Fundamental Properties of Low Mass Stars

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We present preliminary results of the angular diameter measurements of low-mass, K- and M-type main sequence stars from interferometric observations with the CHARA Array. The principal goal of this study consists of providing direct measurements of linear radii and effective temperatures for these stars. The sparse amount of data currently available on late-type stellar radii and temperatures indicates a continuing discrepancy between theory and observation, which seems to be related to stellar activity, metallicity, and possibly convection. Targets were selected based on the following criteria: (1) to be in a region of mass-radius space covering both sides of the transition from partial to full atmospheric convection that is thought to take place below ~0.35 $M_\odot$, and (2) to cover a range of [Fe/H]. This project is uniquely suited by the long baselines of CHARA and will shed light to the nature of disagreement between stellar atmosphere models and observations, and in terms of its implications for other areas of study for low-mass stars, such as the detection and characterization of habitable planets orbiting these objects.

Observations

- Stars observed using the CHARA Array, a six telescope optical/IR interferometer, with maximum baseline of 330 meters (**Figure 1**)
- These data were taken in the K'-band with the CHARA Classic beam combiner
- Complete out to ~6.5 parsecs (K0V – M3.5V) limited by V mag and DEC >−10 °
- To date, we have observed 7 K-type stars and 12 M-type stars.
- Three (wide) binary systems with both components resolved.

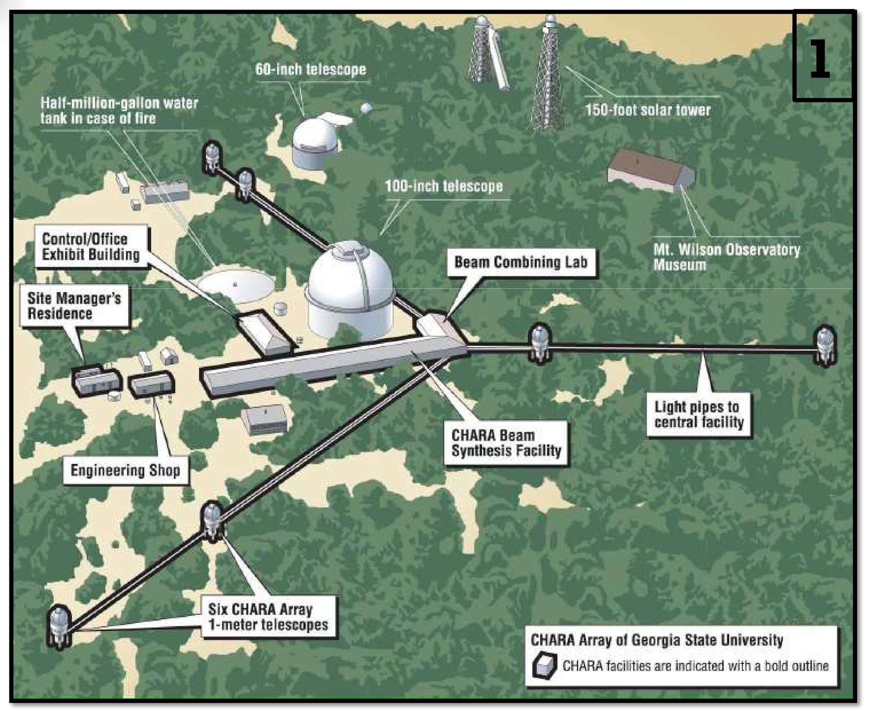


Figure 1: Cartoon showing the layout of the CHARA Array, located at Mount Wilson Observatory, Mount Wilson, CA.

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

$$V = \frac{2J_1(x)}{(x)}$$

Equation 1: Limb-darkened (top) and uniform disk (bottom) visibility functions for a single star. Here, $x=\pi B\theta/\lambda$, J_n is the n^{th} order Bessel function, and μ_λ is the limb darkening coefficient.

