STELLAR ASTROPHYSICS WITH SUB-MILLIARCSECOND OPTICAL INTERFEROMETRY

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1. Introduction

Although stellar interferometers are capable of measuring the angular diameters of stars, with longer baselines they may also be used to measure brightness variations across a star's surface and to provide constraints on models of stellar envelopes. In this paper we will look at the interpretation of visibility data and some of the more exciting prospects within the reach of current interferometers.

2. Measurements of Giant Stars

With sub-milliarcsecond angular resolution and a simultaneous spectral resolution better than 10000, it will be possible to measure limb

darkening and small-scale structures on or near the surface of giant stars. The brightest yellow and red giant stars have photospheres with diameters of several milliarcseconds, sufficiently large to be well resolved in the visible and infrared using baselines of a few tens of meters. This allows us, using longer baselines, to study details on the surface of the star itself and to test astrophysical models.

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Astronomical and Astrophysical Objectives of Sub-Milliarcsecond Optical Astrometry, 149–155.

2.1. LIMB DARKENING

Limb darkening can be detected through measurements of the first sidelobe of the visibility function, and to properly map the intensity across the disk an interferometer must be able to measure fringes whose contrast is less than about 13%. The observations require baselines of about twice those which resolve the star's angular diameter.

Usually, limb darkening of a stellar disk is predicted by modeling the emission in the continuum or photospheric lines. An important test of these predictions is the comparison with interferometric measurements of the star's intensity distribution.

Up until now, only a few attempts have been made to measure limb darkening. These include observations of Sirius with the Narrabri Intensity Interferometer (Hanbury Brown et al., 1974) and observations by Michelson interferometry of the stars α Boo, R Lyr, β Peg, and ρ Per using the I2T interferometer (Di Benedetto & Foy 1986). Figure 1 illustrates a measurement of limb darkening of the star α Boo, made by Di Benedetto & Foy (1986) with I2T. The corresponding fit is indicated. To perform the same measurements with stars of smaller angular diameter, longer baselines are necessary. For α Uma (KOIII, $\phi = 7.2$mas) a baseline of about 30m is required, and for o Uma (G5 III, $\phi \sim 2.6$mas) an 80 m baseline is necessary at visible wavelengths. These baselines are scaled and overlaid on Fig. 1.

2.2. SURFACE STRUCTURE

To observe a star's surface features, one must be able to detect fringes that have low contrast $\sim 5\%$, and which lie close to, or beyond the first zero of the visibility function for the stellar disk. An angular resolution better than 10 or 100 times that necessary to resolve the stellar diameter is necessary to resolve small structures.

Theoretical studies of convection suggests that a small number of convective elements, 50 or less, would be located at the surface of a red giant or supergiant star. These would have a temperature contrast of about ± 1000K and evolve with timescales of 100 to 300 days (Schwarzchild 1974). The existence of such features, driven either by convection or magnetic fields, have been inferred from irregular short-term variations observed by spectroscopy, photometry, and polarimetry. Starspots are also indicated in experiments of Doppler imaging of the surface of some fast rotating stars (Dupree, Baliunas & Guinan 1984).

Such small scale structures should be detectable by long baseline interferometry. The granulation and spots would appear in the spectral continuum or photospheric lines, and prominences and flares could be seen in strong chromospheric lines (H, CaII, MgI). The presence of small size

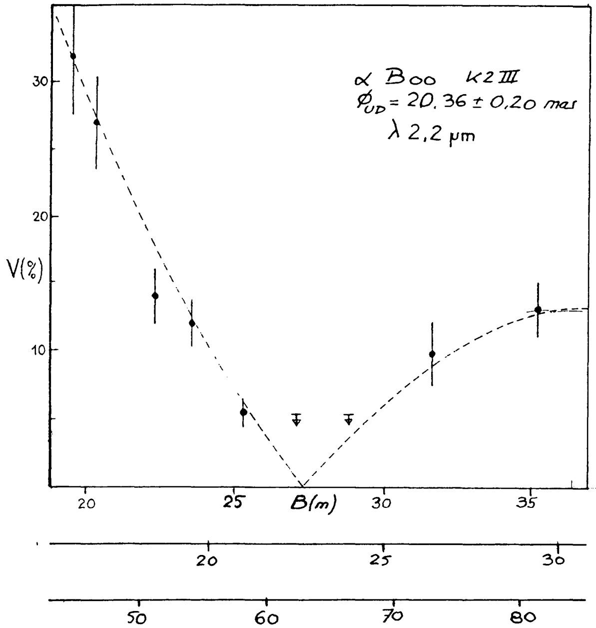

Figure 1. Limb darkening measurement for α Boo. The two baselines at the bottom are respectively for α UMa K0 III $\phi = 7.2$ mas and o UMa G5 III $\phi = 2.6$ mas at visible wavelength.

