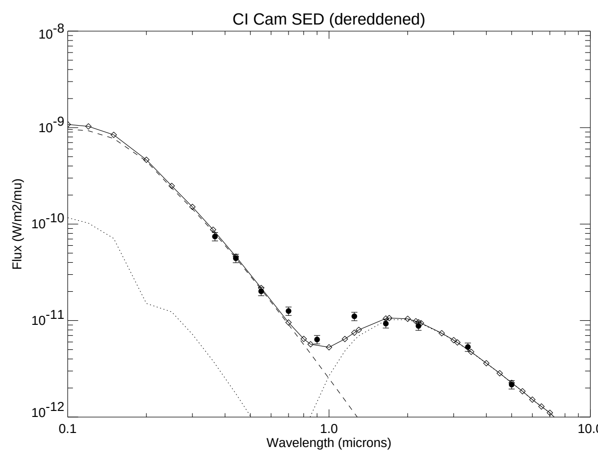
Figure 4. Visibility data on CI Cam (*top*: H band, *bottom*: K′ band) as a function of projected baseline position angle. We show the average visibility in order to emphasize the constancy of the data with position angle, indicating a high degree of circular symmetry for the source of this emission. The projected baseline lengths corresponding to these data are: $32 - 36$ m and $34 - 36$ m for the top and bottom panels respectively.

2.2. Results and Conclusions

Recently there has been renewed interest in CI Cam as more data has been assembled from before and after the 1998 x-ray burst, and as a better picture of the object has begun to emerge.[16,17] The revised picture is that of a supergiant B emission-line star, sgB[e], with hot gas near the star, a surrounding dust shell or torus, possibly seen pole-on, and at a distance of about 5 kpc. The outburst is likely to have been caused by a close encounter with a compact source (NS or BH), in either a long-period orbit or as a chance passer-by. Only 2 other objects with roughly similar characteristics are known, MWC 342 and possibly MWC 349, both of which are possible targets for future observations at IOTA.

The analysis of Clark et al. (2000) suggests that the near infrared SED could be understood in terms of a dust shell. We have used the inferred dust shell parameters to model the expected H and K′ visibilities, using the same software tools, namely the DUSTY code (Ivezic, Nenkova and Elitzur, see *http://www.pa.uky.edu/~moshe/dusty/*). As shown in Fig. 5, the model does indeed fit the spectrum well. However, the computed visibilities are much smaller than we observe at IOTA, such that the angular diameter of the model dust shell is several times too large compared to the measured dust shell.

In summary, at present there is a discrepancy of a factor of a few between the modeled and measured sizes of the source of near infrared emission in CI Cam. The difference may be reconciled by changing the model distribution of dust. We intend to continue modeling and to make additional observations, in an effort to better understand this dramatically unusual star.



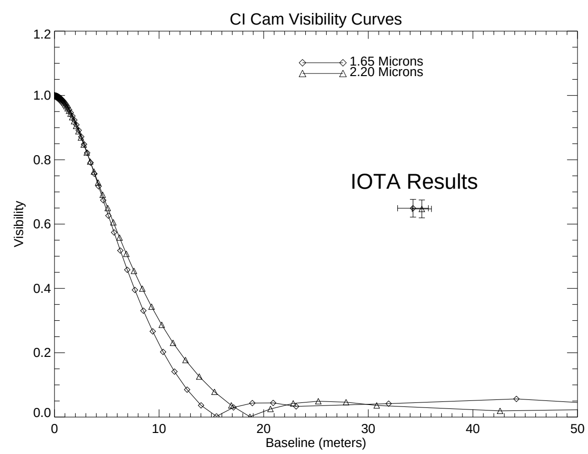


Figure 5. (*left*) Spectral energy distribution data and DUSTY model of CI Cam. The input parameters to DUSTY are as in Clark et al. (2000): $T_{dust} = 1500$ K, $A_V = 3.71$, density power law index $p = 1.75$ and for the stellar model a blackbody of $T_{eff} = 30000\ K$ is used. The resulting best fit (to the spectrum) parameters are: dust shell inner radius: 8.9 mas, star diameter: 0.03 mas and $\tau_K = 0.02$. The dashed line shows the stellar flux, the dotted lines show the scattered stellar flux and dust shell emission, and the solid line represents the composite spectrum. (*right*) Corresponding model visibilities and IOTA data, showing that although the model fits the spectrum well, the visibilities predicted are too small (size too large) compared to the IOTA aobservations.

3. IOTA AND KECK-I APERTURE MASKING OBSERVATIONS OF THE CARBON STAR V HYDRAE

V Hydrae (V Hya) is an unusual evolved carbon star. Its optical properties indicate a normal N type carbon star on the *asymptotic giant branch* (AGB). It is a regular variable with two periods, one of which is typical of normal Miras (the other periodicity is 17 years and its precise origin is unclear, but generally believed to be associated with the presence of a stellar companion). It has a large infrared excess and strong molecular line emission indicative of high mass loss rate, and its IRAS colors are also normal for carbon stars with high mass loss rates. On the other hand, from infrared and molecular line observations it appears that V Hya has a peculiar circumstellar envelope (variable stellar polarization, bipolar outflow, fast winds) and the photospheric spectrum shows unusually broad absorption lines. Taken together, these properties, some typical of normal AGB stars and of some typical of stars in the "super-wind" phase, indicate that V Hya is in an unusual evolutionary stage at very earliest stages of evolution away from the AGB. This rare system is therefore important, as it suggests that the complex morphologies typical of planetary nebulae originate during the final phases of mass loss on the AGB.[18–20]

