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Simultaneous Spectroscopic and Interferometric Measurements of Binaries with the GI2T

D. MOURARD, D. BONNEAU, A. BLAZIT, A. LABEYRIE, F. MORAND, I. PERCHERON, I. TALLON–BOSC, & F. VAKILI
Observatoire de la Côte d'Azur, Dpt Fresnel, URA1361, 06460
Saint Vallier de Thiey, France

1. INTRODUCTION

The "Grand Interféromètre à deux Télescopes" (GI2T) is presently the largest operational interferometer operating at visible wavelengths (Labeyrie *et al.* 1986, Mourard *et al.* 1991). With two telescopes of 1.5-m aperture and baselines reaching 65 m in the North–South direction, it gives stellar spectra containing interference fringes, which provide high angular resolution measurements in the range of one milliarcsecond.

The GI2T optical combination follows the Michelson principle of output pupil remapping to preserve a constant fringe spacing on the detector for stable and economical spatial sampling. The stellar light is dispersed in order to study the fringes parameters simultaneously with the spectral information. The direction of dispersion is perpendicular to that of the recombined pupils. Due to atmospheric turbulence the instantaneous images contain about 100 speckles. To freeze the atmospheric turbulence a temporal resolution of at least 10 milliseconds is needed. Each fringed speckle contains a random atmospheric phase shift. To disperse the images without blurring the fringes coming from different speckles, we use at the entrance of the spectrograph an image slicer formed by three slits each 0.″15 wide. The number of slits is limited by the number of pixels on the photon counting detector. We currently use the CP40 camera build by R. Foy and A. Blazit (Blazit 1988) and we have just began to test a resistive anode camera built at the Space Telescope Science Institute by F. Paresce and his group. Depending on the astrophysical goal, three dispersing modes (R=4300 $\delta\lambda$=30nm, R=1300 $\delta\lambda$=100nm, R=450 $\delta\lambda$=300nm) are available. Therefore, our raw data are photon coordinates in the image plane. They represent dispersed speckles containing interference fringes.

In the current configuration, the fringes are detected by visually observing a low dispersion spectrum from one image slice. The practical limiting magnitude, of about m_V=5, is due to the low sensitivity of the eye. This limitation should be overcome in the near future by installing a photoelectric fringe tracking system.

2. OBSERVATIONS OF BINARIES BY MICHELSON INTERFEROMETRY

The main parameter of a two telescope interferometer is its spatial frequency:

$$\vec{f} = \frac{\vec{L}}{\lambda} \ , \tag{1}$$

where $\vec{L}$ is the baseline vector and λ the wavelength.

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This vector must be projected on the (u,v) plane, which is the conjugate of the incident wave plane (α, δ). The baseline vector $\vec{L}$ has two components, L_n and L_e, with respectively North–South and East–West orientation. Assuming that the baseline is in the horizontal plane, the expression of the frequency vector $\vec{f}$ in the (u,v) plane can be written:

$$\vec{f} = \left| \begin{array}{cc} \frac{-L_n \sin l \sin H - L_e \cos H}{\lambda} & \frac{L_n(\cos l \cos \delta + \sin l \sin \delta \cos H) + L_e \sin \delta \sin H}{\lambda} \end{array} \right| \qquad (2)$$

where l is the latitude of the interferometer, δ the declination of the star, and H its hour angle.

Absolute measurement of the fringe contrast is directly related to the complex amplitude of the spatial spectrum of the object at the above frequency (Roddier & Lena 1984). By obtaining simultaneously a large number of such spatial frequencies, it is possible to sample a large fraction of the spatial spectrum of the object and then to obtain a complete image. This is the principle of aperture synthesis or more precisely of Fourier synthesis. This technique is not yet applied in the visible but is intensively used in radio astronomy (Thompson *et al.* 1986). Maps of radio sources are routinely obtained with the Very Large Array, and the importance of such techniques does not have to be demonstrated.

Up to now, at optical wavelengths, only two–aperture interferometers have been used. In the case of a binary, the main parameter is the projected binary separation p_i along the baseline, which can be written as follows:

$$p_i = \rho \cos(\theta - \Theta) \qquad (3)$$

with ρ and θ the angular separation and position angle of the binary respectively and Θ the position angle of the baseline seen from the star. The expression of Θ is given by:

$$\tan \Theta = \frac{\sin l \sin H}{\cos l \cos \delta + \sin l \sin \delta \cos H} \qquad (4)$$

As Θ is varying with time, ρ and θ can be computed from a set of measurements of p_i.

