

STELLAR GEOMETRIES WITH SPECTRO-INTERFEROMETRY

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ABSTRACT

The most massive stars are important contributors to their host galaxies. During their stellar lifetimes, and even in their demise as supernovae, they deposit a great deal of material and energy into their galactic neighborhood, thus providing the building blocks for the next generation of stars. Near the end of their lives, they begin to shed their outer layers into space via a stellar wind, creating what astronomers call a "circumstellar envelope." These envelopes are thus cosmic fossils of the stars themselves. The physics of stellar winds- more generally referred to as "mass loss," is poorly understood. The geometric structure and molecular composition of this circumstellar material can provide important clues to the mass loss process as well as constrain models of stellar evolution. This information can also help inform models of supernova ejecta by providing detailed information about the pre-existing material that the ejecta will slam into as it expands. Previously, these envelopes have been too small to observe from ground or space-based telescopes. The advent of near infrared interferometry has allowed us to resolve these structures for the first time. A survey of massive stars called Supergiants has been measured using such an instrument; the results of that study are presented here. Support for this work has been generously provided in part by the Rocky Mountain NASA Space Grant Consortium.

Subject headings: infrared: stars, stars: fundamental parameters, techniques: interferometric, stars: supergiants

1. INTRODUCTION

Supergiants are the celebrities of the stellar population: the live hard and fast, and die young. That is because supergiants are among the most massive stars in the universe; the extra gravitational pressure causes them to burn through their nuclear fuel faster. Thus, they move quickly through the stellar evolutionary phases. This short lifetime means that supergiants are fairly rare among stellar populations. However, many of the best-known stars in the sky are supergiants, including Polaris (the North Star, in the handle of the Little Dipper), Betelgeuse and Rigel (Orion's right shoulder and left foot, respectively), Deneb (the brightest star in the summer triangle), and Antares (the brightest star in Scorpius). That is because we can see them from much further away than an average star: they shine up to a million times brighter than the sun. Just like celebrities on earth, supergiants play a prominent role in the evolution of their peers. Toward the end of their short lifetimes, they begin to hemorrhage their outer layers into space. Eventually, they will run out of nuclear fuel and collapse, obliterating their cosmic neighborhood as supernovae. This makes them key players in our understanding of how groupings of stars and even entire galaxies evolve. This study, spanning a decade of observations, is the first interferometric survey aimed at an empirical determination of the fundamental properties of supergiants. With 74 supergiants sampled, it is the largest data set of its kind. Wideband analysis of these data has recently gone to press (vanBelle et al. 2009), and now our attention has turned to the narrowband results (partially) presented here. The purpose of the narrowband studies is to find trends in the geometric structure of these stars that correlate to their metallicity, spectral type, and evolutionary status.

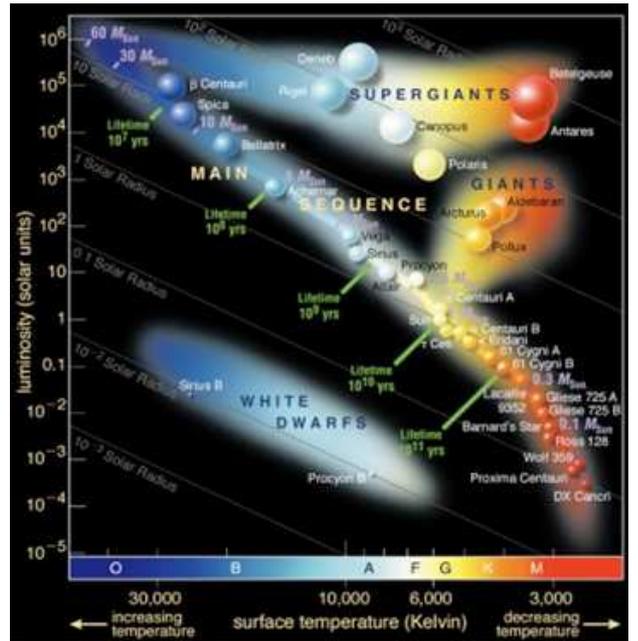


FIG. 1.— The HR Diagram, mapping stellar populations according to luminosity versus temperature. Supergiants are the most luminous stars, located at the top of the diagram.

