Astron. Astrophys. 301, 439–446 (1995)

ASTRONOMY AND ASTROPHYSICS

Sub-milliarcsecond resolution observations of two carbon stars: TX Piscium and Y Tauri revisited*

A. Richichi[1,3], T. Chandrasekhar[2], F. Lisi[3], R. R. Howell[4], C. Meyer[5], Y. Rabbia[5], S. Ragland[2], and N.M. Ashok[2]

[1] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[2] Physical Research Laboratory, Navrangpura, Ahmedabad, 380 009 India
[3] Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy
[4] Physics and Astronomy Department, University of Wyoming, Box 3905, University Station, Laramie, WY 82071, USA
[5] Observatoire de la Côte d' Azur, Avenue Copernic, F-06130 Grasse, France

Received 21 December 1994 / Accepted 11 February 1995

Abstract. We recorded lunar occultation events of the two carbon stars TX Psc and Y Tau. In the case of TX Psc, seven lightcurves were recorded from different sites in the period 1992–1994, at wavelengths ranging from 0.55μm to 3.6μm. In the case of Y Tau, one occultation event was recorded independently at two sites at 2.2μm and 3.6μm. Our observations essentially confirm and refine previous photospheric angular diameter results for these two stars obtained by lunar occultations (Lasker et al. 1973; De Vegt 1974; Dunham et al. 1975 for TX Psc, and Ridgway et al. 1977; Blow 1982; Schmidtke et al. 1986 for Y Tau). The good SNR of some of the traces, and the availability of independent observations, allow us to investigate at the highest angular resolution ever achieved on these stars ($\approx 0\farcs0006$ on average), details such as possible deviations from circular symmetry, and possible presence of circumstellar emission. The weighted average of the best fits to occultation lightcurves yields a uniform–disc diameter of 8.38 ± 0.05 mas for TX Psc, and 8.21 ± 0.08 for Y Tau. However, we also present the results of model–independent data analysis. At least for TX Psc these reveal substantial departure from the simple model of circular disk, which we interpret as due to the presence of warm dust immediately adjacent to the stellar photosphere, and/or of large cold spots on the photosphere itself. We suggest that a circular disc is inadequate to describe the brightness profile of TX Psc at both visual and near–infrared wavelengths. The recent determination by optical interferometry of the angular diameter of TX Psc by Quirrenbach et al. (1994), based on such an assumption, may have been biased and the effective temperature should be correspondingly revised. Our results indicate that it is in the range $3000 - 3150$ K, in good agreement with some recent theoretical estimates. In the case of Y Tau, somewhat surprisingly, no significant presence of circumstellar emission is revealed at the wavelengths of our observations ($\lesssim 1\%$ of the 3.6μ flux in the inner $0\farcs15$). Our determination of the angular diameter is consistent with previous suggestions (Schmidtke et al. 1986) that a regular pulsation of this star's photosphere with the phase in its variability period may have been detected.

Key words: occultations – stars: carbon – stars: circumstellar matter – stars: fundamental parameters – stars: TX Psc – stars: Y Tau

Send offprint requests to: A. Richichi

* Partially based on observations collected at TIRGO (Gornergrat, Switzerland). TIRGO is operated by CNR–CAISMI Arcetri, Italy

1. Introduction

Carbon stars represent a stimulating challenge for our theoretical understanding of the late evolutionary stages of intermediate mass stars. Their extended, cool atmospheres are an ideal environment for the formation of dust grains, as well as of numerous chemical species, which in turn strongly affect the appearance of the carbon star itself, enrich the interstellar medium and are important in other phases of stellar evolution (Fleischer et al. 1992; Tsuji 1986). Theoretical models of carbon stars have traditionally lacked sufficient observational data and constraints. This is partly due to the relative rarity of the carbon star phenomenon, resulting in most of the sources being relatively far and faint, and partly to the intrinsic difficulty of developing a homogeneous interpretation for stars where variability, mass loss and chemical composition anomalies are the rule, and where the individual characteristics of each star play an important role.