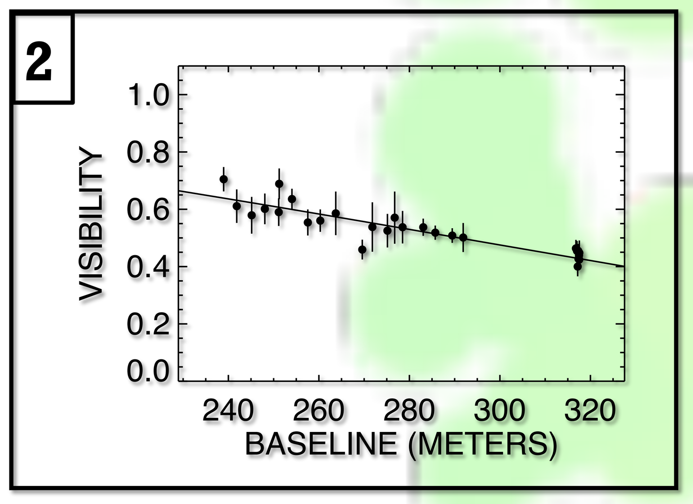
Fundamental Properties of Stars

- Angular diameter found by fitting calibrated visibility measurements to **Equation 1**. An example fit is shown in **Figure 2**.
- Measuring the stellar angular diameter allows us to directly obtain these fundamental properties of stars:

RADIUS: $R = \theta \times \pi$

TEMPERATURE: $F_{BOL} = \frac{1}{4}\theta^2\sigma T^4$

- **Figure 3** demonstrates the increased number of directly determined diameters from this project compared to existing measurements in this region low mass stars.



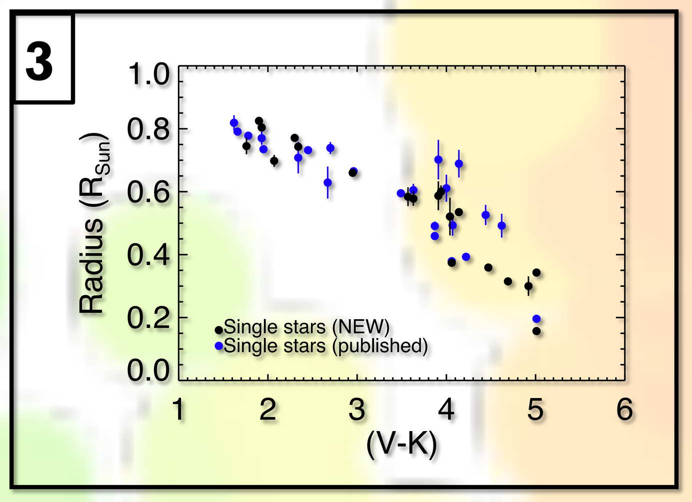


Figure 2: Limb-darkened angular diameter fit for GJ 892. The 1-σ errors on the calibrated visibility measurements are shown. **Figure 3:** V-K color index versus measured radii for stars observed to-date (black). All other single star radii measurements this range are also plotted (blue; Lane et al. 2001, Ségransan et al. 2003, Berger et al 2006, Boyajian et al 2008, Kervella et al. 2008, Demory et al. 2009).

Results

Observations

- To date, we have observed a total of 19 K and M-type dwarfs
- Accuracy of diameters are all better than 4.5%, with a mean error of 3.1%.

Theory Versus Observation

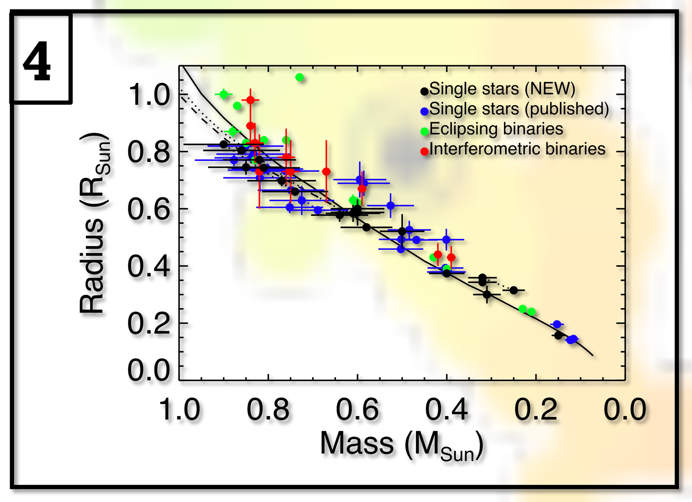
- Stars > 0.6 $M_\odot$
  - Single star radii and binary star radii compared to Baraffe et al. (1998) models agree well.
    - Model with $L_{mix}=H_p$ works well for eclipsing binary stars
    - Model with larger L_{mix} works better for single stars
- Stars < 0.6 $M_\odot$
  - Model under predicts single and binary star radii by average of ~12%, regardless of the method of observation.
  - At this mass range and below, we now have direct observational evidence of the "kink" in the H-R diagram due to H2
    - Currently, we do not have enough data to explain the full properties of the kink with respect to metallicity
    - Is it significant or just coincidental that this transition occurs at same place where models fail to predict radii?
- Is the gap in T_{EFF} (4050-4400 K) real or a selection effect?