1.1. Stellar Evolution

Stars begin their lives burning Hydrogen in their core in what we call the "Main Sequence" phase. This phase corresponds to the diagonal grouping on the Hertzsprung-Russel (HR) Diagram where most stars, including our sun, will spend the majority of their lifetimes (see Figure 1). But while our sun will spend somewhere around 10 billion years burning Hydrogen, a star with 15

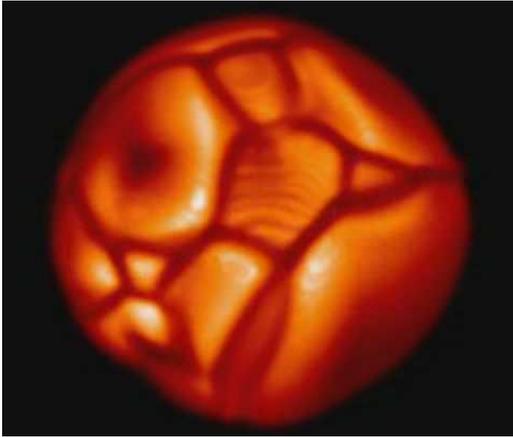


FIG. 2.—: Models by (Josselin et al. 2005) of the photospheres of Supergiants predict the presence of giant convection cells boiling across the surface.

times the mass of the sun will burn through its Hydrogen in about 12 million years. After the Hydrogen runs out, the star will start to collapse, compressing the interior until the temperature and pressure in the core are high enough to start burning Helium (Maeder & Meynet 2008). At this point, the internal furnace heats the outer layers, and the star puffs up to tens of times its Main Sequence size, and becomes a Supergiant. Now the outer layers of the star are very sparse and gaseous, and massive convection cells roil the surface (see Figure 2).

1.2. Background

Past studies of supergiants have been limited to spectroscopic studies. Spectral studies have led to spectral identification (Morgan & Keenan 1973, Gray et al. 2001), and thus parameters such as effective temperature and luminosity (de Jager & Nieuwenhuijzen 1987, Hickman et al. 1995). More recent photometric studies, including le Sadener & Le Bertre (1996), Massey (2005), and Levesque et al. (2005) have found evidence for thin circumstellar dust shells. A few studies have looked at individual stars with near-infrared interferometry, such as Perrin et al. (2005). This study measured varying stellar radii across the K-band due to molecular layers in the outer atmosphere of μ Cep, and suggests that most cooler (red) supergiants should show similar size variability across the K-band. Hotter supergiants are not expected to show the same variability, since the surface temperatures are hot enough to dissociate any molecules that form there. This statistical size of this data offers the first observational test of these theories.

1.3. O/IR Interferometry

Advances in optical technology have made possible the construction of interferometers in optical and near infrared wavelengths. These instruments enable astronomers to spatially resolve stars and their immediate surroundings for the first time. This represents a greater than ten-fold improvement in resolving power over traditional imaging telescopes. However, the improved resolving power comes at the cost of a full, two dimensional image: instead, the resulting measurement is a measure of the extent of a one-dimensional slice of the object,

