Fundamental Stellar Astrophysics Revealed at Very High Angular Resolution

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Introduction

A detailed understanding of stellar structure and evolution is vital to all areas of astrophysics. In exoplanet studies the age and mass of a planet are known only as well as the age and mass of the hosting star, mass transfer in intermediate mass binary systems lead to type Ia Supernova that provide the strictest constraints on the rate of the universe's acceleration, and massive stars with low metallicity and rapid rotation are a favored progenitor for the most luminous events in the universe, long duration gamma ray bursts. Given this universal role, it is unfortunate that our understanding of stellar astrophysics is severely limited by poorly determined basic stellar properties - effective temperatures are in most cases still assigned by blunt spectral type classifications and luminosities are calculated based on poorly known distances. Moreover, second order effects such as rapid rotation and metallicity are ignored in general. Unless more sophisticated techniques are developed to properly determine fundamental stellar properties, advances in stellar astrophysics will stagnate and inhibit progress in all areas of astrophysics. Fortunately, over the next decade there are a number of observational initiatives that have the potential to transform stellar astrophysics to a high-precision science. Ultra-precise space-based photometry from CoRoT (2007+) and Kepler (2009+) will provide stellar seismology for the structure and mass determination of single stars. GAIA (2011+) will yield precise distances to nearly a billion stars, providing accurate luminosities. However, *the unprecedented data from these upcoming missions will only translate to useful calibrations of stellar models if they are performed in concert with high angular resolution measurements provided by ground-based optical and infrared interferometers.*

Very high angular resolution (reaching $<$ 1 milliarcsecond) observational astronomy at optical and infrared wavelengths is still in its infancy. Only in the last decade have multi-element interferometers become fully operational. In this white paper we highlight some of the incredible achievements made with optical and infrared interferometry over the last decade, and use these to emphasize the potential for these facilities, with continued support, to transform stellar astrophysics into a high-precision science.

Accurate Stellar Masses

Arguably the most fundamental parameter for a star is its mass, as this sets the timescale for evolution and determines its ultimate fate. Unfortunately mass is a difficult property to measure directly, and is typically only available for stars in binary systems with observable orbital motion. Mass estimates for the generic single stars must rely on mass-temperature or mass-luminosity calibrations, or worse, the predictions of untested stellar evolutionary models. The high resolution capabilities of optical interferometry have the potential to greatly increase the number and types of stars for which we have dynamical mass estimates, and greatly improve overall mass estimates.

The recent discoveries of young stars in nearby moving groups such as the β Pictoris Association and the TW Hydrae Association (e.g. Zuckerman, B. & Song, I. 2004, ARA&A, 42, 685) provide many new opportunities to determine dynamical masses of young binaries (e.g. Boden, A. et al. 2005, ApJ, 635, 442; Boden, A. et al. 2007, ApJ, 670 1214; Schaefer, G. H., Simon, M., Prato, L., & Barman, T. 2008, AJ, 135, 1659). Mass estimates at this early age are especially important because of the poorly understood input physics (e.g. convection, opacities) of pre-main sequence stars. With precise distance estimates to be provided by

GAIA, relative orbits will provide dynamical masses of stars in rarer evolutionary states, such as those transitioning to the giant phases (e.g. Boden, A., Torres, G. & Hummel, C. 2005, ApJ, 627, 464), traversing the Hertzsprung Gap (Boden, A., Torres, G., Latham, D. 2006, ApJ, 644, 1193), and high-mass main sequence and Wolf Rayet stars (North, J., Tuthill, P., Tango., W, Davis, J. 2007, MNRAS, 377, 415; Kraus, S. et al. 2007, A&A, 466, 649). Only just recently have the prospects of high contrast imaging via non-redundant aperture masking on large-diameter telescopes been realized. This work can provide dynamical masses for sub-stellar objects (e.g. Ireland, M. et al. 2008, ApJ, 678, 463), a mass range where evolutionary models are very poorly constrained due to the age/tempertaure/mass degeneracies. As very high resolution interferometric techniques continue to mature, becoming more adaptable and sensitive, they will become an essential tool for determining stellar masses for stars spanning the entire H-R diagram.