3.1. Observations and Analysis

V Hya is part of a programme of K-band observations of evolved stars combining interferometric data from the IOTA and aperture masking at the Keck-I telescope.[21] The IOTA observations were carried out in February and April 2000 using the FLUOR beam combiner (Fiber Linked Unit for Optical Recombination, Ref. 4), which by using single mode fibers as spatial filters achieves better precision in the measurement of fringe visibilities than bulk-optics combiners (precision of order 1% or better rather than few %). Observations were made using three different configurations of two IOTA telescopes, providing three baselines which taken together cover a range of projected lengths 13 to 28 m. Data reduction of the FLUOR data was carried out using software developed in house using the *Interactive Data Language* (IDL), similar in its main principles to that described in Ref.22. Nearly contemporaneous observations, January 2000, were carried out as part of the Keck-I aperture masking experiment,[23] using a 21-hole Golay mask, and standard methods for aperture masking were used in the data reduction.

3.2. Results and Conclusions

In Fig. 6 we show the composite visibility curve of V Hya using the Keck-I and IOTA data. The power of this experiment in unveiling the source structure is evident from the beautifully sampled curve shown in the figure. The relatively short Keck-I baselines (from zero to about 10 m) are effective at sampling the visibility curve of an extended component (the dust shell), but provide no information at higher spatial frequencies, such that the contribution to the visibilities from the underlying stellar photosphere are un-sampled, and the data can not be properly interpreted. Adding the longer IOTA baselines bridges to the Keck-I data and completely resolves the dust shell component, uncovering and partially resolving the underlying photosphere. A complete model can now be estimated.

By inspection, it is reasonable to assume that the visibilities corresponding to projected baseline lengths greater than about 15 m are entirely due to the stellar photosphere. Therefore, we have used these data to fit this component using a uniform disk (UD) model. The resulting best-fit parameters are UD diameter = 14.5 ± 0.3 mas with 63% of the total flux arising in this component. Using this model to constrain the underlying photosphere, we then fit the ensemble data to a UD+Gaussian intensity, where the Gaussian component is meant to represent the extended dust shell, which has a best-fit FWHM = 35 ± 3 mas or 17.5 AU at the distance 500 pc). It can be seen that the global fit is quite good, although the shortest baseline IOTA data point, which only partially resolves the dust shell, appears to be systematically high, indicating that a more complex morphology for the extended dust shell may be required. Note the remarkably small difference between the size of the stellar photosphere and the characteristic size of the dust shell, factor of only 2.4, a result of the extremely cool stellar effective temperature (~ 2500 K).

In future work, we will simultaneously model the spectrum and visibilities of V Hya using realistic dust distributions, as well as incorporate the newly acquired knowledge about the underlying star in image reconstructions using the full (visibilities and closure phases) Keck-I aperture masking data set.

The unusually broad photosperic absorption lines in V Hya have been attributed by some authors to fast rotation.[18] This interpretation invites the search for elongation fo the stellar volume, as was recently found for the main sequence star Altair by the Palomar Testbed Interferometer.[24] In order to search for this signature, we have fit each of the 37 IOTA visibility data points corresponding to projected baseline lengths greater than 15 m (in order to isolate the stellar photosphere) to circular uniform disk models. The resulting UD diameters show no siginificant correlation with projected baseline position angle, over the sampled range -12 to +36 degrees, as would have been expected from a source which appears elongated on the sky. We will continue however to expand the data set and scrutinize the data calibration in order to firmly establish the important question of whether or not the fast rotation hypothesis in V Hya can be confirmed or ruled out using this technique.

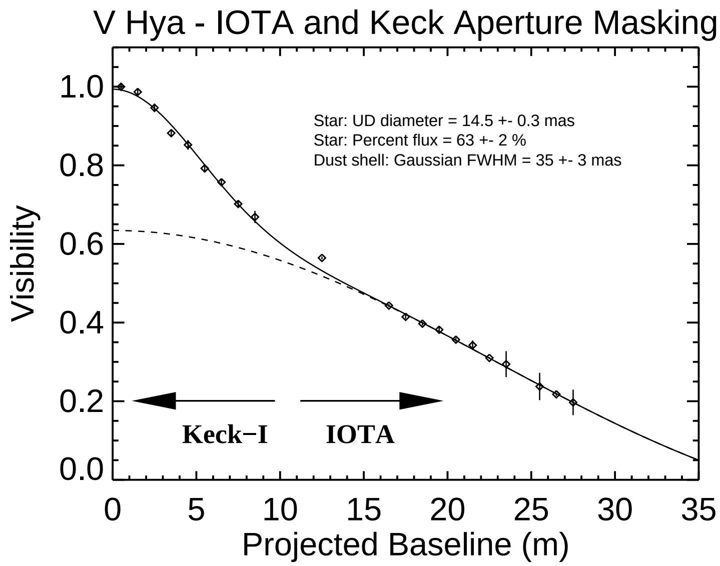


Figure 6. Visibility curve for V Hya (K-band) combining data from the IOTA/FLUOR and Keck-I telescope in Aperture Masking mode. The IOTA and Keck data have been binned in projected baseline length intervals of 1 m. The binned data is well fit by a composite model consisting of a stellar photosphere plus extended dust shell, represented by a uniform disk and a Gaussian intensity respectively. The shortest baseline IOTA data point however does not agree well, perhaps indicating the need for a more complex representation of the dust shell.

ACKNOWLEDGMENTS

This research has made use of software produced by the Interferometry Science Center at the California Institute of Technology, and we thank Andy Boden for using of that software on our behalf.

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