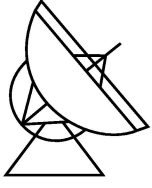


# VINCI VLTI interferometry of Mira stars and determination of stellar parameters

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## Abstract

We present accurate K'-band visibility and angular diameter measurements of Mira stars, obtained with the VLT Interferometer Commissioning Instrument (VINCI) at the Very Large Telescope Interferometer in the commissioning period between April 2001 and February 2003. A total of 49 VINCI observations were carried out from Oct. 2001 to Jan. 2003 and publicly released. For several Mira variables the observed visibility functions (modulus of the Fourier transform of the intensity distribution of the object) and diameters change noticeably with phase. For example, the FWHM Gauß fit diameter of *o* Ceti increased from  $19.23 \pm 0.2$  mas at phase  $\Phi = 0.13$  to  $23.02 \pm 0.2$  mas at phase  $\Phi = 0.4$ . Angular stellar filter radii and Rosseland radii were derived from the measured visibilities by fitting theoretical center-to-limb intensity variations (CLVs) of different Mira star models from Bessell, Scholz & Wood (1996, BSW), Hofmann, Scholz & Wood (1998, HSW), and Tej et al. (2003, TLSW). When available, HIPPARCOS parallaxes allowed us to determine linear radii. From the measured angular diameters and bolometric fluxes we calculated the effective temperatures. The shapes of the measured visibility curves (within the baseline length range of 11 m to 16 m) of *o* Ceti and the determined linear Rosseland radius of  $328 \pm 37 R_{\odot}$  agree well with the near-maximum fundamental mode P model of HSW and TLSW ( $R_{\text{model}} = 318 R_{\odot}$ ). On the other hand, comparison of the data with the first-overtone pulsation models suggests that these models are not a good representation of *o* Ceti.

## Introduction

Mira stars are long-period variables which evolve along the asymptotic giant branch (AGB) with well-defined pulsation periods (80-1000 days). Because of their large visual light curve amplitudes, they are easily identified and classified. Fig. 1 shows the visual light curve of *o* Ceti together with the dates at which the VINCI observations were carried out. The change of CLV and spectral type with phase and cycle, as well as the brief time these stars remain in the variable stage, pose interesting problems for observation and modeling.

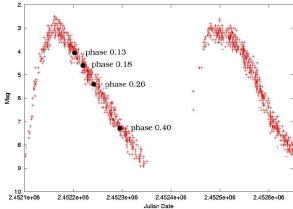


Figure 1: Visual light curve of *o* Ceti between JD 2452100 and 2452700. The visibilities were measured at the following phases: phase 0.13 (22/23 Oct. 2001), phase 0.18 (09/15/17 Nov. 2001), phase 0.26 (06 Dec. 2001) & phase 0.4 (20 Jan. 2002).

## Observations

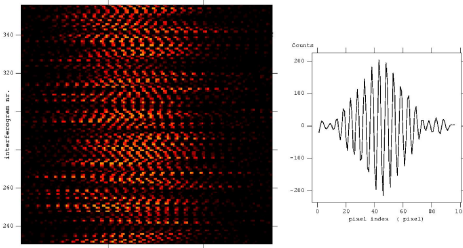


Figure 2: Interferometric fringes obtained with VINCI. Left: Interferograms for *o* Ceti with a baseline of 16 m. The y-axis shows the interferogram number, and each horizontal line corresponds to an individual interferogram (pseudocolor). These interferograms are produced by modulating the optical path difference (OPD) via a mirror mounted on a piezo translator. Right: Single interferogram (no. 223). The y-axis is given in arbitrary units of relative intensity. In both panels the x-axis gives the pixel number which is a measure of the OPD.

Although VINCI was designed only for the VLTI commissioning program, it delivered enough scientific data to allow investigations of several southern Mira stars, many of them being first-time visibility determinations. *o* Ceti is an ideal target for infrared interferometry because of its large photospheric size and its relatively small distance from Earth (HIPPARCOS: 107 pc), together with a substantial infrared flux.