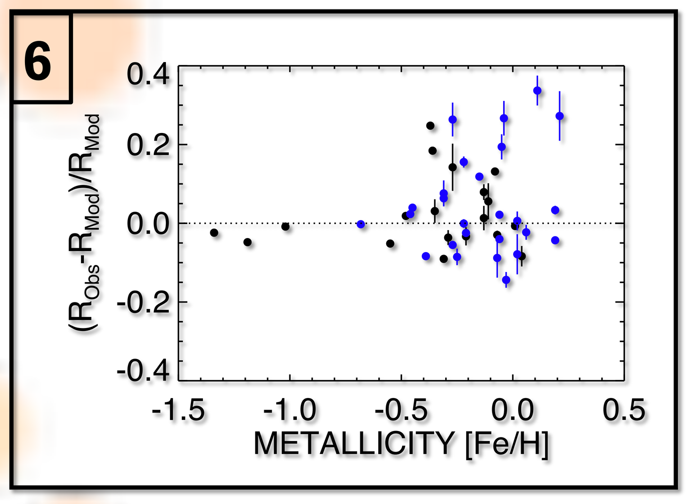
Discussion

Our data set is plotted in **Figure 4** in the mass-radius plane. Also shown are other interferometric measurements of single stars, as well as measurements from eclipsing and interferometric binaries (pulled from Torres et al. 2009), with mass < 0.9 $M_\odot$. The masses for single stars are derived from the K-band mass-luminosity relationship from Delfosse et al. (2000), and assume a 10% error. The solid black line is a 5 Gyr isochrone from the BCAH98 models (Baraffe et al. 1998) for $L_{mix}=H_p$, the dotted and dashed lines are L_{mix}=1.5 and 1.9 H_p, respectively.

By inspection of **Figure 4** (and **Figure 5**), binary stars greater than ~0.6$M_\odot$ are modeled best by $L_{mix}=H_p$, while single stars are modeled better by the higher values of L_{mix}. For masses <0.6, the models have a tendency to under predict the radius of the star by an average of 12%, despite the method of observation. **Figures 6** and **7** show the correlation between the fractional offset in measured versus model radii to metallicity [Fe/H] and activity level (L_x/L_{BOL}) for the single stars in the sample, and it seems as though neither property provides suitable explanation of the differences between models and observations. Introducing these new data provides added evidence that the offset in radii is not due to metallicity (trend seen in Berger et al. 2006), further supporting the conclusions in López-Morales (2007).

For the single stars only, we derive temperatures and luminosities purely from direct measurements. This fundamentally determined H-R diagram is presented in **Figure 8** (and **Figure 9** with respect to mass). In these plots, the somewhat tightly defined temperature versus mass or luminosity relation begins to fan out and drop to lower luminosities and masses for a given temperature at ~0.6$M_\odot$. This is observational evidence of the "kink" due to H2 (see Montalbán et al. 2000). It is interesting to note that this "kink" occurs at the same mass where the models do a poor job at reproducing the observed radii for the stars shown in **Figures 4** and **5**.