Many answers to some of the most intriguing questions can be given only by investigating carbon stars with sufficient resolution to resolve the stellar surface and its immediate surroundings, and by obtaining accurate direct determinations of the effective temperature. Traditionally, this task could be achieved only by lunar occultations (LO): over the years, this method has yielded angular diameters for X Cnc, TX Psc, Y Tau, IRC −20420, AQ Sgr, SZ Sgr, TW Oph, RT Cap, SS Vir, T Cnc (see references in White & Feierman 1987, and Richichi et al. 1991 for T Cnc). Also IRC +10216 was first studied by LO (Toombs et al. 1972), although with time other methods have allowed us to investigate the spatial structure of this peculiar source (Ridgway & Keady 1988). Very recently, optical long baseline interferometry (OLBI) has reached the potential to measure at least a few of the brightest carbon stars, adding UU Aur and Y Cvn to the above list, and providing an independent check on TX Psc (Quirrenbach et al. 1994).

In this paper, we describe results obtained from the recent series of occultations of the carbon star TX Psc by the Moon. Observations were successfully carried out on several different occasions, allowing us to probe the immediate surroundings of this star with unprecedented resolution, both at different wavelengths and at different position angles. For comparison, we also discuss similar observations on the closely related star Y Tau. Other carbon stars for which lunar occultations have recently been observed by some of the present authors include IRC +10216 and IRAS 06088+1909, which however are of a substantially different nature and will be presented in a separate work.

2. Observations

Several telescopes were used to observe the occultation events which constitute the basis of this paper. These include: the 1.5 m telescope of CERGA near Calern, France; the 1.5 m telescope of the Italian observatory TIRGO on Mt. Gornergrat, Switzerland; a small 35 cm telescope at the Mt. Abu Observatory, India; the 2.3 m telescope of the Wyoming Infrared Observatory, USA; the 1.2 m telescope of the German–Spanish observatory on Calar Alto, Spain; the 1 m telescope of the Vainu Bappu Observatory, India. A detailed list of the dates and circumstances of the various events is given in Table 1.

The first three columns are self–explanatory. Columns (4) through (6) list the filters that were used and their spectral characteristics. The spectral transmission of each filter at the operating temperature was accurately accounted for in the data reduction. Column (7) lists the sampling time used for each lightcurve. Columns (8) through (10) list the values of the contact angle (0° when the Moon's center moves exactly over the source, and close to ±90° for grazing occultations), of the position angle of the event (i.e., the direction with which the lunar limb appeared to scan the source), and of the apparent rate of motion of the limb across the source. This rate can be accurately measured during the data analysis by fitting the frequency of the diffraction fringes, and the comparison with the predicted value allowed us to derive the local slope at the lunar limb. The values of the contact and position angles of Table 1 are already corrected for this effect (except for the Calern data, where the predicted values were used, see Meyer et al. 1994). Column (11) lists the angular diameter (under the assumption of a uniformly illuminated disk) derived by a least squares analysis, as described in the next section. Finally, column (12) lists the panels of Fig. 1 where each data set is shown.

InSb photometers were used at K and L, and photomultipliers for the V and R observations. Details on the instruments, with particular reference to previous LO–related work, can be found in Meyer et al. (1994) for the Calern instrument, Richichi (1987) for the Tirgo instrument, Ashok et al. (1994) for the instrument used in the Gurushikhar and Kavalur observations, and Stecklum et al. (1994) for the Wyoming instrument. At Calar Alto, the instrument was a photometer expressly developed for LO work, to be described in a forthcoming paper. In all cases, observations consisted in recording the lightcurve of the disappearing source with a sufficiently high sampling rate. However, some differences exist among the various instruments from the point of view of LO data analysis, and are explained in the next section.

3. Data analysis

Data analysis was performed in a homogeneous way for all the various data sets. Two different, complementary approaches were used. The first is based on the well established least–squares method, originally introduced in LO work by Nather & McCants (1970). A recent description of our implemementation of the method has been described by Richichi et al. (1992). The second approach is based on a model–independent method, described by Richichi (1989).