Taking the phase origin on the system's photocentre, the complex visibility function can be written as follows:

$$\mathbf{V(f)} = \frac{V_1}{1} + Ke^{i}\frac{K\psi}{1} + K + \frac{KV_2}{1} + Ke^{-i}\frac{\psi}{1+K} = V(f)e^{i\phi} \qquad (5)$$

$$\text{with} \qquad \psi = 2\pi\vec{p}\vec{f} = 2\pi p_i f \qquad (6)$$

where V_1(f) and V_2(f) are the amplitudes of the visibility refered to each component and K=I_2/I_1 the intensity ratio of the components. We obtain then the expression of the modulus and phase of the visibility.

$$V(f) = \frac{1}{1 + K\sqrt{V_1}^2} + (KV_2)^2 + 2KV_1V_2\cos(\psi) \qquad (7)$$

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$$tan\phi = \frac{V_1 \sin(\frac{K\psi}{1+K}) - KV_2 \sin(\frac{\psi}{1+K})}{V_1 \cos(\frac{K\psi}{1+K}) + KV_2 \cos(\frac{\psi}{1+K})} \tag{8}$$

So, different observational procedures can be used to derive the position angle and angular separation for a double star from a set of measurements of the composite visibility.

2.1. Time dependence of the spatial frequency:

The time dependence of ψ is used. The observation is carried out at a fixed wavelength for a given baseline. The values of p_i are computed from the time variation of the observed visibility V due to the variation of Θ produced by Earth rotation, thus exploring a fraction of the (u,v) spatial frequency plane. This technique is intensively used on the Mark III interferometer by combining observations carried out with independent North–South and East–South baselines (Shao *et al.* 1988).

2.2. Spectral dependence of the spatial frequency:

The wavelength dependence of ψ is used. For a fixed baseline at a given time, the amplitude of the visibility function V is modulated as a function of wavelength. The dispersed interference pattern looks like a channeled spectrum which contains information about the amplitude and the phase of the complex visibility of the source intensity distribution projected on the baseline. Figure 1 represents a computer simulation of this visibility modulation. This technique requires a moderate spectral resolution and a large spectral bandwidth in order to record several complete modulations in the composite image. At the time of the observation, p_i can be derived from the positions of the maxima and minima of the fringe contrast in the spectrum. The parameters ρ and θ can be computed from values of p_i taken at different times i.e. for different values of the position angle Θ of the baseline.

This method was first experimented for observations of Capella with the I2T 15 years ago (Koechlin *et al.* 1979) and also for the first direct resolution of the eclipsing binary β Aurigae (Koechlin *et al.* 1981). It is not yet operational on GI2T, mainly due to the absence of correction of the atmospheric dispersion and of the chromatic aberrations of the set-up.

An optical setup using glass plates of variable thickness to compensate for the atmospheric dispersion induced by the inequality of air path in the interferometric arms will be implemented. We also plan to build new focal instrumentation free of the chromatic aberrations and designed to include an adaptive optics system, a fringe tracker, and a third telescope.

In both cases, the intensity ratio K and the angular diameter of the two components can be estimated from the maxima and minima of the absolute visibility function obtained after the calibration of the observed fringe contrast. Observations of reference stars is fundamental in order to calibrate the instrumental and atmospheric point–spread function. This is routinely done in the visible with the Mark III interferometer (Pan *et al.* 1990) and was occasionaly tested in the near IR on I2T some years ago (Di Benedetto 1985).

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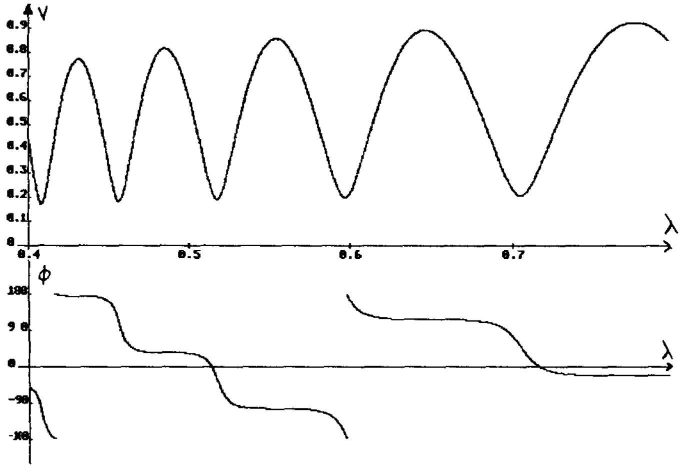

FIGURE 1. Computer simulation of the spectral visibility modulation induced by a binary system. $\theta_{1(ud)} = 1.0$ and $\theta_{2(ud)} = 1.0$ are the uniform disk angular diameters of the components in mas. $\Delta m=0.5$ is the magnitude difference; Sep=20 is the binary separation in mas in the North–South direction; Base=40.0 is the baseline in meters.

