Interferometric Surveys and Results on Variable Stars: Now and in the Future

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Abstract In this century, various ground-based interferometric techniques have been developed and applied to precise measurement of the angular sizes of a large number of variable stars. In this paper I describe the interferometric approach to variable star studies, highlight results from several interferometric surveys of long period variable stars and Cepheids, and discuss future challenges in high angular resolution variable star research.

1. Introduction

High angular resolution interferometric observations of evolved giants and supergiants can provide important information on the structure of their extended atmospheres and circumstellar environments. For example, accurate determination of their photospheric angular diameters is crucial for establishing the effective temperature scale (Ridgway and Joyce. 1980). For pulsating stars such as Miras, an accurately measured photospheric angular diameter, when combined with the measured distance to the star, yields its linear diameter, which can then be used to determine the mode of pulsation (Ostlie and Cox 1986). Presently, it is uncertain whether the oscillation mode of Mira-type variables is a fundamental or a first overtone. Once the pulsation mode is determined, it will be possible to better define the evolutionary place of Mira variables, and their relation to other types of long period variables (LPVs) (Willson 1982; Willson 2006).

Among the pulsating stars, Cepheids are most notable because of their importance for establishing the primary distance scale. Presently, the calibration accuracy of the zero-point of the distance scale is about 10%. With the advent of long baseline interferometers operating in the optical and infrared, a new opportunity has appeared to improve the accuracy of the Cepheid distance scale using the Baade-Wesselink techniques (Sasselov and Karovska 1994). A precise interferometric measurement of the angular radius of a Cepheid, combined with the radial displacement computed from the Cepheid's integrated radial-velocity curve, will allow a direct and very accurate distance determination. This should lead to a reliable zero-point of the Cepheid distance scale.

In the following, I will highlight the interferometric approach to exploring the structure of extended atmospheres of evolved giants and supergiants, and discuss future developments in interferometric studies of variable stars.

2. Interferometry

An image of an astronomical source obtained from space can be mathematically described as the convolution of the brightness distribution of the source with a blurring function introduced by the limited aperture of the telescope and the limited size of detector pixels. The size of the aperture defines the diffraction-limited angular resolution of the telescope at a given wavelength. The larger the aperture, the smaller the angle of the sky that can be resolved. The resolution power of a telescope increases as the wavelength of observation decreases. According to the Nyquist criterion, detector pixel size must be less than half the diffraction limit of the telescope in order to obtain diffraction-limited observations.

As an example of diffraction-limited observations from space, Figure 1 shows an image of the Mira AB system obtained using the 2.5-meter aperture Hubble Space Telescope (HST) and the Faint Object Camera (FOC) at 5010Å (Karovska *et al.* 1997). Both components of the system are variable stars: the primary, o Ceti (Mira), is the prototype of Mira-type variables, and the secondary, VZ Ceti, is an accreting white dwarf.

The HST observations were carried out at Mira's minimum, based on a prediction made using AAVSO observations (J. Mattei 1996, private communication), which allowed detection of both components simultaneously. The separation between the components is only 0.6 arcsecond.

The diffraction-limited image of Mira appears substantially larger than the image of the companion and is clearly resolved by the 2.5-meter telescope. The companion is unresolved by the telescope and one can discern the diffraction ring in its image. The diffraction limit of the HST in the optical is about 50 milliarcseconds (mas). The size of the detector's pixels is approximately three times smaller, 14 mas. The measured size of Mira's atmosphere at this wavelength is 60 mas.

If similar observations of this system were carried out using a 2.5-meter ground-based telescope, the binary would have been barely resolved because the images would have been blurred by the atmosphere. The seeing-limited size of each individual image would have been comparable to the size of the binary separation in the system.

In 1920, Michelson and Pease found a way to enhance the resolution of ground-based observations degraded by atmospheric seeing effects by using a technique based on the interference of the light from two mirrors in an interferometer. The baseline (separation between the interferometer mirrors) defines the resolution power of the instrument; at a given wavelength, the resolution power increases as the baseline increases.

At Mt. Wilson, Michelson and Pease constructed two interferometers (with approximately 7-m and 17-m baselines). They used these interferometers to make the first direct measurements of the angular sizes of stars other than our Sun. For example, over a period of seventeen years they measured diameters of two variable stars, the red supergiants α Ori and α Sco. Assuming uniform brightness distribution on the stellar disk, they obtained diameter measurements of α Ori ranging from 34 mas to 54 mas. For α Sco, the measured diameters range from 28 mas to 40 mas (from White 1980, and references therein).

In 1975, Labeyrie applied a novel approach to eliminate the degrading effects of the atmosphere on the ground-based images. Using a technique called speckle interferometry, which is based on light interference in a single-aperture telescope, he resolved the components of the binary system Capella, (separated by only 50 mas) using the Mt. Palomar 5-m aperture telescope. The separation between the components of this system is 10–20 times smaller than the size of the direct image of the system degraded by the atmospheric seeing.