In the first method the 1–D brightness profile of the source is taken to be a simple analytical parametric function (for the case of a circular disc, see Eq. 4 in Richichi 1989), whose parameters (among them the angular diameter) are varied until the best fit with the data is achieved. Also a limb–darkening coefficient could in principle be introduced as a free parameter in the analysis, but the SNR in LO lightcurves is generally not sufficient to permit its determination. Therefore, it is necessary to make an a priori assumption about this parameter. We have chosen a uniformly illuminated disc. The main reason for this is that, as will be shown in the next section, the hypothesis of a simple circular disc is in any case unsatisfactory, at least for TX Psc. Secondly, the limb–darkening coefficient is generally believed to be small for late–type stars expecially at infrared wavelengths (Manduca 1979; Willson 1987). The choice of a uniform disc allows a more immediate comparison with previous results, and can be rescaled easily if required. In the extreme case of a fully darkened disk, the correction would amount to ≈13%. In the near–infrared, the amount of limb darkening is generally limited and the required corrections to the uniform disc diameter are of the order of 4% (see discussion on Y Tau in Sect. 4.2). Another aspect of the least-squares analysis which must be mentioned is the correction of scintillation effects by means of fitting the low–frequency part of the lightcurve by Legendre polynomials, after a suggestion of Knoechel & von der Heide (1978) and as described in Richichi et al. (1992). Such correction was necessary for the lightcurves shown in Fig. 1*g* and 1*i*. We stress that without such correction, the derived angular diameter would be biased towards larger values.

The model–independent analysis is a powerful method to obtain the brightness profile of the source, when this cannot be

Table 1. Summary of the occultation events

(1) Source	(2) Observatory	(3) UT Date	(4) Filter Name	(5) λ_0 (μm)	(6) $\Delta\lambda$ (μm)	(7) Δt (ms)	(8) Observed Geometry CA	(9) PA	(10) ″/s	(11) ϕ_{UD} (mas)	(12) Fig.
TX Psc	Calern[a]	12-03-92	V	0.55	0.06	1.000	43°	98°	0.2590	9.5 ± 1.1	1a
	Calern[a]	12-03-92	R	0.71	0.09	1.000	43°	98°	0.2590	8.8 ± 0.7	1b
	Tirgo	12-03-92	K	2.21	0.35	4.608	35°	92°	0.2910	9.82 ± 0.10	1c
	Gurushikhar	27-01-93	K	2.20	0.40	1.000	24°	76°	0.2965	7.5 ± 0.5	1d
	WIRO	27-10-93	K	2.18	0.38	2.000	−56°	5°	0.2017	7.72 ± 0.06	1e
	Calar Alto	20-12-93	L	3.56	0.86	2.000	−14°	50°	0.3864	9.7 ± 0.2	1f
	Kavalur	13-02-94	K	2.20	0.40	1.000	−29°	40°	0.4126	8.6 ± 0.5	1g
Y Tau	Calar Alto	20-02-94	L	3.56	0.86	2.000	−27°	73°	0.3384	8.22 ± 0.09	1h
	Tirgo	20-02-94	K	2.21	0.35	2.432	−58°	42°	0.2311	8.18 ± 0.16	1i

[a] From Meyer et al. (1994).