Asteroseismology and Interferometry

While binary stars will continue to be the dominant device to determine stellar masses, density measurements provided by powerful asteroseismology measurements combined with radius measurements by optical interferometry offer a method to estimate masses for single stars. The photometric oscillations observed by asteroseismology reveal interior stellar properties through their dependence on the density (sound speed) distribution within the star. Since such distributions are a function of both mass and age, both of these fundamental stellar parameters are probed. Reliable masses and ages from asteroseismology require tight constraint of global stellar parameters, most importantly the stellar radius. Stellar radii from interferometry accurate to 3% when coupled with asteroseismology yield single star masses accurate to 4% (Cunha et al. 2008, A&A Rev, 14, 217). In the case of the nearby subgiant β Hydri, this has been done to a precision of 2.8% (North, J. et al. 2007, MNRAS, 380, L80). Other examples of connections between asteroseismology and interferometry include a check on the mass of a δ Scuti star in the Hyades (Armstrong et al. 2006, AJ, 131, 2643) and a radius and age for asteroseismology target τ Ceti (G8 V) (Di Folco, E. et al. 2004, A&A, 426, 601). The synergy between ground-based interferometry and both ground-based programs (HARPS, CORALIE, ELODIE, UVES, UCLES, SIAMOIS, SONG) and spaced-based (MOST, CoRoT, WIRE, Kepler, PLATO) high-precision photometric missions will play a vital role in determining fundamental stellar masses.

Precise Radii and Temperatures

With available mass estimates, astronomers can begin the next step in high precision stellar astrophysics - testing the temperature and size predictions of stellar evolutionary models as a function of age. Historically the only stars that astronomers could measure accurate radii and (relative) temperatures of were in eclipsing binary systems (Andersen, J. 1991, A&A Rev, 3, 91). Long-baseline optical/infrared interferometry has changed this dramatically by providing sufficient resolution to measure the angular size of many nearby stars. Angular measurements with errors well under 1% are now commonplace. The limb-darkening corrections, normally modeled, are now subject to direct interferometric verification.

In order to convert a stellar angular diameter into a physical diameter, the distance must be known. Accurate binary orbits can provide this in some cases, but a more general solution

