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Evidence for one-armed oscillations in the equatorial disk of ζ Tauri from GI2T spectrally resolved interferometry

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Abstract. We report sub-mas observations of the Be Shell star ζ Tauri with the Grand Interféromètre à 2 Télescopes (GI2T) on November '93 and October '94. In '93, the Hα line presented a V/R ratio of 0.57 with a central absorption shell component. On October '94 the Hα line presented a reversed V/R ratio of 1.26 with a shallower absorption component. For both epochs we analysed the amplitude and phase of the fringe signal relative to the local continuum as a function of Doppler-shift across Hα. We clearly resolve the Hα emitting envelope on October '93. We find that the bulge of the emission which occurs around RV=+130 km.s^{-1} has a N-S projected position of 0.7 mas to the South of the continuum source. This value corresponds to a linear separation of 3.6 photospheric radii. For October 94, the same analysis shows that the projected position of this bulge, occuring around RV=-70 km.s^{-1} has moved to 0.5 mas, i.e. 2.6 photospheric radii, North of the continuum source. On account of the opposite V/R values between 93 and 94 and the long term Hα cyclic variability of ζ Tauri this apparent motion corresponds to the first interferometric detection of an axi-asymmetric envelope around a Be star that we interpret as direct evidence for a prograde one-armed oscillation of its equatorial disk.

Key words: stars: circumstellar matter – stars: emission-line, Be – stars: imaging – stars: individual: Zeta Tauri – line: profiles

1. Introduction

ζ Tauri is one of the brightest Be stars (HD37202, B1III, mv=3.0, HIP26451) exhibiting strong emission lines in Balmer series and undergoing long term V/R variations with typical cycles of 3-6 years (Guo et al. 1995, G95 hereafter). It is also a single line spectroscopic binary whose hypothetical secondary is a G8III, 1.3 $M_\odot$ star orbiting in 132.97 days around the 11 $M_\odot$ primary with marked periods of emission activity (Harmanec 1984, Floquet et al. 1989). ζ Tauri is also one of the first Be stars whose envelope was resolved by the Mark III interferometer at Mount Wilson (Quirrenbach et al. 1997, Q97 hereafter). Although the geometrical parameters of this object and 6 other Be stars are now well established, interferometric observations have so far ignored the remarkable temporally variable aspect of the Be phenomenon. In recent years, numerous theoreticians and observers have tried to deal with the long-standing controversy of Be star V/R cyclic variability (Telting et al. 1994, Okazaki 1996, O96 hereafter). The V/R quantity, which accounts for the intensity ratio of the violet to red components of an emission line at any time, is often used to infer the kinematics of Be circumstellar envelopes and their extent (G95, Hanuschik 1996). According to the theory of one armed oscillations in a quasi-Keplerian disk around a Be star, the V/R cycle can range from 2 to 13 years depending on the spectral type and luminosity class of the underlying star (Mennickent et al. 1997 and references there in). On regard of this range it is not so surprising that optical interferometry has not so far adressed this property of Be stars although the possibility was suggested a few years ago (Vakili et al. 1994). The present paper aims to describe the first attempt to tackle this remarkable property of Be stars on the basis of spectrally resolved interferometry of ζ Tauri using the optical interferometer GI2T at Observatoire de la Côte d'Azur in France (Mourard et al. 1994).

The paper is structured as follow. In the next section we describe the observational material on ζ Tauri for 1993 and 1994, and the data reduction based on cross-spectral analysis of Hα and its neighbouring continuum. In Sect. 3 we discuss our results in the framework of ζ Tauri V/R long term variability and other characteristics of this star from spectroscopy and interferometry. Finally we conclude on future applications of the differential technique described in this paper to diagnose the different mechanisms producing Be star variability at different time scales from hours to a few years.