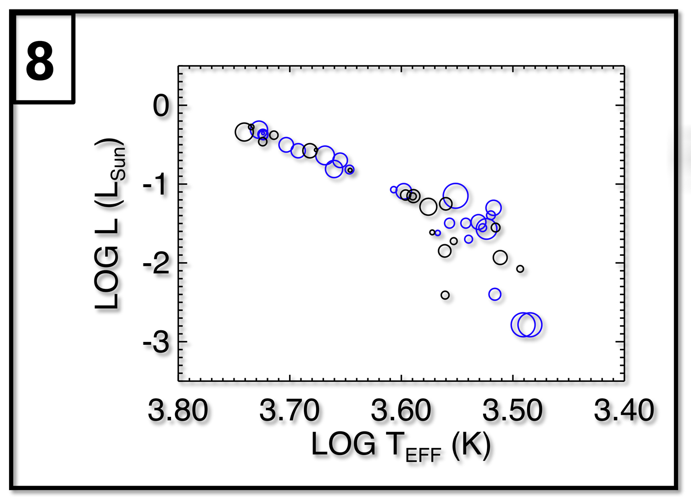
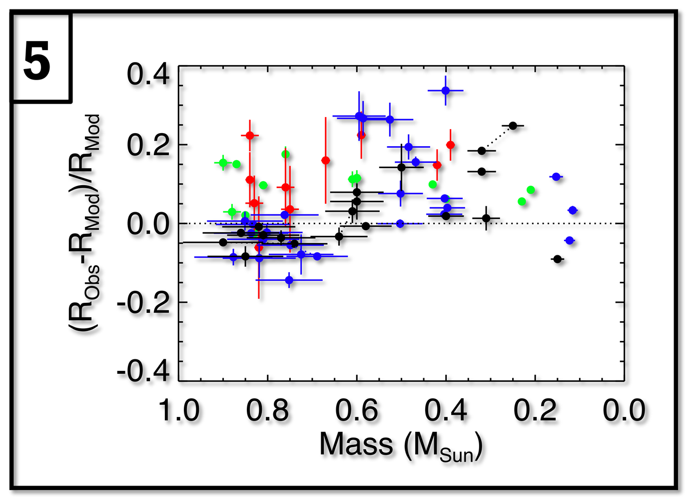
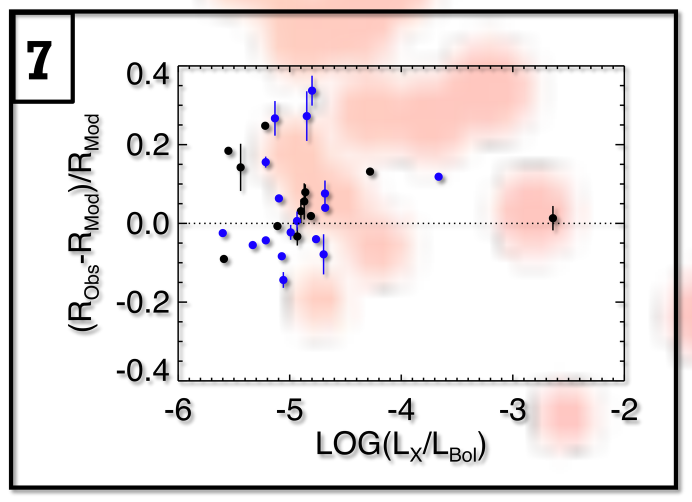
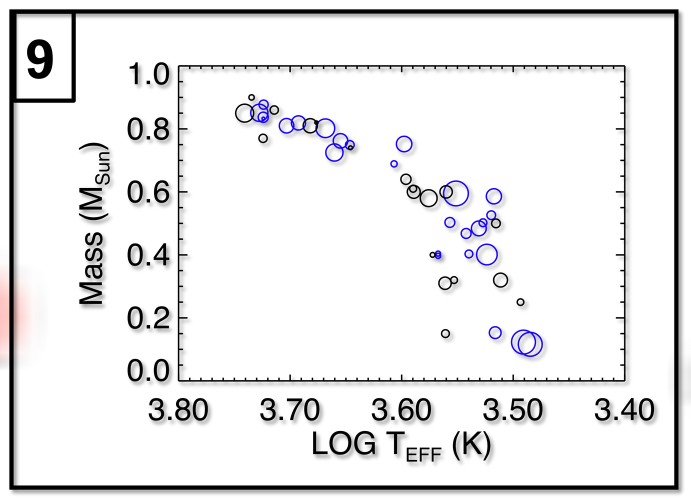


Figure Notes: Relations for stars with Mass < 0.9 $M_\odot$. Color scheme is identical to Figure 4 throughout all figures. Isochrones shown are for solar metallicity (Baraffe et al. 1998). Black dotted line signifies zero deviation in the observed versus model radii in Figures 5-7. Stars in wide visual binaries where both components are resolved with interferometry are connected with dotted lines of their respective color in Figures 4 and 5. The 1-σ radii and mass errors are displayed in Figures 4-7. The symbol size is proportional to the metallicity of the star in Figures 8 and 9.







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