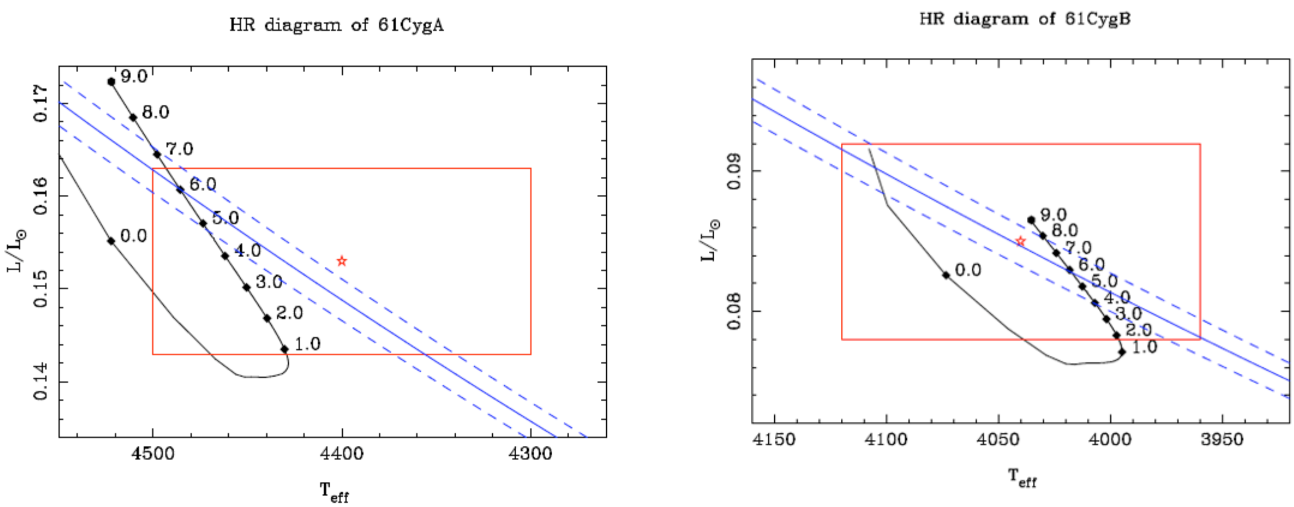

Figure 1: Evolutionary tracks in the H-R diagram for 61 Cyg A (**left**) and B (**right**). The labels indicate the age in Gyr relative to the ZAMS. The rectangular box represents the classical $L - T_{\rm eff}$ error box, and the diagonal lines represent the radius and its uncertainty determined by a combination of interferometry and the Hipparcos parallax (Kervella et al. 2008 A&A, 488, 667).

is increasingly possible, with Hipparcos, GAIA and SIM providing/promising 1% distances to 10, 500 or 2500 pc. Interferometric + Hipparcos measurements of single M-dwarfs show that they are 10-15% larger than currently predicted by models (Berger et al., ASPC 2008, 384, 226), with a suggestion that the discrepancy increases with elevated metallicity. Examples of ultra-precise radii and temperatures (see Figure 1) have been measured for coeval binary stars (Kervella et al. 2008 A&A, 488, 667), metal poor population II stars (e.g. Boyajian et al. 2008 ApJ, 683, 424), giant stars in the Hyades (Boyajian et al. 2009, ApJ, 691, 1243), and the enigmatic λ Boo itself (Ciardi et al. 2007, ApJ, 659, 1623).

Regarding stars with variable radii, a great achievement during the last decade has been the interferometric measurement of the pulsating diameters of seven classical cepheids: ζ Gem (Lane et al. 2000, Nature, 407, 485), η Aql, W Sgr, β Dor, l Car (Kervella et al. 2004 A&A, 416, 941), δ Cep (Mérand et al. 2005, A&A, 438, L9), and Y Oph (Mérand et al. 2007, ApJ, 664 1093). The precision of the δ Cep (see Figure 2) and Y Oph measurements was such that the projection factor, a value normally predicted by models and needed to correct radial velocity measurements, could be observationally constrained. GAIA distances will extend detailed study to a broad range of Cepheids.

The $T_{\rm eff}$ of a star is one of the small number of fundamental parameters of a stellar model. In order to confront models with real stars, the corresponding description of the star must be known. It is defined in terms of the luminosity and the radius by

$$T_{\rm eff} = \left[\frac{L}{4\pi R^2 \sigma}\right]^{1/4} = \left[\frac{4 f_{\rm bol}}{\theta_{\rm LD} \sigma}\right]^{1/4}$$

where $f_{\rm bol}$ is the bolometric flux, $\theta_{\rm LD}$ is the angular diameter corrected for limb darkening, and σ is the Stefan-Boltzmann constant.

For a classical star with a well-defined surface, this lets us determine the $T_{\rm eff}$ by measuring the angular diameter and the observed flux, and modulo an understanding of any extinction,