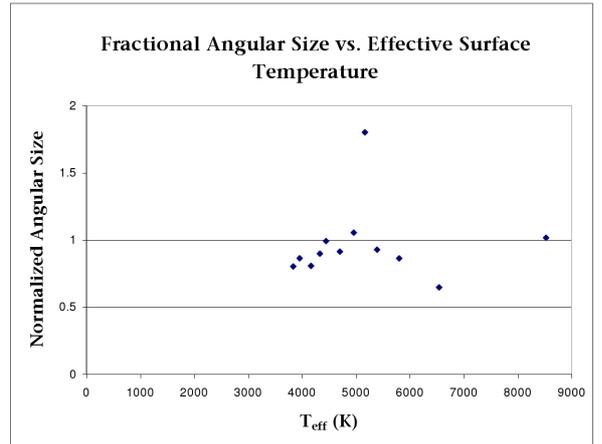


FIG. 3.—: Preliminary results of the data analysis, showing the Normalized Angular Size vs. T_{EFF} for a subset of the sample.

where the angle of the slice is determined by the on-sky projection of the physical baseline's orientation.

1.4. Wideband Results

Previous work on this data is found in vanBelle et al. (2009), where we took an average K-band size for each star and deduced an effective temperature. In general, stellar effective temperature, T_{EFF} , is defined in terms of the star's luminosity and radius by $L = 4\pi\sigma R^2 T_{\text{EFF}}^4$. Rewriting this equation in terms of angular diameter θ_{LD} and bolometric flux F_{BOL} , T_{EFF} can be expressed as $T_{\text{EFF}} \propto (F_{\text{BOL}}/\theta_{\text{LD}}^2)^{1/4}$. We were thus able to derive an empirically derived expression relating effective temperature and spectral type:

$$T_{\text{EFF}} = -123(\pm 25) \times ST + 4724(\pm 175) \quad (1)$$

where we found a reduced χ^2_{ν} of 0.34, and the spectral type $ST = -2, \dots, 0, \dots, 5, 6, \dots, 14$ corresponding to G8, ... K0, ... K5, M0, ... M8 as in Dyck et al. 1998.

2. OBSERVATIONS

The Palomar Testbed Interferometer (PTI) data presented here was taken over a period of several years, from 1998 until 2008. The sample includes 74 Supergiant stars, of which partial results are presented here. Each star was observed on multiple nights; the results reported here are the average of many observations.

2.1. Stellar Sample

The sample stars were selected for their brightness (K band magnitude of 5 or brighter) and their estimated angular size, as described in §3.1. The stars that were chosen were estimated to have an angular size that would fall in the interferometer's "sweet spot," or most sensitive range.

When such stringent observational criteria are imposed, selection effects will clearly be present in the data. The distribution of the sample stars can be seen in Figure 4. As such, it is important to keep in mind that the results presented here represent properties of galactic supergiants residing for the most part in the spiral arm of the Milky Way.

