Interferometric Measurement of the Angular Sizes of Dwarf Stars in the Spectral Range K3-M4

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ABSTRACT

We have used the Palomar Testbed Interferometer to measure the angular diameter of five dwarf stars of spectral types K3-M4. Using the 110-m baseline and observing in H and K bands allows us to measure angular diameters with an accuracy of 2–8% for stars with apparent angular diameters approaching 1 milli-arcsecond. We provide results for both uniform disk and limb-darkened models, and compare our results with theoretical predictions. At the current level of precision our measurements are consistent with most widely accepted models, but further observations should be able to provide useful empirical constraints.

Subject headings: stars:fundamental parameters–techniques:interferometric

1. Introduction

M stars dominate the stellar census. However, despite this importance, M stars are not well understood. Their Mass-Luminosity-Radius (MLR) relation is not well measured as there are only three M-dwarf systems for which model-independent mass-radius-luminosity determinations have been made: YY Gem, CM Draconis & GJ 2065A (Leung & Schneider 1978; Metcalfe et al. 1996; Delfosse et al. 1999). This lack of precision measurements makes it difficult to assess the contribution of M dwarfs to the total mass of the Galaxy. The exact behavior of the mass-radius relation in this regime may also be of interest for other reasons, as Clemens et al. (1998) claim that the mass-radius relation steepens between 0.2 and 0.3 solar masses and this steepening is the cause of the well known gap in orbital periods of cataclysmic variables.

The MLR relation needs to be defined empirically since the physics of M dwarfs is quite complicated (Chabrier & Baraffe 1995; Allard et al. 1997). Molecular transitions are a significant contributor to the atmospheric opacity of M dwarfs, and dust starts contributing to the opacity below 3000 K (Jones & Tsuji 1997). Even the supposedly simple fully-convective interiors may be complicated; for example, Clemens et al. (1998) question whether gradients in mean molecular weight (μ) may develop and also worry about non-ideal corrections to the interior equation of state.

The importance of improving fundamental stellar parameters has not escaped the attention of astronomers. Henry et al. (2000) have proposed a program of accurate mass determination with the Space Interferometry Mission and Clemens et al. (1998) stress the importance of increasing the sample of eclipsing M dwarf binaries with the goal of measuring their radii. Long baseline interferometry offers a method by which the radii of the nearby M dwarfs can be measured. Here we report direct measurements of the apparent angular diameters of several nearby dwarf stars using the Palomar Testbed Interferometer (PTI). PTI is 110-m long single-baseline infrared direct-detection interferometer located on Palomar Mountain, California (Colavita et al. 1999).

2. Observations

We selected a small number of relatively bright dwarf stars in the spectral range K3-M4 (see Table 1) and observed them with PTI in order to determine their apparent angular diameters. Each object (science target and 2–3 calibrators) was observed for a 130-s integration 4–8 times per night, during at least two nights during the 1999 and 2000 observing seasons.

Calibrators were selected and observed so as to minimize both time- and position-dependent changes in the system response; observations of calibrators and science targets were interleaved over a 10-minute timescale, and calibrators were chosen so as to be no more than 10 degrees away from the science targets on the sky. Observations were obtained in both H and K bands on separate nights. Further discussion of the data reduction and calibration procedures used are available in Colavita (1999b) and Boden et al. (1998).

3. Visibility and Limb Darkening

The interferometric observable measured by PTI is the contrast or visibility of the fringes that are produced when starlight from two apertures is combined. For this work we assumed the intensity profile of the stars of interest to be well approximated by a linear limb-darkening law

$$I(\mu) = I(1)(1 - u_\lambda(1 - \mu)) \tag{1}$$

where μ is the cosine of the incidence angle and u_λ is the linear limb-darkening coefficient. We used passband-specific linear limb-darkening coefficients from Claret et al. (1995).

From basic interferometric theory it follows that the visibility of such a limb-darkened disk of angular diameter θ_{LD} is given by (Hanbury-Brown et al. 1974):

$$V = \left(\frac{1-u_\lambda}{2} + \frac{u_\lambda}{3}\right)^{-1} \left[\frac{(1-u_\lambda)J_1(x)}{x} + \frac{u_\lambda(\pi/2)^{1/2}J_{3/2}(x)}{(x)^{3/2}}\right] \tag{2}$$

where $x = \pi B\theta_{LD}/\lambda$, B is the projected baseline length and λ is the observing wavelength. J_1 and $J_{3/2}$ are Bessel functions of the first and three-halves order, respectively. We define the uniform-disk diameter θ_{UD} as the diameter of a model in which $u_\lambda = 0$.