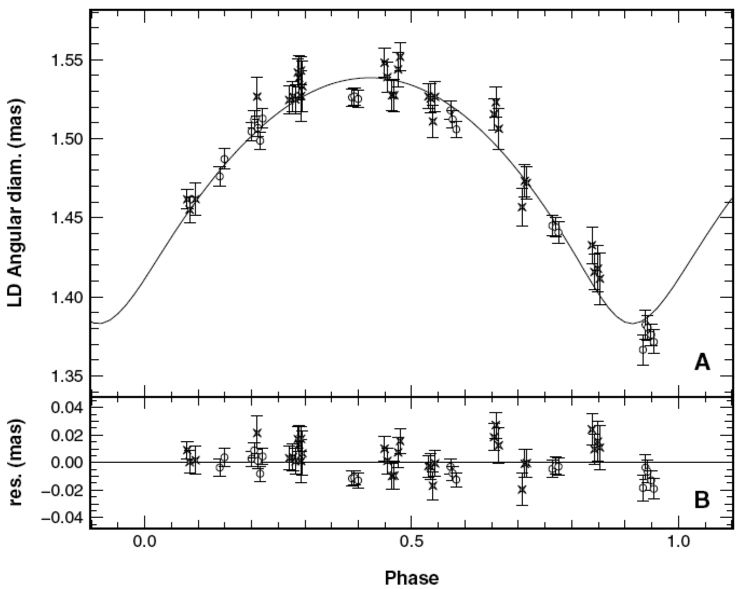

Figure 2: Angular diameter measurements showing the 5.36 day pulsation of δ Cephei with a model fit (A) and residuals (B) (Mérand et al. 2005, A&A, 438, L9). The solid curve is predicted from radial velocity data, where only the amplitude of the curve is adjusted to determine the projection factor.

gives a precise answer. The determination of $T_{\rm eff}$ is typically limited by the photometry (or, with good photometry, by the absolute calibration of the photometry). In fact, with accumulating interferometric stellar measurements, it is now possible to turn the question around and, from stellar photometry alone, predict the angular diameters and $T_{\rm eff}$ of common spectral types to 1-2% (Kervella et al. 2004 A&A, 426, 297). In the case of stars with a poorly defined surface (e.g. due to extended atmosphere, accretion disk, mass loss shell), an imaging capability allows a more detailed confrontation of observed and modeled brightness distributions (eg. Perrin et al. 2004, A&A, 426, 279; Wittkowski et al.2008, A&A, 479, L21). In the case of very hot stars, $T_{\rm eff}$ is particularly difficult to determine owing to the inability to observe the turnover of the Planck function in the far ultraviolet. With a measured angular diameter, a single photometric measure can give the surface brightness, and thanks to the simplicity of the spectrum, a reliable $T_{\rm eff}$, and with distance a reliable luminosity, see Figure 3.

Limb Darkening

While precise masses and radii obtained from interferometric observations test and constrain stellar structure and evolution models, very high resolution observations of stellar photospheres test stellar atmosphere models, models that are vital for the construction of synthetic stellar spectral energy distributions and high-resolution synthetic spectra. Measurement of the center-to-limb intensity variation of a stellar photosphere probes the temperature structure of that atmosphere. This was first done for the Sun just over 100 years ago and helped to constrain models for the transport of energy in the solar atmosphere. Such studies are now possible for other stars.

Until recently, with the exception of Sirius (A1 V) (Hanbury Brown, R. et al 1974, MNRAS, 167,475), interferometric limb-darkening measurements have been limited to a small number of stars cooler than the sun: α Cas (K0 III) and α Ari (K2 III) (Hajian, A. R. et al. 1998, ApJ, 496, 484); Arcturus (K1.5 III) (Quirrenbach, A. et al. 1996, A&A, 312,160);