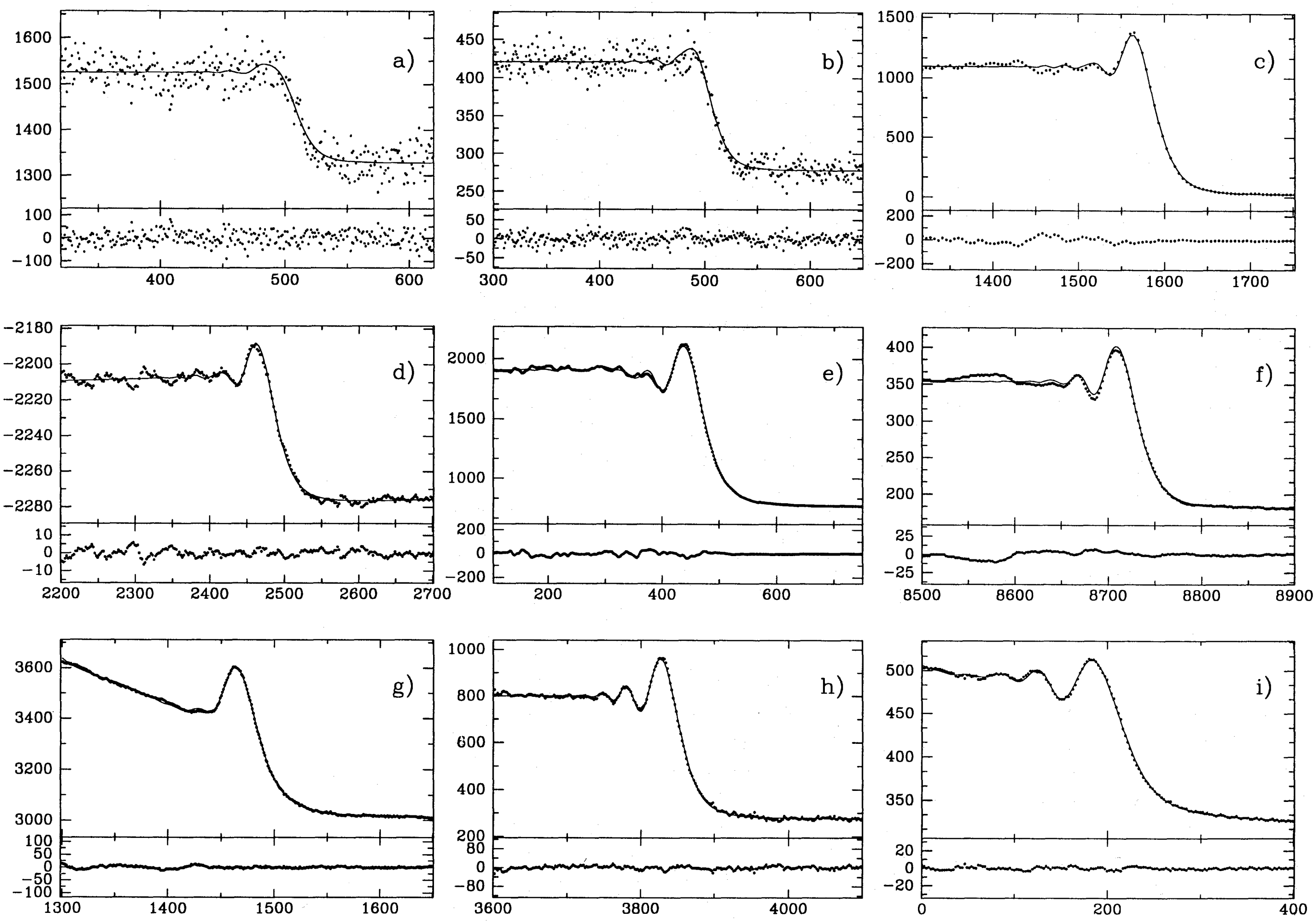

Fig. 1. Data, least–squares best fits and residuals for the occultations of TX Psc and Y Tau listed in Table 1. The horizontal axes report relative time in ms, the vertical axes intensity in arbitrary units

easily described by a parametric model as required by the least–squares analysis. A typical situation would be, for instance, a circumstellar shell. The starting guess is a flat profile which extends over a relatively large range of angles (typically $\pm0\farcs15$ in the present cases), and which is modified iteratively based on both a deconvolution by means of Lucy's algorithm (Lucy 1974), and by least-squares fitting of the remaining parameters. There are two aspects of this method that should not be overlooked. Firstly, the problem of recovering the brightness profile from a lunar occultation lightcurve does not have a unique solution. The method we use converges to the most–likely solution in a statistical sense (see Lucy 1974, and Richichi 1989), and indeed our results for the various independent lightcurves of TX Psc show a high degree of consistency (see Fig. 2). However, in the case of a "naked" stellar disc the result has to be interpreted with some caution, as will be the case later in our discussion of Y Tau. Secondly, since this kind of analysis will attribute to the sought–for brightness profile any deviation of the observed lightcurve from the theoretical diffraction pattern of a point–source, it is clear that fluctuations in the signal caused by scintillation can seriously bias the result. In our experience, we have found that the recovered profile is actually rather insensitive to high–frequency noise, however slow fluctuations (timescales $\gtrsim$ 0.1 s) are often interpreted as fictitious additional sources. For this reason, we decided not to use the model–independent analysis on the lightcurves shown in Fig. 1*g* and 1*i*.