2.3. Spectral dependence of the object:

The wavelength dependence of K, V_1 and V_2 is used. If the spectral resolution of the focal instrumentation is high enough, wavelength dependence of the object morphology over a limited spectral bandwidth centered on a peculiar spectral feature can be evidenced from the complex visibility function obtained. This method was implemented on the GI2T where interferences fringes are recorded with a spectral resolution of about 0.15 nm over a 30-nm band. First applied to the study of Be stars, this method has proven the power of combining interferometric and spectroscopic information (Mourard *et al.* 1989) and is now extended to the study of spectroscopic binaries.

Data with one milliarcsecond angular resolution on close binaries should provide information on the classical morphological physical parameters but also on mass–loss phenomena and on the existence of circumbinary envelopes. We discuss now two examples under development on GI2T.

3. DOUBLE–LINED BINARIES: β AURIGAE

This binary is an interesting object from an astrophysical point of view. Combining spectroscopic radial velocity measurements and photometric light variation due to its eclipsing nature with high–angular resolution measurements, the individual stellar masses and radii can be obtained without any *a priori* knowledge of the distance. Thus, independant determination of the semi-major axis and of the apparent orbital radius directly provides the orbital parallax.

β Aurigae is the brightest (V=1.85) eclipsing and double–lined spectro-

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TABLE 1. Fundamental parameters for β Aurigae.

System		Star 1	Star 2
P=3.96004 d	T=2431075.759	K_1=107.5 km s^{-1}	K_2=111.5 km s^{-1}
e=0.0	ω=0°.0	$\mathcal{M}_1$=2.35 $\mathcal{M}_\odot$	$\mathcal{M}_2$=2.27 $\mathcal{M}_\odot$
i=77°.8	γ=−17.1 km s^{-1}	R_1=2.61 $R_\odot$	R_2=2.38 $R_\odot$
a=17.53 $R_\odot$	π=0″.041	$M_{V,1}$=0.73	$M_{V,2}$=0.73

scopic system. The components have the same spectral type (A2 IV) and almost the same luminosity; the difference of magnitude between both stars being less than 0.1 mag. The total amplitude of the radial velocity reaches about 220 km s^{-1}. Table 1 presents the spectroscopic and photometric orbital parameters as well as the derived physical parameters for β Aurigae (Smith 1948, Johansen 1971).

Preliminary determinations of the apparent orbital radius (a=2.2±0.3 mas) and of the position angle of the node (Ω=50° ±5°) were derived from observations with I2T, using the spectral visibility modulation (Koechlin *et al.* 1981).

In the case of double–lined spectroscopic binaries, the radial velocity of each star is large enough to separate the two spectra. Measurements of the two radial velocities are possible in certain spectral lines, and they provide some orbital parameters. For interferometric observations, the first–order effect is a displacement of the photocentre as a function of the wavelength in the double line. The amplitude of this displacement is directly related to the value of p_i. Measurements of such effects may be achieved by using the Differential Speckle Interferometry method (Petrov, these proceedings) but the angular resolution is not sufficient to separate close binaries. With the interferometer, the photocentre displacement corresponds to a fringe displacement, i.e. to a variation of the fringe phase. In the case of a two–aperture interferometer, the absolute phase cannot be known due to the atmospheric effects. However, by using intercorrelation techniques, we estimate the relative phase of the fringes between two separate spectral bands and in particular between the two lines. The relative phase is directly related to the phase of the object's visibility function. Indeed, the atmospheric phase is the same in the two spectral bands, taken in the same spectral coherence width of the atmosphere, which is about 50 nm.

We have made some simulations of the complex visibility in the Hα double line of β Aurigae and the results are presented in Figure 2. As a first approximation, we assume a gaussian profile for each Hα line and we calculate the intensity of each star as a function of the wavelength. In order to attain a reasonable signal–to–noise ratio, we take a numerical spectral resolution of about 0.5 nm. This value is magnitude dependent and is determined so as to have one photon per speckle per spectral band and per exposure time at least. The gaussian profile is a crude approximation, as can be easily seen from the observed profiles. However, the expected effects do not depend strongly on the exact profile. If a detection of the expected effect is achieved, a more detailed version of the model will be studied.