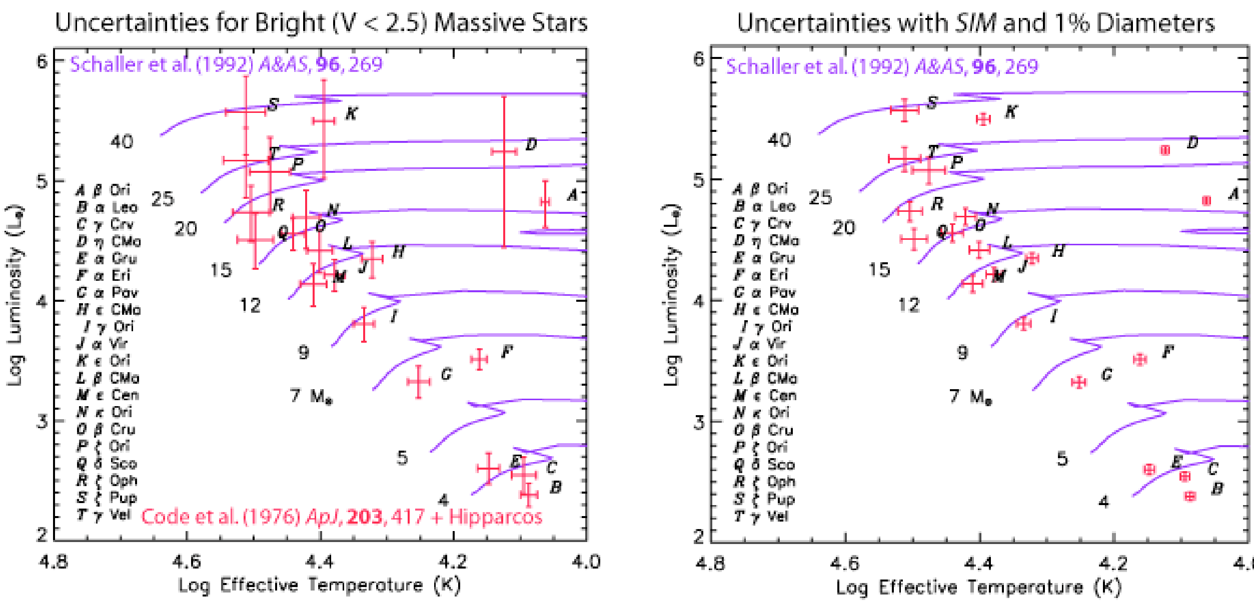

Figure 3: **Left:** The original Hanbury Brown intensity interferometer diameters together with the Hipparcos parallaxes, compared to massive star evolutionary tracks. **Right:** Expected error bars with SIM parallaxes and optical amplitude interferometry angular diameters, compared to evolutionary tracks.

Betelgeuse (M1Iab) (Perrin, G. et al. 2004, A&A, 418,675); γ Sagittae (M0 III), V416 Lac (M4 III), and BY Boo (M4.5 III) (Wittkowski, M. et al. 2001, A&A, 377,981); ψ Phoenicis (M4 III) (Wittkowski, M., Aufdenberg, J. and Kervella, P. 2004, A&A, 413,711).

In the last five years as long baselines have come on-line, hotter stars have been measured: Altair (A7 V) (Ohishi, N., Nordgren, T. E., Hutter, D. J. 2004, ApJ, 612, 463), Vega (A0 V) (Aufdenberg et al. 2006, ApJ, 645, 664; Peterson et al. 2006, Nature, 440, 896), α Cyg (A2 Ia) and β Ori (B8 Ia) (Aufdenberg et al. 2008, in Power of Optical/IR Interferometry, ESO Symposium, page 71). The interferometric confirmation that Vega is a pole-on, rapidly rotating star (see Figure 4) has recently driven astronomers to search for a replacement star, or set of stars, for defining photometric systems (Rieke, G et al. 2008, AJ, 135, 2245).

Limb Darkening and Convection

High precision multi-wavelength angular diameter measurements reveal the wavelength dependence of limb-darkening. Such measurements of Procyon (Aufdenberg et al. 2005, ApJ, 633,424) and α Cen B (Bigot et al. 2006, A&A, 446, 635) provide tests of 3-D convective transport models. The interferometric data indicate a temperature gradient shallower than provided by the standard 1-D mixing-length convection. Further limb-darkening measurements, in particular at high spectral resolution (up to R$\sim$30,000), will allow for more stringent tests and constraints on the state-of-the-art multi-dimensional stellar atmosphere codes, those responsible for the recent substantial revision in the Sun's oxygen abundance (Asplund et al. 2004, A&A 417, 751). *Global convective instabilities are present either in the core or envelope of most stars. Nevertheless, the appropriate modelling of convection remains one of the most difficult tasks in the context of stellar astrophysics.* - Cunha et al. 2008,