Labeyrie and his group measured the diameters of several variable stars using the speckle interferometric technique, including evolved giants such as Mira and R Leo. These measurements were made assuming a uniform brightness distribution on the stellar disk (Labeyrie *et al.* 1977).

The results of these observations showed that within the same pulsation phase there is a significant variation in the diameter measurements obtained using filters centered in different spectral regions. This difference was clearly detected using filters with FWHM of 200Å bandpass, increasing as filters with narrower bandpasses were used, as shown in Table 1 (from Labeyrie *et al.* 1977) for Mira's diameter measurements.

Today there are more than a dozen ground-based interferometers around the world operating at wavelengths ranging from optical to IR and radio wavelengths. Their baselines range from a few meters to several hundred meters. Other interferometric groups are successfully using single-aperture techniques such as speckle interferometry and non-redundant aperture masking for high angular resolution observations of variable stars.

Several feasibility studies are presently being carried out for future interferometers in space. The beginning of the 21st century may see the first prototype interferometers in space (e.g., Space Interferometry Mission (SIM); DARWIN), which will open new frontiers in variable star research.

3. Interferometric surveys

Surveys of evolved variable giants and supergiants have been carried out at wavelengths ranging from the optical to the radio spectral domains, using single- and multiple-aperture interferometric techniques. Diameters as small as a few milliarcseconds have been measured with high precision in optical. These include diameter measurements of cool giants at optical wavelengths using the MkIII stellar interferometer (Quirrenbach *et al.* 1993).

Several surveys of Miras have been carried out in the optical (e.g., using non-redundant aperture masking technique and the 4-meter William Herschel Telescope, Haniff *et al.* 1995), and in the near-infrared (e.g., using the Infrared Optical Telescope Array, IOTA, van Belle *et al.* 1996).

Recent observations at Mt. Wilson using the Infrared Spatial Interferometer (ISI), have measured for the first time the diameters of several Miras and red supergiants in the mid-infrared spectral domain, in the 11-micron wavelength range. They detected dust shells around most of the stars on their list. The measured inner radius of these dust shells ranges from about two to several dozen stellar radii. The results of the initial survey of thirteen stars are described in Danchi *et al.* (1994). Also detected were two expanding dust shells around α Ori, one at one arcsecond's distance, formed 150 years ago, and another at 100 mas, formed more recently in the 1993–1994 time frame (Bester *et al.* 1996).

The sizes of the radio photospheres of several long-period variables (Miras and semiregular variables) have been measured using the Very Large Array (VLA) at the centimeter wavelength range (Reid and Menten 1997). Their observations suggest that these stars have a radio photosphere near 2 stellar radii, where the stellar radius is defined by line-free regions of the optical spectrum. For Mira-type variables, they did not find any substantial variability at the centimeter wavelength. This puts limits on the variations of the temperature and radius to ±150 K and $\pm 4 \times 10^{12}$ cm, respectively.

In addition to diameter measurements, images of several stars, including Mira, R Cas, α Ori, and α Her, have been obtained using single-aperture interferometric techniques. These multiwavelength images show substantial asymmetries in the extended atmosphere of these stars (Karovska *et al.* 1991; Haniff *et al.* 1992; Wilson *et al.* 1992; Tuthill *et al.* 1994).

The cause(s) of the observed asymmetries are still unknown. The asymmetries could be due to unresolved bright spots on the surface of the star or in the extended atmosphere. They could be related to the pulsation process; plausible mechanisms include instabilities in the pulsating atmospheres, and non-radial pulsation.

The first measurement of the mean diameter of the prototype of Cepheid variables, δ Cep, has been made using the GI2T (Grand Interferometer 2 Telescopes) (Mourard *et al.* 1997). They find that the uniform disk mean angular diameter of δ Cep in optical wavelengths is 1.6 mas.

With the ongoing development of very long baseline (more than 100 m) stellar interferometers (e.g., Sydney University Stellar Interferometer, SUSI; and the Navy Prototype Optical Interferometer, NPOI) it will soon be possible to resolve the disks of many galactic Cepheids (e.g., Davis 1994). This will provide a new avenue for determining their distance scale via the Baade-Wesselink method (Sasselov and Karovska 1994).

4. Future studies

Interferometric diameter measurements of evolved giants and supergiants are now made by using models ranging from uniform disk and Gaussian distribution, to brightness distributions calculated from various model atmospheres to estimate the effects of brightness nonuniformity (e.g., Haniff *et al.* 1995; van Belle *et al.* 1996).

These models often produce a very simplified and usually incomplete description of the physical characteristics of the extended atmosphere because they do not simultaneously incorporate crucial elements such as pulsation, opacities, dust, and so forth. In addition, these models assume that the atmosphere is spherically symmetric, despite the fact that presently there is substantial evidence that Miras and red supergiants are not symmetric. Stellar size measurements based on inadequate models produce a large scatter in the estimated diameters (e.g., van Belle *et al.* 1996), which can bias the calculated effective temperature scale and will affect the accuracy of the derived mode of pulsation.