We have observed β Aurigae with the GI2T during two consecutive nights at the end of December 1991 and with a baseline of 22.5 m. The data have not

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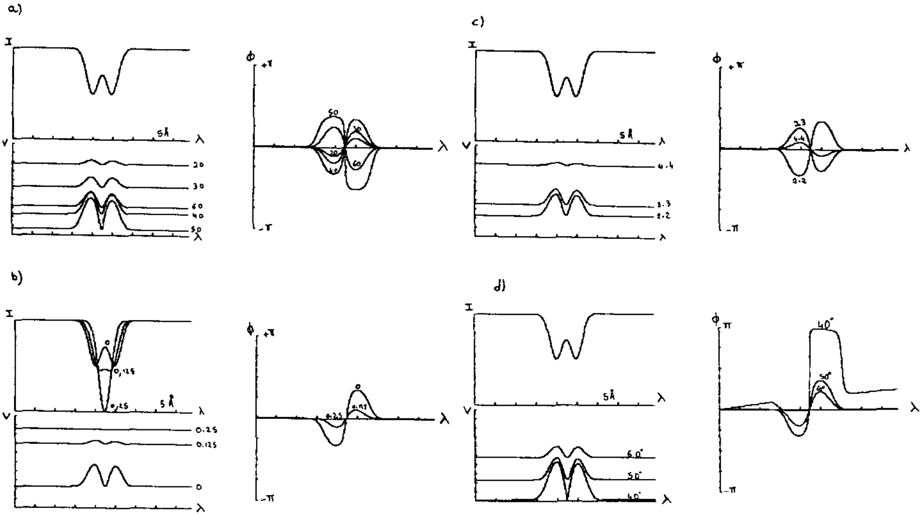

FIGURE 2. Computer simulated visibility in the Hα double line of β Aurigae. The baseline length is 40 m, the orbital phase is 0, the apparent orbital radius is 2.2 mas and the node angle is 50°. a) Effect of variation of the baseline length L; b) Effect of variation of the orbital phase φ; c) Effect of variation of the apparent orbital radius πa; d) Effect of variation of the node angle Ω.

been completely processed yet. We present in Figure 3 the two spectra obtained during these two nights and the expected visibility effects, assuming a position of the binary deduced from the values given in Table 1.

4. SEMI-DETACHED BINARIES: β LYRAE

The eclipsing binary star β Lyrae remains one of the most puzzling, as well as most important, close binary stars. A recent analysis of this system is given in Mazzali *et al.* (1992).

In this case, we do not use the wavelength dependence of the photocentre displacement but the object's shape dependence. Different spectral bands originate from different spatial regions, and we study the relative size and position of these different emitting or absorbing regions. We obtained a large sample of interferometric data at different spectral regions, photometric orbital phases and angular resolutions during the summer of 1991.

As for β Aurigae observations, our spectra are not completely corrected (flat field, spectral calibration). However, they already indicate an orbital phase dependence, as presented in Figure 4. This effect was already studied in the Hα and HeI feature and was interpreted in terms of stellar winds (Etzel & Meyer 1983, Batten & Sahade 1973). We plan here to study the influence of this dependence on the fringe parameters. Such measurements could provide strong constraints on the physical characteristics of interacting binaries.

We are currently working on the data reduction. The processing procedure

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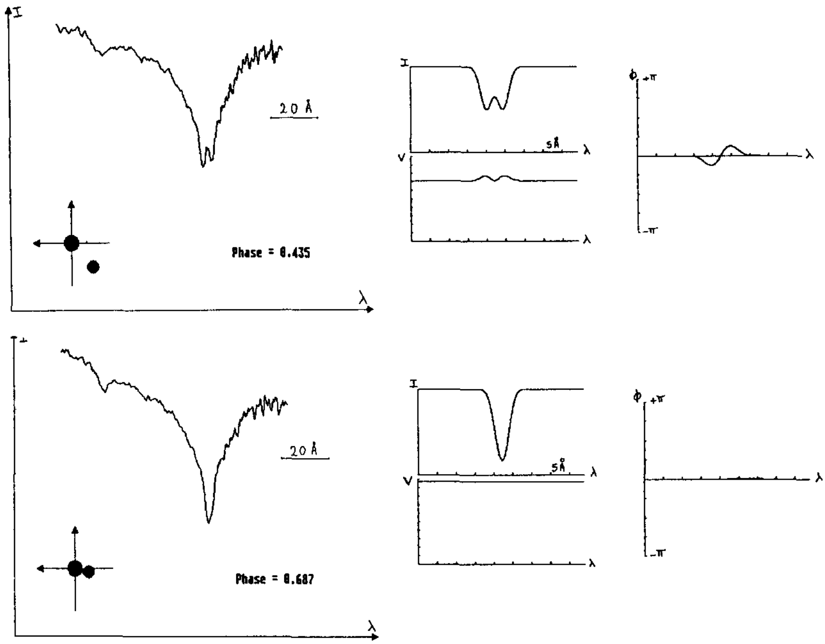