A point worth mentioning, and common to both the model–dependent and model–independent analysis, is the response of the instrument to rapidly varying signals such as those encountered in LO lightcurves. With each instrument, we recorded occultations of point–like sources (i.e., with an expected angular diameter $\ll$ 1 mas), and we obtained measurements of the response to step signals. This information was used during the data reduction to ensure that fringe smoothing due to the instrument finite frequency response was adequately accounted for. The procedure has been described in some detail by Richichi et al. (1992). Also the effects of the filter transmission and of the telescope aperture were included in the analysis.

4. Results and interpretation

4.1. TX Psc

The results of the disc–fitting analysis for TX Psc listed in Table 1 would indicate, if viewed as a homogeneous set and after a weighted average, an angular diameter $\phi = 8.38\pm0.05$ mas (we shall imply always uniform disk values, unless otherwise noted). This might seem to confirm and strengthen quite remarkably the previous estimates by LO observations quoted in the abstract, which yield a weighted average $\phi = 8.6 \pm 0.7$ mas. Quirrenbach et al. (1994), from a set of 5 OLBI measurements, adopted $\phi = 10.5 \pm 1$ mas; if the same averaging process was applied to their results the error would be reduced, $\phi = 10.5\pm0.2$ mas. Before discussing further these values, however, one cannot overlook the fact that the differences between the measurements often exceed the respective formal errors, for both techniques and in some cases very significantly. Quirrenbach et al. already proposed a possible explanation for this, by observing that the angular diameters appear to correlate with the V magnitude of this variable star, in the sense of measured diameters being larger when the magnitude was brighter. We do not believe that this alone can completely justify the observed differences. The range of variations in the diameters is $\approx$40% (8 to 11.1 mas), while the range in brightness is just 0.16 mag: the relation would require a drop in temperature of $\Delta T_{\rm eff} \approx$400 K, in contrast with the effort of the same authors to derive a unique accurate value of the effective temperature for TX Psc. Besides, the diameter values of Table 1 would not fit at all in the proposed correlation. In fact, one could postulate that the relatively small brightness variations, which are known to be irregular, are produced more simply by local obscuration by dense clumps of circumstellar matter or by the presence of cold/hot spots on the stellar photosphere, without necessarily a change in diameter.

Here we would like to propose an alternative explanation of the apparent discrepancy in the diameter determinations, based on a model–independent analysis of our occultation lightcurves of TX Psc, which has allowed us to reconstruct the actual brightness profile of this star at the various wavelengths and at different position angles. The profiles are shown in Fig. 2, where it should be noted that the position of the zero in the angular scale is arbitrary since the observations were obtained independently. Only in the case of the V and R profile the two profiles can actually be reliably superimposed. Furthermore, it should be noted that the data of Fig. 1*g* (filter K along PA=40°) could not be used, since they are drastically affected by scintillation (the event was observed at 8 airmasses!): while the model–dependent analysis could still be applied, the model–independent result would be strongly biased as was explained in Sect. 3. The profiles were obtained with an angular sampling matched to the resolution of the lightcurves (columns (7) and (10) in Table 1). This was on average $\approx$0.6 mas. The noise in each lightcurve was accurately modelled and used as a constraint to stop the iterations. The 1–D profiles are plotted so that the positive angular values are in the direction of the quoted PA. We do not show the corresponding best fits, which are similar to the model–dependent fits shown in Fig. 1.