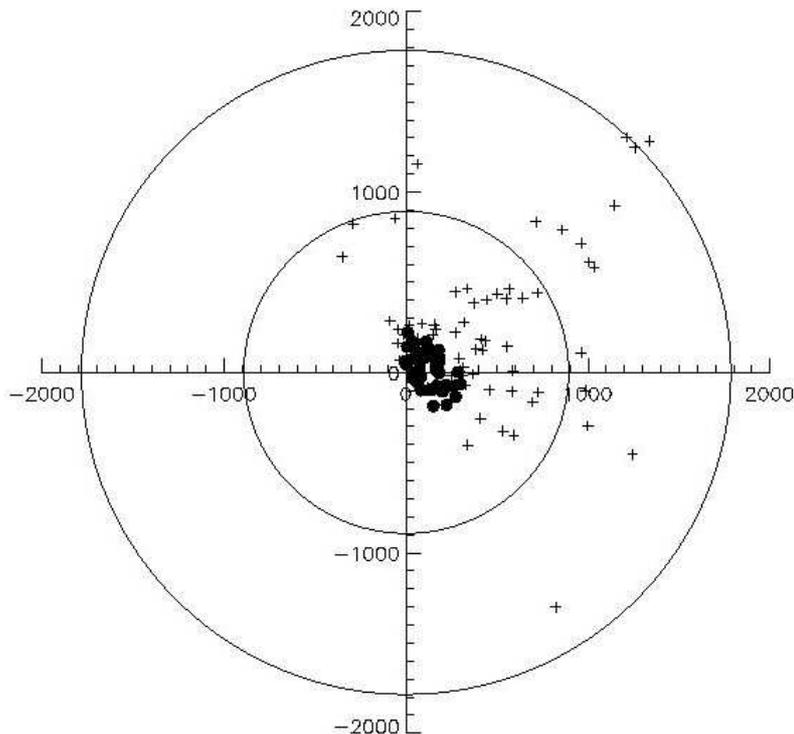


FIG. 4.—: Distribution of stars included in stellar sample in galactic coordinates, where our solar system is located at the origin. Units are in parsec; the x-y plane is the galactic plane, and the positive x-axis points toward the galactic center.

2.2. Instrumentation

The Palomar Testbed Interferometer is an 85 to 110 m H- and K-band interferometer located on Palomar Mountain outside of San Diego, California. Detailed specifications on the instrument and its capabilities can be found in Colavita et al. (1999). PTI has three 40-cm siderostats telescopes used in pairwise combinations for a total of three possible baselines. Light collected at each telescope is then sent down a delay line to be combined with light from another telescope. The resulting measurement is a “fringe visibility,” which can be produced for any object ranging in angular size from 0.05 to 5.0 milliarcseconds. The instrument can resolve individual sources $\theta > 1.0$ mas in size (van Belle et al. 2008).

The calibration of the supergiant V^2 data is performed by estimating the interferometer system visibility (V_{SYS}^2) using the calibration sources with model angular diameters and then normalizing the raw supergiant visibility by V_{SYS}^2 to estimate the V^2 measured by an ideal interferometer (Mozurkewich et al. 1991, Boden et al. 1998, van Belle & van Belle 2005). Uncertainties in the system visibility and the calibrated target visibility are inferred from internal scatter among the data in an observation using standard error propagation calculations (Colavita 1999).

We can use this visibility to infer an angular size for each star, in each wavelength channel. First, we will assume these stars have an on-sky brightness distribution similar to a uniform disk. After fitting the data to a uniform disk model, we will apply corrections for limb dark-

ening effects as quantified in Scholz & Takeda (1987). From the relationship between visibility and uniform disk angular size, $V^2 = [2J_1(x)/x]^2$, where $x = \pi B\theta_{UD}\lambda^{-1}$, we may establish uniform disk angular sizes of the observed stars in each spectral channel.

3. SUPPORTING DATA

3.1. Angular Size Estimates

An angular size estimate was based on a spectral classification derived from Spectral Energy Distribution fits of stellar models by Pickles (1998) to photometric measurements from Johnson UBV (Eggen 1963, Eggen 1972, & Moreno 1971), Stromgren $ubvy\beta$ (Piirola 1976), 2Mass JHK_s (Cutri et al. 2003), Geneva (Rufener 1976), Vilnius $UPXYZS$ (Zdanavicius et al. 1972), $WBVR$ (Kornilov et al. 1991), and IRAS 12 μm flux (Neugebauer et al. 1984). See Figure 5 for a sample fit.

3.2. Spectral Type

Spectral types of the target stars were taken from Johnson & Morgan (1953), Morgan & Keenan (1973), Keenan & McNeil (1989, 2006). Spectral types were used as a proxy for effective surface temperature (T_{EFF}) for those stars that do not have published T_{EFF} .