features on the stellar surface is suggested in the observations at visible wavelengths of α Aur Ab (G1III, $\phi = 6.4$mas) by the Mark III interferometer (Hummel et al. 1994) and that of β And (M0III, $\phi = 13.7$mas) from near IR observations with I2T interferometer (Di Benedetto & Bonneau 1990). Figure 2 shows the visibility curve for the star β And that does not drop to zero as expected, which suggests a detection of small structures. The solid line corresponds to a theoretical visibility. It was computed assuming a limb-darkened stellar disk with $\phi = 13.7$ mas, upon which a point source was superimposed that contributes 7 % of the total flux at 2.2 micron. Also indicated are the range of baseline needed to obtain the same measurements at visible wavelength for the stars β And and μ UMa (MO III, $\phi = 8$mas).

3. Envelopes of Early Type Stars

Interferometry can also provide strong constraints on circumstellar modeling. As a star evolves it follows a path through the HR diagram that is dependent on its mass, and at some stage will exhibit a radiative stellar wind. The mechanisms that produce a stellar wind depend on the effective temperature and spectral class of the star, and may include the following:

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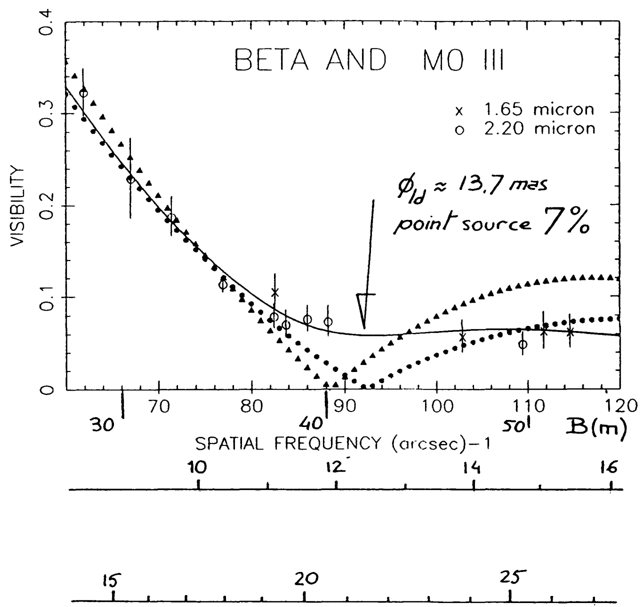

Figure 2. Detection of small structures for β And. The two baselines at the bottom are respectively for β And and μ UMa M0 III $\phi = 8$ mas at visible wavelength.

1. Thermal pressure, as in the case of the solar wind.
2. Radiative pressure on both continuum and lines, for hot stars with effective temperatures of ~15000–20000 K.
3. Radiative pressure on dust for relatively cool stars.
4. Other physical phenomena such as magnetic fields or stellar rotation.

The way in which long baseline interferometry can be used to constrain different models will be illustrated using a radiative wind model we have developed at the Observatoire de la Côte d'Azur and adapted to the Be star γ Cas.

3.1. BE STARS

Be stars possess a B spectral type and at one time in their life have exhibited emission lines in their spectra, most often Balmer lines. They are not supergiants stars. They are presumed to be fast rotators spinning at 0.5 to 0.9 of their critical velocity and have a large stellar wind and high mass loss. This stellar wind seems to be at the origin of what is usually called a *two component* envelope, which is characterized by

1. An equatorial plane with high density and low expansion where the Balmer emission lines are formed.

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2. A polar region with low density and high expansion where the UV absorption line profiles are Doppler shifted with velocities up to 2000 km/s.

This envelope is also responsible for a linear polarization by free electrons of about ~1.0–1.5%, and an IR excess that has been measured by IRAS. Based on this, many ad-hoc models have been computed which usually attempt to fit some Balmer line profiles and possibly the continuum emission flux. However, none of these reproduce intensity maps as a function of wavelength or incorporate high angular resolution data by computing theoretical visibilities.

3.2. A MODEL OF γ CAS

We have built a model which reproduces both spectroscopic and interferometric data that have been measured with the GI2T interferometer. It is a latitude-dependent radiative wind model for Be stars which clearly shows that the morphology of the circumstellar envelope depends strongly on the central observational wavelength and bandwidth (Araújo & Freitas Pacheco 1989; Araújo et al. 1994; Stee & Araújo 1994). This hydrodynamic code enables us to consider the effects of the viscous force in the azimuthal component of the momentum equations. The line force is the same as used by Friend & Abbott (1986), but we introduce a varying contribution of thin and thick lines from pole to equator by adopting radiative parameters which are latitude-dependent. The velocity fields and density relationships derived from the hydrodynamic equations are then used for solving the statistical equilibrium equations. By adopting the Sobolev approximation, we have calculated the electron density and hydrogen level populations throughout the envelope. We have modified this code in order to build a possible scenario for the Be star γ Cas which has been observed with GI2T during an international observational campaign in autumn 1993.