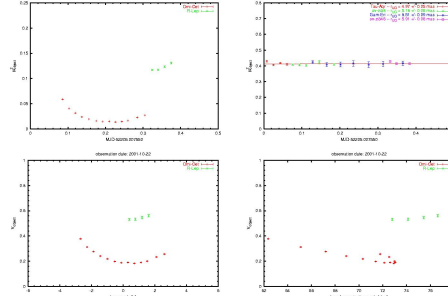


Figure 3: Top left: Uncalibrated visibilities of the objects *o* Ceti and R Lep plotted vs. modified Julian date (MJD). The curved shape of the visibilities arises from the change of the projected baseline length caused by the Earth's rotation. Top right: Linearly fitted transfer function (i.e. measure of the instrument's fringe contrast loss) obtained from calibrator stars measured during the same night. The transfer function is used to calibrate the raw object visibilities. Bottom left: Calibrated visibilities of the objects *o* Ceti and R Lep plotted vs. hour angle. Bottom right: Calibrated visibilities plotted vs. baseline projection angle (PBA). The PBA change of less than 10 deg does not allow for a study of asymmetries.

## Diameter-phase relationship

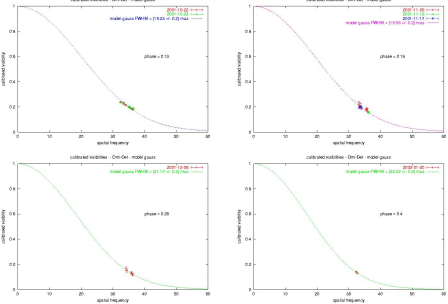


Figure 4: Visibilities vs. spatial frequency for *o* Ceti at four different phases (see labels). The solid lines are Gauß fits whose FWHM is a measure of the angular diameter.

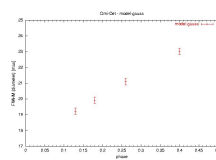


Figure 5: Diameter of *o* Ceti at four different phases ( $\Phi = 0.13$ : FWHM =  $19.23 \pm 0.2$  mas;  $\Phi = 0.18$ : FWHM =  $19.93 \pm 0.2$  mas;  $\Phi = 0.26$ : FWHM =  $21.10 \pm 0.2$  mas;  $\Phi = 0.4$ : FWHM =  $23.02 \pm 0.2$  mas). The plot clearly shows a monotonic diameter increase with decreasing brightness, in line with most theoretical predictions.

After the reduction and analysis of the data, all measurements were binned according to phase. The visibilities measured at four phases within one cycle are presented in Fig. 4 together with fitted Gauß visibility models (which were found to be a better representation of the observations than uniform or fully darkened disk models). The FWHM of the Gauß fit gives the angular diameter. The diameter-phase relationship measured for *o* Ceti shows a monotonic increase of the diameter from phase 0.13 (FWHM =  $19.23 \pm 0.2$  mas) to phase 0.4 (FWHM =  $23.02 \pm 0.2$  mas), as can be seen from Fig. 5. Therefore, as the visual intensity decreases, the diameter of *o* Ceti increases.

## Center-to-Limb Variations

The data for each phase bin were compared with all available BSW/HSW/TLSW models. These theoretical calculations for Mira atmospheres use non-linear pulsation models for both fundamental and first-overtone pulsation modes. Among the out-

puts, they produce light curves and synthetic spectra, as well as giving radius and effective temperature. The visibilities measured for *o* Ceti at phase 0.13 (observation date: 22/23 Oct. 2001) are best fitted with the TLSW model P22. This model was calculated for *o* Ceti at phase 0.2 in the second cycle of computation. The P series fundamental mode models agree best with the measured visibilities and the derived radii, whereas the D series models do not represent Mira well. From the CLV fit of the visibility curve, together with HIPPARCOS measurements, a Rosseland radius of approximately  $330 R_{\odot}$  was obtained. The accuracy of the fit for three models (P22, fully darkened disk and uniform disk), together with the shape of the model CLV, can be seen in Fig. 6.