3.3. K-band Spectra

Spectra of the sample stars are used to determine which channels best represents the continuum source, i.e., the stellar photosphere. K-band spectra of each individual star are not available, so representative spectra for each

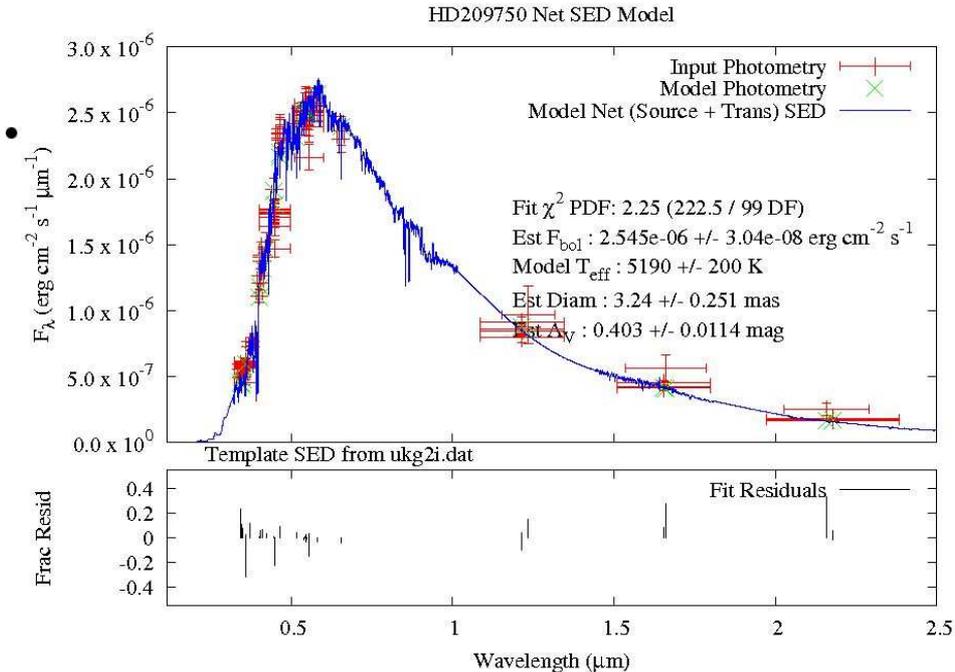


FIG. 5.—: Spectral energy distribution fitting for HD 209750, as discussed in §2.1, with a G2 I spectral template (Pickles 1998) being fit to photometry available for the star. Vertical bars are errors associated with the photometric data; horizontal bars represent the bandwidth of each photometric data point.

spectral type from Wallace & Hinkle (1997) were used for this purpose.

4. RESULTS

I present here preliminary results from the analysis of narrow-band data reduction. For each star measured, we have taken the angular size in each spectral channel and normalized it to a “continuum” channel, that is, a channel that is being emitted directly from the photosphere of the star. I have chosen the 2.1 micron channel as the continuum channel, based on the spectra mentioned above. Light coming from channels containing absorption features should appear to come from the shell of absorbing dust, which is some distance out from the photosphere. Thus, we expect that the star will look larger in these channels. The normalized size in the 2.4 micron channel, which contains the CO bands, was then compared across spectral type. Using the Effective Temperatures published in Arellano Ferro et al.(1990), Kovtyukh & Gorlova (2000), Malagnini et al.(2000), Schiller & Przybilla (2008) and Kovtyukh (2007). I plotted the Normalized Angular Size against T_{EFF} . The results can be seen in Figure 1.3. As expected, there is a correlation between the two. There is no theoretical prediction for this correlation, so the fit produced from this data will be the first of its kind. However, it is important to note that many other factors can influence this Normal-

ized Angular Size, such as the strength of gravity at the stellar surface and the abundance of heavier elements (a parameter astronomers call “metallicity”) in the star’s chemical composition. Thus, we do not expect a perfect correlation between these two variables.

5. CONCLUSIONS

As discussed in §1.2, we expect molecular layers to be present in the cooler stars, but disappear with increasing temperature. Because these molecular layers are located some distance from the stellar photosphere, the angular size of the star should appear larger when we look isolate emission from the molecular layers. The preliminary data presented here nominally supports this theory; however, the inclusion of more data is necessary before any statistical statements can be made.

6. ACKNOWLEDGEMENTS

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