Sasselov and Karovska (1994) recently showed that the differences in model brightness distributions have significant effects on the interferometric angular size measurements of Cepheids. They demonstrated that using a uniform brightness distribution will lead to an underestimate of the size of the Cepheid of up to 40% in the continuum, and an overestimate of approximately 25% in the Ca II line. The behavior of the Ca II λ 8498 line is characteristic of strong lines of abundant species: high levels of scattering above the limb, and sensitivity to local dynamic disturbances (shock waves, velocity gradients, etc.).

Further progress in understanding the structure of the atmosphere of evolved giants and supergiants depends not only on the results of the multiwavelength interferometric observations, but also on the further development of more realistic models incorporating asymmetries, proper abundance information, and physical processes such as propagation of shock waves and dust formation. These models should produce phase-dependent brightness distributions in selected spectral regions important for such atmospheric structure diagnostics as: different TiO bands and selected regions within a given TiO absorption band, the continuum (UV, optical and especially in the near IR), and emission lines carrying shock signatures.

High angular resolution interferometric observations of evolved variable stars with extended atmospheres should be carried out at various pulsation phases (determined by AAVSO photometric monitoring) in several spectral regions using a set of adequately chosen filters. Key input parameters that must be measured with high accuracy include diameters in selected spectral regions, and the brightness distribution across the stellar disk as a function of wavelength and pulsation phase.

The results of these observations should be used as feedback for models to further improve their prediction accuracy. Based on such high-precision size measurements at different phases of the pulsation process, and with the appropriate model atmospheres, one can determine the true diameter and diameter changes needed for effective temperature scale, pulsation mode, and distance scale calculations.

5. Addendum, 2006

We are now at the dawn of a new and exciting age of interferometric studies of variable stars. Interferometry methods and technologies have been advancing with giant steps since the time this review paper was written. We now stand on the threshold of a new era in interferometric studies of variable stars. Several new ground-based interferometers are now operational (e.g., Keck, VLTI, CHARA, see http://olbin.jpl.nasa.gov) and are providing unprecedented views of many classes of variable stars. Some of the questions that were highlighted in my review paper have been now answered (e.g., pulsation mode of Miras), however, many others (e.g., highlighted in the "Future Studies" section of this paper) are still open. Furthermore, important new questions have emerged that only future observations, especially using large space-based interferometers operating at UV and Optical wavelengths (e.g., the Stellar Imager, see http://hires.gsfc.nasa.gov/si/), will be able to answer completely.

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Table 1. Mira diameter variations as a function of wavelength and pulsation phase.

Date	*Phase*	$\lambda/\Delta\lambda$	*UD angular diameter*
1972.479	0.09	4500/200	0.070 ± 0.010
1972.479	0.09	5150/200	0.057 ± 0.005
1972.479	0.09	7500/200	0.051 ± 0.005
1972.479	0.09	10400/200	0.05
1972.742	0.38	6700/200	0.062 ± 0.005
1972.742	0.38	7000/200	0.058 ± 0.005
1972.742	0.38	7500/200	0.055 ± 0.005
1977.025	0.11	6080/80	0.071 ± 0.015
1977.025	0.11	6200/80	0.103 ± 0.020
1977.025	0.11	6470/30	0.072 ± 0.014
1977.025	0.11	6720/175	0.075 ± 0.015
1977.025	0.11	6960/80	0.031 ± 0.006
1977.025	0.11	7120/80	0.061 ± 0.007
1977.025	0.11	7400/50	0.034 ± 0.007

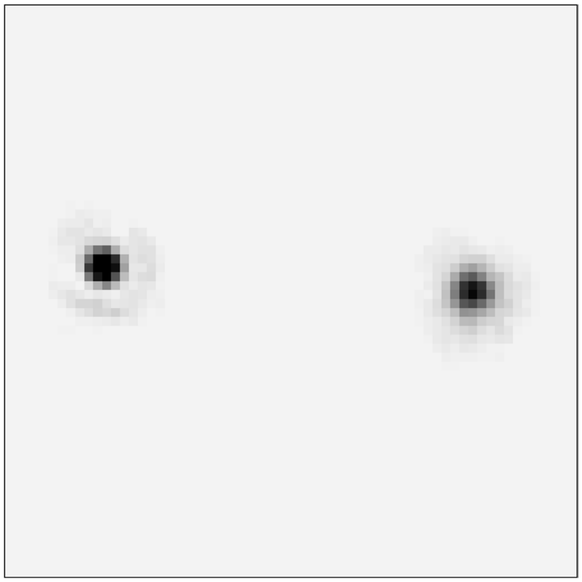

Figure 1. Diffraction-limited HST images of Mira (right) and its companion (left) at 5010Å.