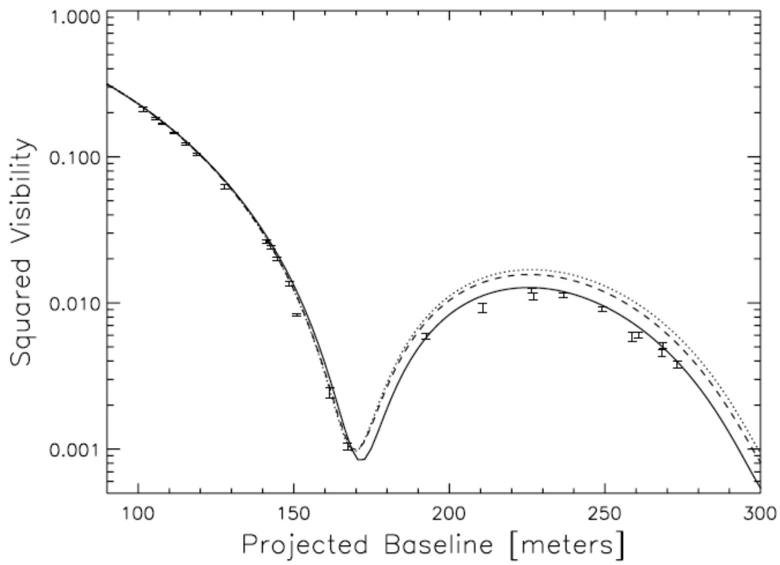

Figure 4: A visibility curve for Vega (A0 V) showing the first and second lobes. The first lobe yields the angular size, while the second lobe contains limb-darkening information. In the case of Vega, a pole-on rapid rotator, the data show both limb and gravity darkening (solid line) (Aufdenberg et al. 2006 ApJ, 645, 664). Such data are vital for probing the temperature structures of stellar atmospheres.

A&A Rev, 14, 217. High-resolution studies of stellar surfaces will play an important role in testing improved models for convection as they develop.

Stellar Rotation

Rotating stars offer a powerful tool for insight into stellar interiors. The mass distribution, opacities, and processes such as differential rotation and convection are normally lost in the spherical uniformity of normal stars. In rapid rotators, these factors contribute to the stellar shape and temperature distribution, which may follow more or less closely the idealizations of Roche and von Zeipel, and these factors will be implicated differently for stars of differing mass. A range of rotation rates for similar stars effectively constitutes a series of experiments. Interferometric imaging shows the distorted stellar shape. A first measurement of rotational deformation in α Eri (de Souza et al. 2003, A&A 407, L47) has already stimulated 14 publications of follow-up or interpretation. More recent imaging shows also the distribution of brightness temperature across the disk, and the limb darkening (eg. Zhao et al. 2009, in preparation, see Figure 5). For rapid rotators, of which Be stars are the classic example, interferometry can map the ejected material, which may be found in disks (Tycner et al. 2006, AJ 131, 2710) and/or polar winds (Kervella et al. 2009, A&A, 493, L53). Imaging may also serve an important role in understanding the interaction of rotation and pulsation, as in for example δ Sct stars (Peterson et al. 2006, ApJ 636, 1087) and other non-radial oscillators (Jankov et al. 2001, A&A 377, 721).