Although the measured visibility shapes are in good agreement with the predictions made by the TSW P models, we nevertheless want to point out that the observed visibility function might also arise from an asymmetric shape of the stellar disk or inhomogeneous surface structures such as supergranulation.

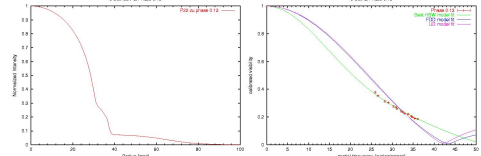


Figure 6: Left: CLV of the TLSW model P22 for *o* Ceti at phase 0.2. The intensity is normalized to 1 at the disk center, and the angular diameter is given in mas. The extended wing of the CLV is probably caused by water molecules in the outer region of the atmosphere. Right: Visibility of *o* Ceti measured at phase 0.13. The green line denotes the model visibility curve derived from the intensity distribution shown in the left panel. As can be seen, the model visibility shape is in good agreement with the observations in the observed baseline range. The blue and purple lines show the visibility function derived from a fully darkened disk (FDD) and an uniform disk (UD) respectively.

## Radii and effective temperatures

Angular stellar filter radii and Rosseland radii were derived from the measured visibilities by fitting theoretical center-to-limb intensity variations of different Mira star models to the observed visibilities. When available, HIPPARCOS parallaxes allowed us to determine linear radii. The bolometric flux was obtained by integration of the spectral energy distribution (SED) for each Mira star at different phases. The effective temperature  $T_{\text{eff}}$  was derived from the Rosseland diameter and the bolometric flux. We estimated an error of 20% for the bolometric flux determination. Results for *o* Ceti, R Lep, and S Ori are summarized in Table 1.

	$\Phi$	model	$d/\text{mas}$	$R/R_{\odot}$	$T_{\text{eff}}/\text{K}$	$R_{\text{model}}/R_{\odot}$	$T_{\text{eff,model}}/\text{K}$
<i>o</i> Ceti	0.13	P22	$28.40 \pm 0.2$	$328 \pm 37$	$3040 \pm 70$	318	2700
R Lep	0.2	P22	$15.20 \pm 0.2$	$400 \pm 90$	$2214 \pm 60$	318	2700
S Ori	0.8	P28	$9.78 \pm 0.2$	-	$2700 \pm 80$	190	3550

Table 1: Phases  $\Phi$ , model used, angular Rosseland diameters  $d$  of *o* Ceti, R Lep, and S Ori (derived by fitting P model visibilities to the observed visibilities), derived linear Rosseland radii  $R$ , effective temperature  $T_{\text{eff}}$  (derived by using P models), P model Rosseland radii  $R_{\text{model}}$ , and P model effective temperatures  $T_{\text{eff,model}}$

## Conclusion

- Rosseland radius and effective temperature were determined for *o* Ceti and other Mira stars (see Tab. 1).
- The FWHM Gauß fit diameter of *o* Ceti increased from  $19.23 \pm 0.2$  mas at phase  $\Phi = 0.13$  to  $23.02 \pm 0.2$  mas at phase  $\Phi = 0.4$ .
- The visibility shape of the TLSW model P22 is in good agreement with measured visibilities in the observed baseline range.
- The  $T_{\text{eff}}$  for *o* Ceti derived from the observations is 10% higher than the model  $T_{\text{eff}}$ , which is possibly due to uncertainties in reconstructing the SED.
- Comparison of the model Rosseland radius (model P22,  $R = 318 R_{\odot}$ ) and derived Rosseland radius of *o* Ceti at ( $R = 328 \pm 37 R_{\odot}$ ) at  $\Phi = 0.13$  show good agreement.

## References

Bessell, M. S., Scholz, M., & Wood, P. R. 1996, *A&A* 307, 481  
Hofmann, K.-H., Scholz, M., & Wood, P. R. 1998, *A&A* 339, 846  
Tej, A., Lançon, A., Scholz, M., & Wood, P. R. 2003, *A&A*, in press

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