4. Calibration

In order to correct for the inherent loss of fringe visibility due to the instrument and the atmosphere, we used calibrator stars of known diameter to determine the response function of the instrument. The measured visibility of the science object was then calibrated by dividing it by the system response. Calibrators were selected so as to be as point-like as possible; thus even though the fractional uncertainty in diameter may be relatively large, because the apparent diameters of the calibrators are much smaller than the instrument resolution the resulting uncertainty in system response (and thus also diameter of the target star) is small. As an example, the 7% uncertainty in diameter of HD 171834 only produces a 0.7% uncertainty in the system response.

We determined the apparent diameters of the calibrator stars by using archival photometry to fit a blackbody model for the bolometric flux of the star in question, while either simultaneously fitting for the effective temperature of the star, or constraining it to the expected value based on the spectral type. We also calculated the expected diameter using the expected physical size based on spectral type (Allen 1982) and the Hipparcos (Perryman et al. 1997) distance to the star. We adopted the weighted mean of the results from all three methods as the final diameter, and the uncertainty in the determination was taken to be the deviation. The calibrators and their estimated sizes and uncertainties are given in Table 1.

5. Results

Apparent angular diameters for the target stars were estimated by fitting both uniform disk and limb-darkened models to the calibrated visibilities; the uniform disk model is provided, despite being less physically accurate, in order to allow follow-up work using different limb-darkening corrections. A representative fit is shown in Figure 1 and results are given in Table 2. The differences between uniform-disk and limb-darkening models are too small to be readily apparent in the plot, but do amount to a few percent in diameter.

The uncertainties in the angular diameter estimates in Table 2 come from three sources: statistical uncertainty (estimated from the internal scatter in a 130-s integration), uncertainty in the angular diameters of the calibrators, and uncertainty in the limb-darkening parameters used. The uncertainty in the limb darkening parameters was estimated by adopting a 200 K uncertainty in the program star effective temperature. These uncertainties were propagated separately in the estimates, and added in quadrature to derive a total uncertainty. Finally the observed limb-darkened angular diameters were converted into linear radii using parallax data from Hipparcos, and the associated parallax uncertainties were added in quadrature to the total uncertainty.

In Figure 2 we compare the measured diameters with the expected values based on a theoretical (Baraffe & Chabrier 1996) and an empirical model; the latter is the $[M_V, V-I]$ fit derived by Reid & Gizis (1997) transformed in the same manner as in Clemens et al. (1998) (who derive both log(R) and log(M) as a function of M_V). Masses for these stars were estimated from photometry using the mass-M_K relation from Henry & McCarthy (1993).

As can be seen in Figure 2, at the current level of measurement precision the measured diameters are consistent with the models. However, distinguishing between models will require further observations. While some of these observations can be obtained with PTI, longer baseline interferometers such as CHARA and NPOI will be able to provide many more such diameter measurements. The same interferometers in conjunction with newly commissioned IR spectrometers will also be useful in improving mass estimates of M dwarfs through observations of binaries.

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Program Star	Calibrators	Spectral Type	θ_{UD} (mas)
Gl 699	HD 161868	A0V	0.64 ± 0.06
	HD 171834	F3V	0.42 ± 0.03
Gl 411	HD 90277	F0V	0.58 ± 0.06
	HD 101501	G8V	0.91 ± 0.02
Gl 15A	HD 1671	F5III	0.65 ± 0.08
	HD 5448	A5V	0.66 ± 0.11
	HD 1279	B7III	0.19 ± 0.07
Gl 380	HD 84737	G2V	0.81 ± 0.005
	HD 89744	F7V	0.52 ± 0.02
Gl 105A	HD 16970	A3V	0.74 ± 0.08
	HD 7034	F0V	0.36 ± 0.02

Table 1: The calibrators used and their estimated uniform-disk diameters.

Object	Spectral Type	u_λ 1.6μm	u_λ 2.2μm	Diameter θ_{UD}	Diameter θ_{LD}	Uncertainty σ_{Total} ($\sigma_{stat}/\sigma_{sys}$)	Log($R/R_\odot$)
Gl 699	M4V	0.513	0.427	0.987	1.026	0.04 (0.013/0.035)	-0.697 ± 0.017
Gl 15A	M2V	0.407	0.335	0.984	1.014	0.05 (0.032/0.042)	-0.410 ± 0.023
Gl 411	M1.5V	0.391	0.322	1.413	1.464	0.03 (0.026/0.015)	-0.397 ± 0.010
Gl 380	K7V	0.397	0.328	1.268	1.175	0.04 (0.042/0.005)	-0.211 ± 0.017
Gl 105A	K3V	0.442	0.378	0.914	0.941	0.07 (0.027/0.064)	-0.137 ± 0.036

Table 2: Measured diameters for the target stars, for both uniform-disk and limb-darkened models. Also shown are published spectral types of the target stars, along with linear limb-darkening parameters (u_λ) from Claret et al. (1995), selected using the appropriate effective temperature and gravity; a model calculated for log(g)=4.5 was used in all cases except for Gl 699 where we used a log(g)=5.0 model.