The profile that emerges is different from what would be expected for a simple circular disc, regardless of limb–darkening. Only few details can be made out of the V and R profiles, since the corresponding lightcurves have relatively low SNR: at the visual wavelengths, one would conclude that there appears to be an inner core, surrounded by some amount of extended emission, possibly asymmetric. With increasing wavelength, however, the profiles show more structure, and in particular reveal the presence of side peaks which have a brightness at least comparable to the central core in K, and are clearly dominant at L. It is noteworthy that there seems to be little or no separation between the side peaks and what presumably could be identified as the edge of the stellar disc. Finally, although the coverage in PA is only partial, we believe that the plots of Fig. 2 indicate that the observed structure is not circularly symmetric. The reader may want to compare for instance the profiles for the K band,

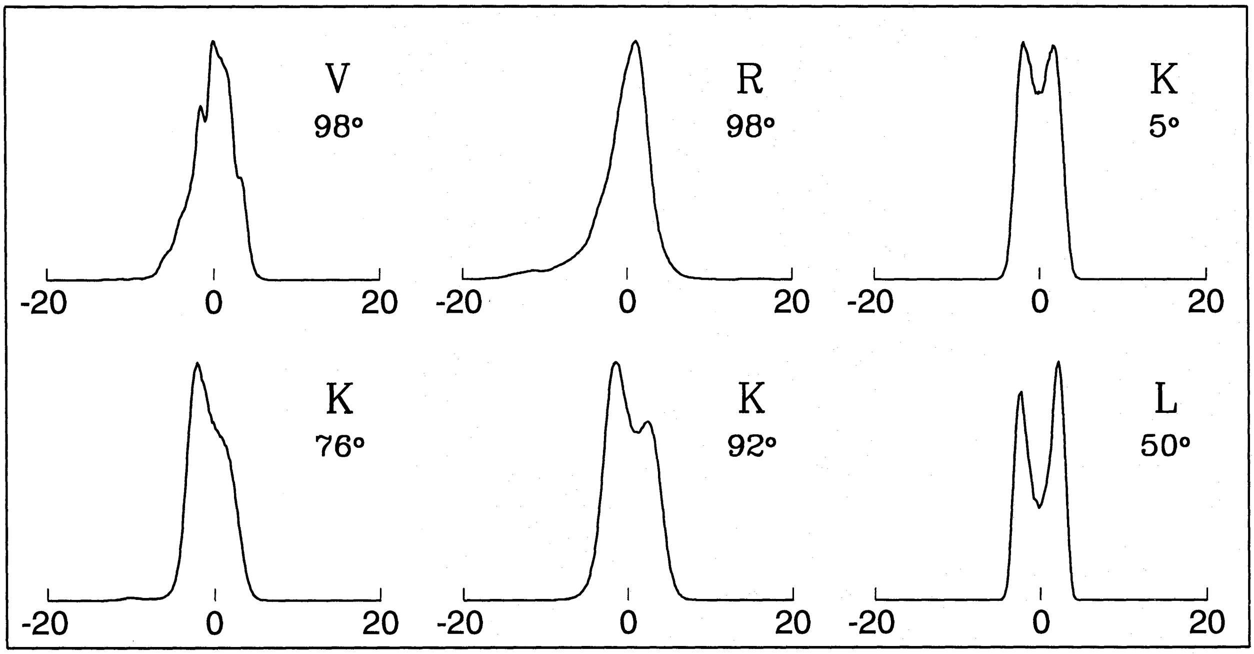

Fig. 2. Brightness profiles for TX Psc reconstructed by the model–independent method described in the text from the data shown in Fig. 1. The profiles are renormalized to the same arbitrary value. Horizontal axes are in milliarcseconds (1 mas ≈0.3 AU at the distance to TX Psc). The zero in the angular position is arbitrary, since the data come from independent lightcurves, except for the V and R lightcurves

which indicate that the circumstellar emission is more extended along the E–W than the N–S so direction.