Recent observations have spurred theoreticians to replace the Roche formalism (which uses a potential where the mass is a point source) with a more physically realistic model including a self-consistent gravitational potential and differential rotation (Jackson, S. et al. 2005, ApJS, 156, 245; MacGregor, K. et al. 2007, ApJ, 663, 560). These models predict that rotation significantly reduces the luminosity of young stars, by reducing the central core

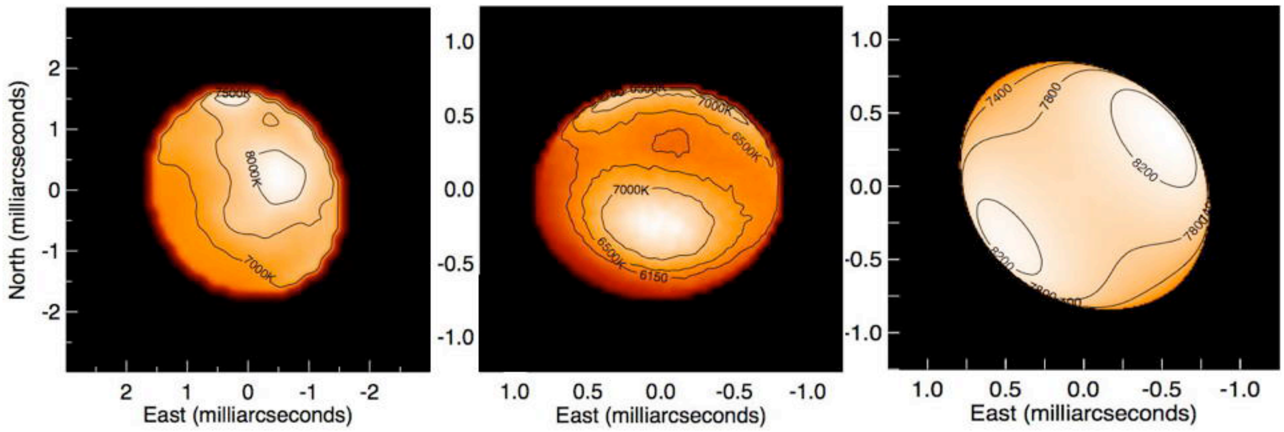

Figure 5: Model-independent images of rapid rotator stars α Aql (**left:** Monnier et al. 2007, Science, 317, 342) and α Cep (**middle:** Zhao et al. 2009, in preparation) showing the shape effects of centripetal forces, and brightness distributions determined by polar brightening and equatorial darkening, polar axis projected angle, and limb darkening. **Right:** A Roche-von Zeipel model for α Oph based on interferometric data (Zhao et al. 2009, in preparation.)

temperature, resulting, for example, in a 1.2 $M_{\odot}$ star with a luminosity of 1.0 $L_{\odot}$. Such models make matters worse for resolving the faint young Sun paradox (e.g. Minton D. A. and Malhotra, R. 2007 ApJ, 660, 1700), where the standard solar model predicts the young Sun too cool to support life on the early Earth 4.0 Gyr ago, in contradiction to the geologic and fossil records. Testing the latest models of rapidly rotating stars with interferometric imaging will have an impact across stellar astrophysics.

High Angular Resolution Imaging in the Next Decade

Interferometric techniques already cover a large parameter space. In the near-IR, angular resolutions reach <1 milliarcsec, with single-measurement precision as fine as 20 microarcsec. Wavelength coverage extends over most of the atmospheric windows from 0.48 to 12.5 μm. Spectral resolutions are available up to 30,000 in R and I, 12,000 in J-H-K, adequate for characterizing most molecular bands and some individual spectral lines. In the N band, spectral resolutions up to 200 are well matched to grain and molecular opacity structure. Instrumentation and facility developments already underway will augment these capabilities somewhat, improve limiting sensitivity, and so forth. But the most dramatic development will be in the quality of imaging achieved. Most interferometric measurements are still made with only one telescope pair. Beam combination with 3, 4 or 6 telescopes is just in its infancy, but will rapidly come to be the preferred observing mode for the kinds of science described above, owing to its far more rapid accumulation of image information. Interferometry has important complementary potential for space, as well, for missions such as SIM, SI (Stellar Imager), and SPIRIT (Space Infrared Interferometric Telescope). The coming decade will be a period of rich development for high resolution stellar science.