2. Spectrally resolved interferometry of ζ Tauri by the GI2T

2.1. Observation and Data reduction

The journal of observations is given in Table 1. We reduced our data following the cross-spectral density method described

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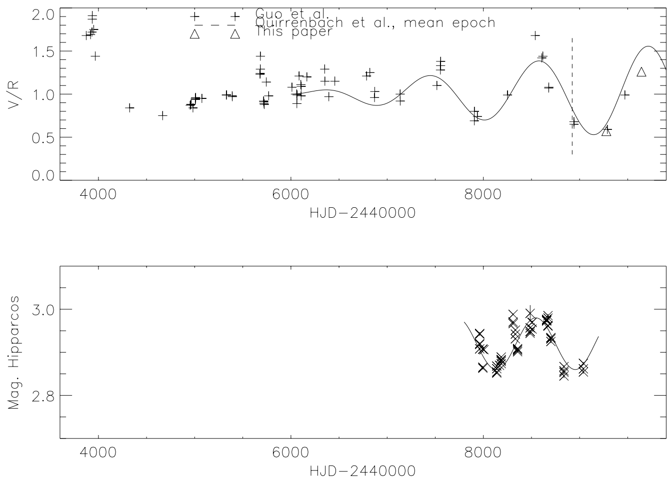

Fig. 1. Top: long term Hα V/R variability of ζ Tauri from Guo et al. (crosses) and GI2T (triangles) spectroscopy. The oscillation curve corresponds to the fit of a sine wave amplifying after 1988 with a period of 3.1 years. The vertical dashed line corresponds to the mean epoch of Mark III observations of ζ Tauri in 1992. Note that the sine-wave model has a purely qualitative value in order to infer the range of V/R cyclic variability. Bottom: photometric data from the Hipparcos mission. Note that the star became bright just at the V/R minimum epoch as determined by the GI2T on November 1993.

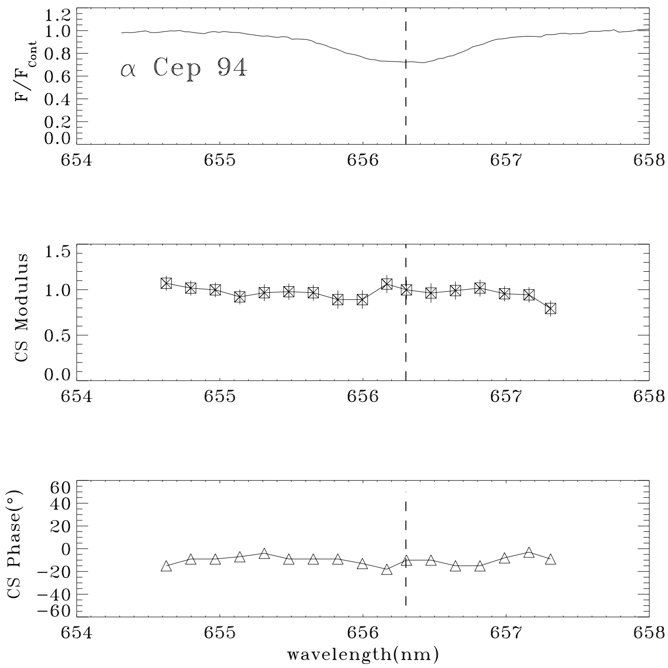

Fig. 2. Hα profile of the reference star α Cep (top) on October 1994. Relative modulus (middle) and phase (bottom) of the interferometric signal as a function of Doppler-shift across Hα. Errors on modulus, corresponding to 1σ, are estimated from the actual photon-statistics in the cross-spectral density of short exposures. Errors on phase, including detector geometrical effects, are on the order of 4°, actually smaller than the size of the triangle symbols plotting the phase diagram

Table 1. Journal of observations of ζ Tauri in 93 & 94 and the reference star α Cep. Columns 3 to 6 from left to right: the average Universal Time of the observation, the mean Hour Angle of the observation, the total time of interferometric records, the baseline B projected on the sky in meter, the fringe period in mas (λ/B) for the wavelength of λ=656.0 nm and the Hα violet to red wings intensity ratio.

Star	Date	UT	H [min]	ΔH [min]	B(m) [m]	Fp mas	V/R
ζ Tauri	93/25/11	00:50	+30	52	23.6	5.7	0.57
	94/17/10	03:24	+54	60	15.0	9.0	1.26
α Cep	94/17/10	19:02	+25	30	27.5	4.9	ref.