We have obtained an Hα emission profile from our model that is in good agreement with the observed spectra. Our computed intensity maps, in both the continuum and Hα, agree reasonably well with maps derived from observed visibilities. The model indicates that a radiative wind, driven mainly by optically thin lines at the equator, is a likely scenario for γ Cas. This is discussed in greater depth in Stee et al. (1994).

measurements it is The variations in visibility play an important role in understanding the data. Figure 3 illustrates two line profiles and the corresponding visibility curves, computed for two given set of parameters. Considering the spectroscopy by itself, we see that both line profiles agree roughly with the observed spectrum (dotted line). However, their corresponding visibility curves are quite different, and it is obvious that the

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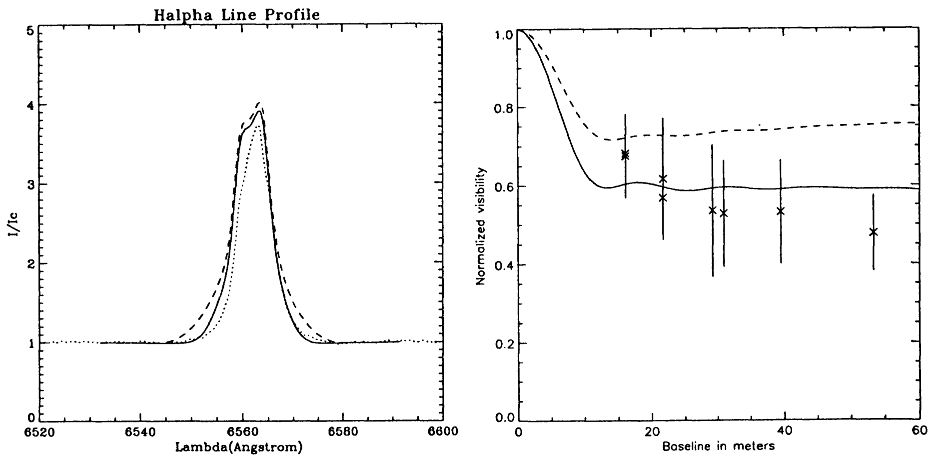

Figure 3. Two Hα line profiles and their corresponding visibility curves. Solid line and dashed line: model, dotted line: observed Hα line profile.

model with the higher visibility can be easily ruled out.

The importance of the spectral resolution, in association with a high angular resolution should also be stressed. Figure 4 shows the observed visibility along the Hα line profile and the computed visibility from our model. The error bars are large because each measurement is taken within a 4 Å bandwidth which restricts the number of detected photons and yields a low signal-to-noise ratio. Nevertheless, to a first order the model agrees well with the data, although a bump is apparent in the blue, which seems to indicate that the envelope size in the blue part of the line is systematically larger than in the red part. Such an effect could be produced if Hα radiation is being emitted by a larger or higher density region which is moving towards the observer along the line of sight.

4. Conclusion

Observations with existing and future optical interferometers will provide insight and open new horizons in problems of stellar astrophysics. The solution of these problems requires both high spectral and spatial resolution, obtainable through long baseline measurements. These must be tied into stellar models, as theoreticians have already done with spectroscopic, photometric, and polarimetric data.

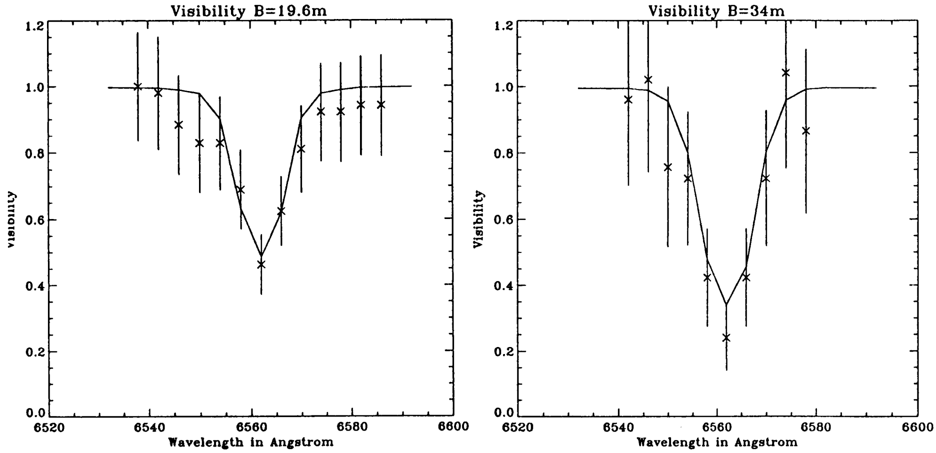

Figure 4. Visibility along Hα line profile for a 19.6 and 34 meters baseline.

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