FIGURE 3. Hα spectra of the double-lined binary β Aurigae obtained with the GI2T 29–30 December 1991. At this time, the calculated spectroscopic orbital phase indicate the following values: 0.435 and 0.687. The corresponding binary position are ρ=2.02mas, θ=225° and ρ=0.95mas, θ=257° . We also include the calculated visibility effects as expected with these configurations. The baseline length is 22.5 m.

is now well established and consists of computing the fringe contrast in different bands (continuum, Hβ, HeI 587.5nm, Hα, HeI 667.8nm) and also in determining the relative phase of fringes between different lines and the neighbouring continuum. Preliminary results indicate a spectral dependence of fringe contrast but not of fringe phase in the Hα line and no dependence in the HeI (667.8nm) line for a baseline of 51 m and an orbital phase of 0.675. The results are shown in Figure 5. As a first approximation, the depression in the visibility modulus across the Hα line seems to indicate that this emitting region is resolved, but centered on the object's photocentre in agreement with the constant phase. On the contrary, the HeI (667.8 nm) emitting region appears to be unresolved with these observational parameters.

We will now continue processing all the data for this star, and with this large sample of measurements we may be able to answer some of the unsettled questions concerning β Lyrae; for example, about the existence of a circumbinary envelope.

5. CONCLUSIONS

We have shown the potential of binary observation with GI2T and the particular astrophysical interest of simultaneous spectroscopic and interferometric

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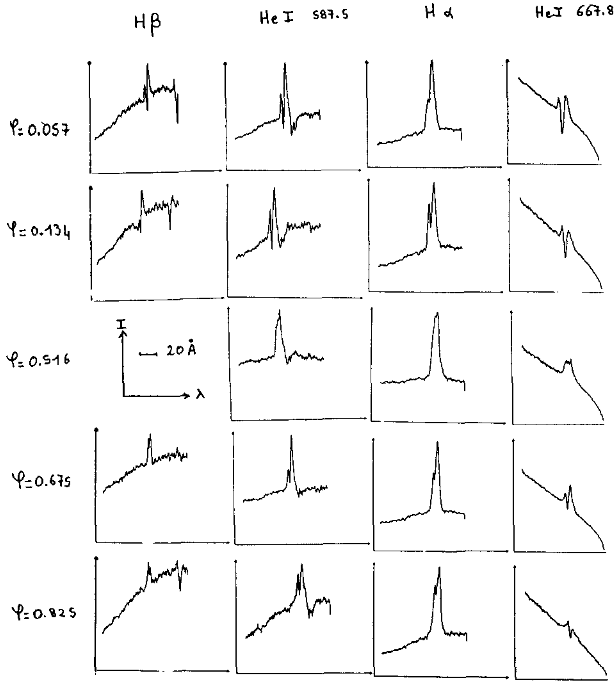

FIGURE 4. Observation of β Lyrae during the summer 1991. Each spectrum is referenced by its spectral region and its photometric orbital phase. All these data were recorded with a spectral resolution of 0.15nm.

measurements. It seems fundamental to program simultaneous campaigns on a few objects. These methods are complementary, and a large and simultaneous set of data is very precious in terms of external reference or calibration. Some free parameters in one observation could be determined by another one and vice versa. A campaign for the study of o Andromedae is organized next autumn. Spectroscopic, photometric, speckle and interferometric observations are envisioned.

High-angular resolution information should be exploited in astrophysics. Semi-physical models describing objects in accordance with spectroscopic or photometric measurements should provide predicted maps at differents wavelengths in order to compute the predicted object visibility and to fit the high angular resolution data.