in details for studying the LBV star P Cyg (Vakili et al.1997, V97 hereafter). Here we develop those aspects relevant to the present work. We first paid particular attention to spectrophotometric reduction of our Hα data. After flatfielding long exposures of ζ Tauri we determined the effective resolving power of GI2T's spectrograph as 0.17 nm from a HeNe reference source. From calibrated Hα profiles we estimated the V/R ratios (Andrillat et al. 1982) as 0.57 and 1.26 for '93 and '94 respectively. It can be checked from Fig. 1, that our V/R estimates are in excellent agreement with those determined from classical spectroscopy (G95). Having derived the total Hα line widths as 2.3nm and 2.8nm for November 25th '93 and October 17th '94 we estimated also the emission force F_α/F_{Cont} as 3.2 and 2.9 for those epochs respectively. Finally we corrected ζ Tauri Hα spectra for a systematic RV of +22 km.s^{-1} (Harmanec 1984). For the interferometric analysis we derived the relative moduli and phase of the fringe signal across Hα for 0.34 nm spectral channels by steps of .17nm starting from the blue and finishing in the red continua next to Hα. The relative modulus and phase diagrams are plotted in Fig. 2 and Fig. 3 as a function of Doppler-shift across Hα in '93 and '94 both for α Cep and ζ Tau. We recall that the relative phase diagram plotted versus Doppler-shift informs, to a first order, on the angular position of iso-radial velocity regions of the ζ Tauri disk with respect to the continuum source (V97). The errors quoted on fringe modulus and phase were estimated from actual photon statistics in GI2T short exposure interferograms. Although the cross-spectrum technique is little sensitive to atmospheric noise (Chelli et al. 1995) within the spectral bandwidths used for this study (0.34 and 2nm for line and continuum channels respectively), we checked for the consistency of our error estimates on other reference sources observed on the same night or during other runs. Fig. 2 shows a typical cross-spectrum diagram on the reference star α Cep observed a few hours before ζ Tauri in '94. In general the dispersion in GI2T phase diagrams is dominated by detector geometrical instabilities rather than by photon or atmospheric noise. Therefore in the errors quoted on angular separations given above we included these effects by computing the dispersion of the continuum reference phase.

2.2. Interpretation of interferometry results

From Fig. 3, it can be readily seen that for the '93 observations the minimum fringe modulus signal estimated as (0.58 ± 0.13) (middle-left), occurs at the same Doppler-shift as the red-