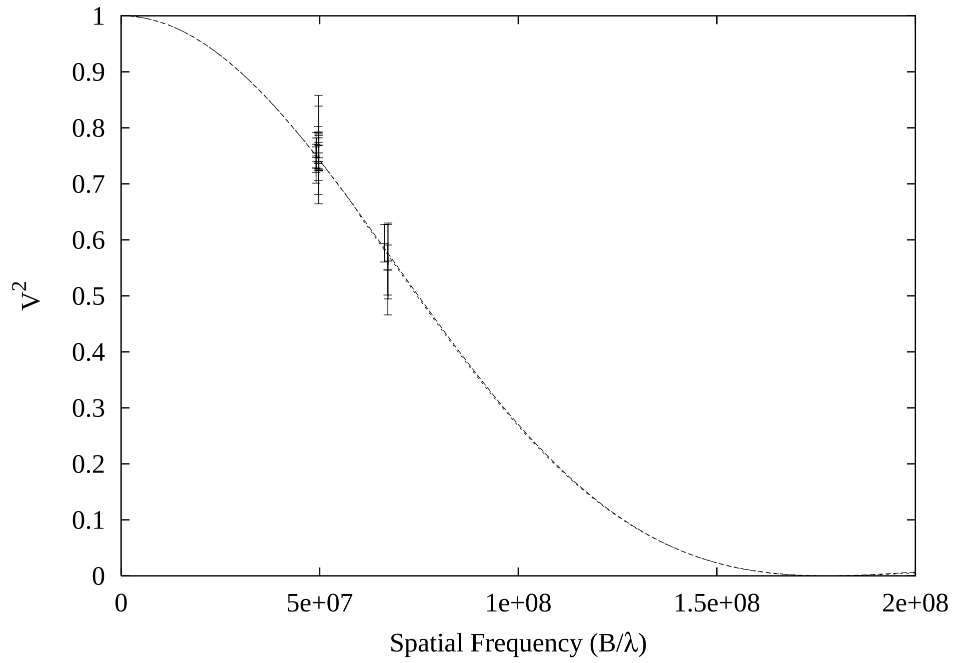

Fig. 1.— Measured visibilities (V^2) for Gl 411, together with the best-fit limb-darkened disk model. The model is given by Equation 2. The two clusters of data points correspond to observations in H and K bands.

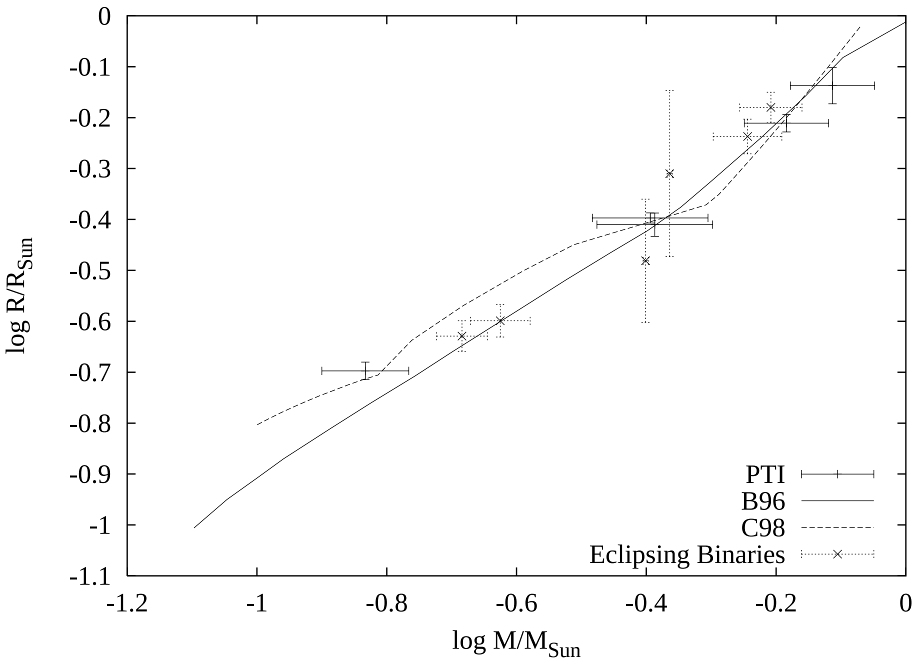

Fig. 2.— Mass-Radius diagram, showing our results as well as those obtained from eclipsing spectroscopic binaries. Masses of the single stars were estimated from photometry, using the Henry & McCarthy (1993) relation (based on speckle binaries), while radii are based on apparent angular diameters measured at PTI, together with Hipparcos parallax. Models shown are from Baraffe & Chabrier (1996)(B96, *solid line*) and the transformed fit of Reid & Gizis (1997) (C98, *dotted line*).