The importance of imaging stellar sources directly cannot be understated. The current limitations of interferometry result from the very poor number of spatial frequencies measured simultaneously. We are currently involved in the definition and first studies of the Optical Very Large Array project (Labeyrie *et al.* 1991) and the European Very Large Telescope Interferometer (Beckers 1991). For imaging stellar sources, a good temporal resolution is necessary to freeze the rotation and variation of the shape. In the case of close binaries, this temporal resolution must be shorter than a few hours in order to avoid variation of the position angle. Snapshot imaging is absolutely necessary, and for this a large number of simultaneous baselines are required. The Optical Very Large

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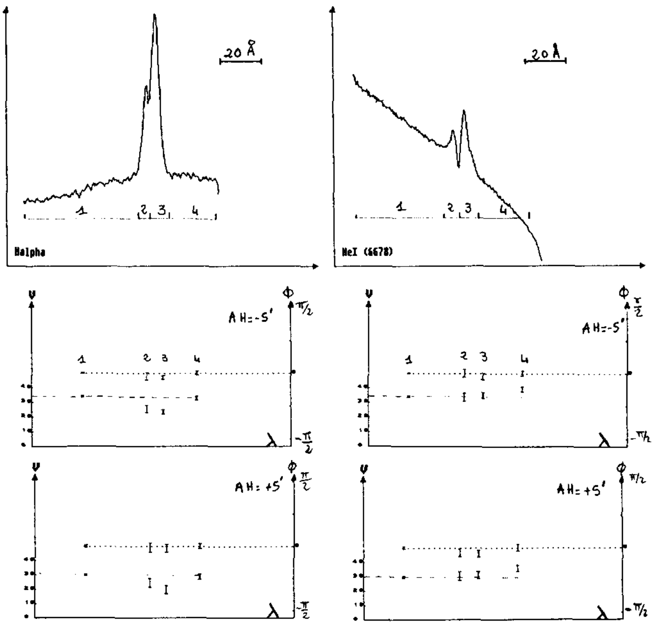

FIGURE 5. Variation of the complex visibility in the Hα and HeI 667.8nm lines of β Lyrae. The photometric orbital phase is 0.675 and the baseline length is 51m. The visibilities are not calibrated but we consider their spectral dependence.

Array is currently foreseen with 27 telescopes of 1.5-m aperture and will provide simultaneously 351 spatial frequencies.

6. ACKNOWLEDGMENTS

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8. DISCUSSION

ABT: I do not understand why you can use larger apertures, namely 1.5 m, while the Mark III group argued that only small apertures could be used because of the coherence length of the atmosphere.

MOURARD: The reason is simple: many speckles are processed simultaneously. There is no conceptual difference between speckle interferometry and long–baseline interferometry, and the same principles can be applied. Each speckle contributes independently to the signal.

ARMSTRONG: On the Mark III, we track fringes in a single speckle. The advantage is better visibility calibration, while the advantage of the GI2T is more photons.

MOURARD: The bad visibility calibration on the GI2T does not come from the fact that we use larger apertures but from the fact that rapid switching from the object to the reference source is not possible due to the mechanics of the GI2T. This visibility calibration is not so different from the speckle calibration, which is already achieved on large telescopes. To compensate for this bad calibration, we observe self–referenced objects, by using the spectral dependence of the object's shape.

QUIRRENBACH: You mentioned that your system suffers from some chromatic aberration. Do you know which components in the system cause this degradation?

MOURARD: Yes, it comes essentially from the two cylindrical lenses which produce the anamorphosis of the image in order to adapt the pixel size and fringe spacing for good sampling. A new optical set–up is under development for this purpose.

POVEDA: Are you using adaptive optics? What is the limiting magnitude that you can reach?

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MOURARD: Currently not, but we are working on the definition of a new optical set–up for the GI2T which will include an adaptive optics module. It will be an adapted copy of the system built by F. Roddier at the University of Hawaii. In the current configuration, the fringes are detected and tracked by visually observing a low–dispersion spectrum of one image slice. The practical limiting magnitude is V = +5 due to the low sensitivity of the eye. The new set–up is designed to include a photoelectric fringe tracking system, and we hope to reach the tenth magnitude.

ISOBE: First, what is your effective gain by using large apertures compared with the 20-cm telescopes of the Mark III? Second, could you tell us a little bit about your efforts to have a third telescope for the GI2T?

MOURARD: The effective gain goes as the number of simultaneously recorded speckles. We cannot reach fainter magnitudes because of the visual detection of fringes, but we reach a higher dispersive mode which is very important from the astrophysical point of view. The new optical set–up of the GI2T will accept a third beam. The third 1.5-m telescope is under construction. The mount is completed and tested, and we are working now on a thin mirror and its active support. Details are given in the Labeyrie *et al.* (1991) reference included in my paper.

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