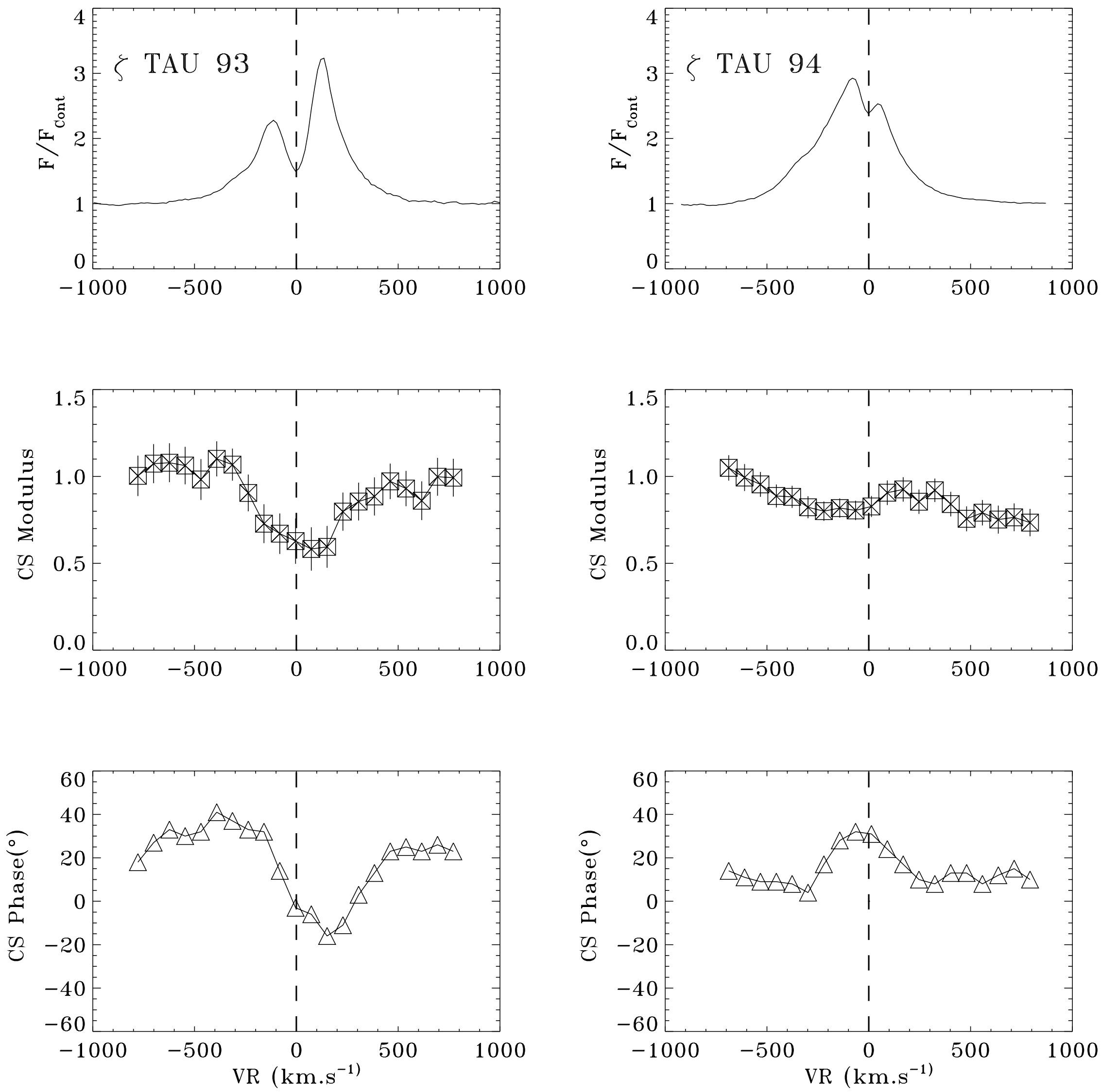

Fig. 3. Hα GI2T profiles (top) versus Doppler-shift for 93 and 94 observations of ζ Tau. Fringe amplitude and phase diagrams (CS Modulus middle & CS Phase bottom). Error quotation follows the same definition as in Fig. 2

maximum emission of Hα (top-left). The same remark applies to the relative phase (bottom-left) attaining its minimum value around the Doppler-shift of +130km.s^{-1}. At this Doppler shift we find a maximum deviation of $(44 \pm 6)°$ from the average phase of continuum fringes. In terms of angular separation, computed from the fringe period λ/B=5.7 mas, this deviation yields (0.7 ± 0.1) mas to the South of the continuum source. In other words the Hα emitting region of ζ Tauri at RV=130km.s^{-1} has a N-S projected position of (3.6 ± 0.5) photospheric radii to the South of the central star. The star diameter is determined from the Barnes-Evans relation as 0.39 mas (Barnes&Evans 1976) and we adopt the approximation that the continuum flux is mainly emitted by the underlying star. The '94 fringe modulus diagram (Fig. 3, middle-right) does not show any clear signature of the Hα envelope being resolved. There is at most a slight local minimum in this diagram occurring around the same Doppler-shift as the blue-maximum of Hα while the modulus follows on average a negative slope for increasing RV's. The dispersion of the modulus values (see also the CS Modulus diagram of the reference star in Fig. 2) being of the same order of magnitude as this apparent minimum we conclude that ζ Tauri remains essentially unresolved in '94. This is not so surprising since the '94 baseline is 36% shorter than in '93 and it will be argued in the next section that, due to its apsidal motion, ζ Tau's envelope could have been only resolved with a longer baseline in '94. On the other hand the 94 phase diagram (Fig. 3, bottom-right) shows a noticeable reversed extremum occuring at the Doppler-shift of -70 km.s^{-1} similar to that of the Hα blue-maximum emission. At this Doppler-shift the maximum phase deviation from the average phase in the continuum attains $(20 \pm 3)°$. This corresponds to an angular separation of (0.5 ± 0.1) mas yielding a N–S projected envelope separation of (2.6 ± 0.4) photospheric radii to the North of the underlying star. Note that absolute orientations given for '93 and '94