There are at least two possible explanations for the observed morphology. To begin with, one can postulate the existence of circumstellar dust, with an inner shell radius very close to, or even in contact with, the stellar photosphere ($\lesssim 2R_\star$). At visible wavelengths the dust emits mostly through scattering of the light from the central source, and hence we see a broadened brightness profile of the central source and relatively broad wings around it. In the K band the dust thermal emission becomes substantial and at L it is dominant. This scenario would constrain the range of possible dust temperatures significantly, since the dust should have T <1300 K to explain the increase in emission from K to L, and at the same time would have to be relatively hot because of the vicinity to the stellar photosphere. The dust would have to be optically thin, and/or occur in clumps, since even at the visual wavelengths the central star is clearly revealed in the profiles. An alternative explanation is to postulate large spots on the stellar surface, either areas of lower temperature, or the result of obscuration by intervening dust clumps very close to the star. Such spots would not affect the brightness profile significantly in the visual wavelengths, where they would be essentially dark. If their area is large enough, however, at longer wavelengths they would contribute significantly to the total emission. Clearly, the two explanations could co–exist, and in fact they are very closely related.

In the light of this new findings, it is worth us revisiting briefly the general picture of TX Psc and its shell, both from the point of view of theoretical modelling and of the previous observational efforts to measure its angular diameter and effective temperature. The star has a quoted spectral type between $C_{5,2}$ and $C_{7,2}$ (see for instance Richer 1971; Griffin & Redman 1960; Kholopov 1985). Estimates of its distance vary from 230 pc (Bergeat et al. 1978) to 370 pc (Loup et al. 1993); we can then assume that 1 mas corresponds to ≈0.3 AU. Bergeat et al. (1976) regarded TX Psc has having no circumstellar shell, and predicted on the basis of their model an angular diameter ϕ = 13.5 mas and $T_{\rm eff}$ = 2560 K. At the other extreme, Scargle & Strecker (1979) used a method that, in their words, "*...appears to be more accurate than any known direct measurement*", to obtain ϕ = 6.2 mas and $T_{\rm eff}$ = 3790 K. Jørgensen (1989) found that the near infrared spectrum and particularly the 3μm band could be satisfactorily reproduced by his model only if $T_{\rm eff}$ = 3100 K, with a very small uncertainty of < 70 K. Observations in the UV, mid–infrared and millimeter wavelengths now suggest that while a shell is certainly present around TX Psc, it is probably far from being conspicuous and the mass loss rate is far from extreme for this stellar class, $< 2 \times 10^{-7}$ $M_\odot$/yr (Eriksson et al. 1986; Olofsson et al. 1987; Mauron & Caux 1992; Heske et al. 1989; Volk & Cohen 1989; Zuckerman 1993). Wirsich (1991) studied the physical properties of this dust shell, and derived an inner radius of $2.25R_\star$, with a peak dust temperature of 1155 K.

To return to the brightness profiles shown in Fig. 2, it is clear that the very definition of angular diameter is somewhat uncertain in this case. The photosphere is hard to disentangle from the extended emission, at least until some convincing quantitative model can be put forward for the nature of the latter.

Qualitatively, we can state that TX Psc has an angular diameter close to 9.0 mas, and this yields general agreement with (at least some of) the most recent theoretical or semi–empirical predictions, in the direction of an effective temperature in the range 3000–3150 K. It is noteworthy that this is also in good agreement with previous LO determinations, at least when viewed in average. On the contrary, the recent determination by Quirrenbach et al. (1994), who quote $T_{\rm eff}$ = 2805 ± 126 K, seems to be somewhat underestimated. The reason is probably that, as stated by the same authors, the interferometric data do not have sufficient SNR to include the presence of extended structure in the source and the result was correspondingly biased towards a larger diameter for the central star.

It is noteworthy to remember that already Lasker et al. (1973), commenting on their LO observation of TX Psc, noted that the fit of a simple stellar disc was less than optimal. Later, Bogdanov (1979) inferred, from a model–independent analysis of two LO lightcurves with a method rather different from ours, that the brightness profile of TX Psc showed evidence of extended outer structure, with a photospheric diameter of 8.2 mas and emission extending out to ≈14 mas. The reader may find that his conclusions are in qualitative agreement with the profile that we show in Fig. 2 for the R data. This might be interpreted as some evidence that the extended features are relatively long–lived, although this point would clearly need more observational support.