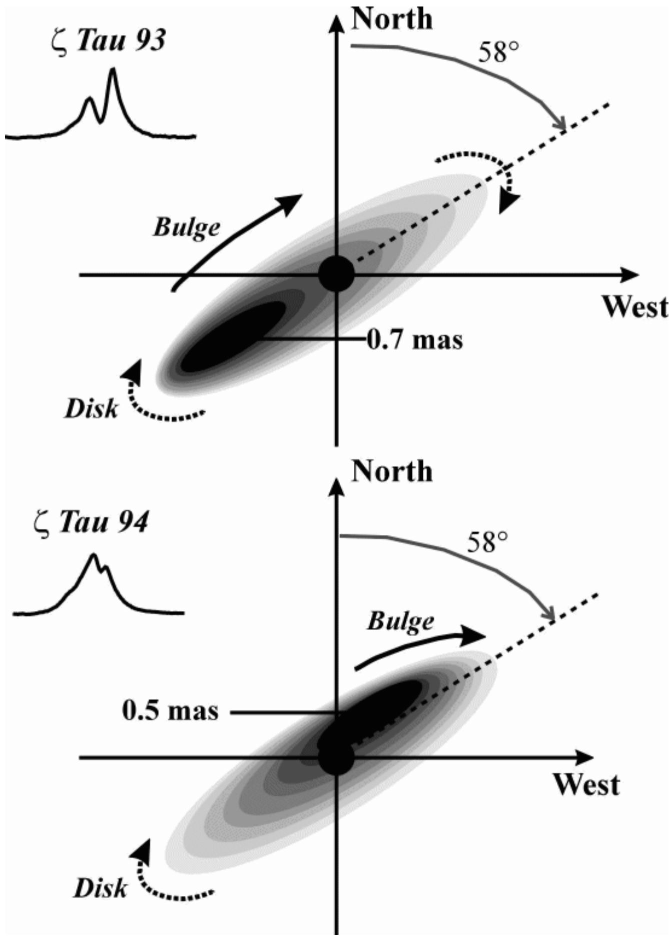

Fig. 4. Schematic representation of ζ Tauri Hα long term variability according to GI2T. In November '93 the Hα emission has a VR=.57 and originates in a region of the envelope whose N-S projected position is at 0.7 mas South of the central star. In October '94 VR=1.26 and this region has a NS projected position at 0.5 mas North of the central star. The orientation of the maximum elongation of the envelope is taken from Mark III observations as 58°West from the North. The curved arrows marked $Bulge$ depict the absolute prograde sens of rotation of the bulge in the equatorial disk of ζ Tauri whose sense of rotation is marked by $Disk$.

were obtained from the dispersed-fringe records from GI2T's spectrograph (V97).

3. Discussion

Since our GI2T observations are isolated in time and limited to 2 baselines, in order to push further our investigation it is useful to compare our results to Mark III interferometry of ζ Tauri in '92 (Q97).

From a 2D gaussian fit, Quirrenbach and co-workers estimated the angular extent of ζ Tau's Hα envelope as (4.53 ± 0.52) mas with an axial ratio of 0.28 and a position angle of the maximum elongation at 58° West from the North. The GI2T baseline is N–S and the projected size of the envelope, according to Q97, is 2.4 mas which gives 1.2 mas elongation for the receding and approaching wings of this envelope from the central star. With the GI2T we find 0.7 and 0.5 mas for the projected separations of the bulge of emission in '93 and '94. Despite this apparent discrepancy, Mark III and GI2T results remain compatible since GI2T data provide the separation of photometric barycenters of envelope receding and approaching wings and not its elongation. Note that at the mean epoch of Mark III 1992 observations Hα had a V/R$\simeq$0.84 ratio. This means that the emitting bulge, if present at that epoch, was very close to the central star and could hardly be detected by Quirrenbach and co-workers (besides the fact that Mark III measures only the modulus of the interferometric signal).

Indeed it is worth to compare the projected positions of the emitting bulge in ζ Tau's equatorial disk to the predictions of one armed oscillations of Be star disks related to the V/R long term variability (Savonije et al. 1993, O96). In order to do this, we fitted an amplifying-damping sine wave (Hubert-Delplace 1971) to the Hα long term variations from G95 and GI2T present V/R estimates (Fig. 1). The best fit, having only a qualitative value, yields a 3.1 years period falling in the range of 3-12 years predicted by theory (O96). Accordingly, GI2T '93 observations were carried out slightly after a V/R minimum. Taking the Mark III $58°$ orientation of the elongated disk to the West from the North means that the GI2T's N–S projected separation of 0.7 mas for '93 corresponds to a bulge at a linear distance of 6.8 stellar radii from the central star (Fig. 4). Now the Doppler-shift of the bulge is determined as RV=+130 km.s^{-1} by the GI2T. Okazaki's model (see Fig. 2. in O96) predicts the emitting region of the equatorial disk at such an RV to be roughly at a linear distance of 5-7 stellar radii from the central star which is very good agreement with GI2T's value. The distance of the emitting region from the star is inferred from the isoradial velocity curves of O96 and assuming ζ Tau's envelope being optically thin. On the other hand the GI2T '94 observations were carried out 327 days or 0.3 cycles (deduced from the sine period of 3.1 year) after '93's run. Assuming the bulge follows a circular orbit in the equatorial disk plane, i.e. it remains at ~7 stellar radii from the central star, the apparent distance from the central star will depend on the inclination angle i. This angle, estimated from spectrophotometric (Mennickent et al. 1997, Floquet et al. 1989) and interferometric (Q97) studies, should be in the range of $55° - 75°$. In order to be compatible with GI2T's 0.5 mas N-S projected bulge-star separation, corresponding to a vector separation of 3.1 stellar radii, i must be ~67°. Now the Doppler-shift of the bulge estimated by the GI2T in '94 is RV=-70 km.s^{-1}. According to Okazaki's model at an orbital phase of 0.29, the iso-radial velocity emitting region at RV=-70 km.s^{-1} is separated by 2–3 stellar radii from the central star which again is in very good agreement with GI2T's result. Finally in order to match GI2T's measured bulge-to-star N–S projected separation of 0.5 mas in '94, this bulge must have moved clockwise in the equatorial disk (Fig. 4). This can be easily understood since a bulge at the South-West would be at the same projected position on the N–S direction of GI2T's baseline as the central star and could not have been detected as a separate source. This last result conclusively shows that the one-armed oscillation is prograde since the absolute orientation of V and R wings of the equatorial disk defines the latter's direction of rotation (Fig. 4).

The general picture derived from GI2T interferometry and spectroscopy can be further compared to ζ Tau's photometry as mesured by the Hipparcos mission (Hipparcos 1997). According to Hipparcos, ζ Tauri attains a maximum brightness around JD2449000 (Fig. 1, bottom) just before the epoch of the maximum bulge-to-star separation on November '93 (according to our model this maximum occurs on JD2449160). From the absolute direction of rotation of the bulge and the disk one expects the bulge being in the part of the disk closest to the observer. Accordingly, the line of sight projection of ζ Tauri equatorial disk material on the bulge would be thin and the overall brightness of ζ Tauri would be augmented, which is witnessed by Hipparcos photometry. Therefore at the epoch of GI2T observations in November '93 Hipparcos independently reinforces our picture. We also fitted a sine variability for Hipparcos photometry neglecting rapid temporal variations (Fig. 1, bottom). Its period turns to be 2.3 years significantly different from our V/R model. On regard of the sparse temporal coverage of V/R data compared to the sampling of Hipparcos photometry obtained during a very shorter time, we think that any further comparison between these periods would be speculative. However it can be stated that high angular resolution runs must be systematically carried as part of multi-site/techniques observations, as we did for the Be eclipsing binary β Lyr (Harmanec et al. 1996).

4. Conclusion

In this paper we reported the first clear detection of an axi-asymmetry in the equatorial disk of the Be shell star ζ Tauri. The monitoring of its variability in Hα by the GI2T enabled us to directly confirm the one-armed oscillation mechanism in the equatorial disk to be driving its V/R long term variability. As a by product we also determined the absolute orientation of the receding and approaching regions of the equatorial disk on the sky and most of all the absolute direction of rotation of the one-armed oscillation in the disk which turns out to be in prograde motion. This finding directly answers to the pro-versus retrograde controversy on one armed oscillations of Be star disks (Mennickent et al. 1997). It must be emphasized that this result became possible by using decametric baselines and sub-mas super-resolution differential interferometry from the dispersed fringe technique pioneered at the Calern Observatory many years ago (Labeyrie 1980) and benefiting from ζ Tau's disk orientation on the sky as determined by the Mark III interferometer (Q97). Pending a third 1.5m telescope for phase-closure imaging, we plan to use the GI2T-REGAIN facility for Earth-rotation synthesis (Thureau et al. 1998) and to carry out patrol observations of long term Be variables. More generally, it is hoped that spectrally resolved interferometry will bring new insights in the stratification of the extended atmosphere of Be stars (Stee et al. 1998) and directly detect morphological features such as Non-Radial Pulsation on Be photospheric disks (Vakili et al.1990).

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