4.2. Y Tau

We believe it might be of interest to compare our findings for TX Psc with those obtained, with the same methods, for the similar star Y Tau, where we find a very different situation. The model–dependent analysis shows an angular diameter which is identical, within the errors, in both the K and the L band, along two scan directions that differed by about 30°. This is indicative already of the fact that the circular disc model is a good approximation to the actual brightness profile. Also the model–independent analysis does not reveal any sensible departure from a symmetrical profile for the L lightcurve, as shown in Fig. 3. In the interpretation of the figure, the reader should be aware that the apparently gaussian profile is not physical. This particular situation has been investigated and explained by Richichi (1989). Following the guidelines of that paper, we conclude that the observed profile is consistent with a circular disc having $\phi_{\rm UD}$ = 7.9 mas, in agreement with the disc–fitting result. This is in agreement with the model–dependent result given in Table 1, which we shall use in the following. Based on the noise in the data, we can state that any extended emission in the inner ≈ 0.″15 must emit < 1.3% of the total brightness at 3.6μm. We decided not to analyze the K lightcurve by the model–independent method, because of possible bias from scintillation as was explained in Sect. 3.

Also Y Tau is a cool carbon star, with spectral type generally quoted as $C_{6,4}$ although a slightly cooler classification has also been reported (Lambert et al. 1986). The effective temperature of Y Tau is generally believed to be cooler than

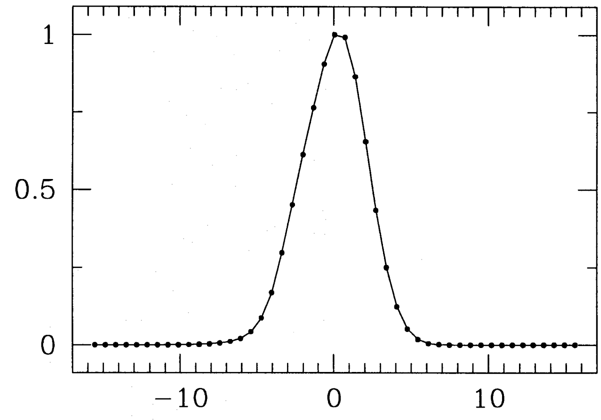

Fig. 3. Normalized brightness profile for Y Tau reconstructed from the data shown in Fig. 1h (filter L along PA=73°), using the same model–independent method used for TX Psc (compare with Fig. 2). The orizontal axis is labelled in units of milliarcseconds (1 mas ≈0.5 AU at the distance to Y Tau). The profile is consistent with a circular disc having $\phi_{\rm UD}$ = 7.9 mas, as explained in the text, and very little or no near–stellar extended emission

that of TX Psc: Lambert et al. summarize the determinations available for both stars according to several methods (among them direct measurements by LO), and adopt $T_{\rm eff}$ = 2600 K for Y Tau and 3030 K for TX Psc. The distance in this case is larger, with estimates in the range 300 to 570 Kpc; Young et al. (1993) adopt 480 pc. Bergeat et al. (1976) invoked a circumstellar shell around Y Tau, which according to their model should have an inner radius of 14.5 mas, or just 1.6$R_\star$, with $T_{\rm dust}$ = 1470 K: this is inconsistent with the observational evidence that we have presented. Millimeter observations have indeed revealed $CO_{(J=1\rightarrow0)}$ (Olofsson et al. 1988) and possibly $HCN_{(J=1\rightarrow0)}$ (Zuckerman & Dyck 1986), but IRAS observations failed to resolve a shell around Y Tau, unlike TX Psc (Young et al. 1993). This might indicate comparatively less massive circumstellar material, a point that correlates well with our negative detection of extended emission in the immediate surroundings of the central star.

An interesting point is that of the possible time variations of the angular diameter of Y Tau. Unlike TX Psc, this star has large amplitude fluctuations ($m_{\rm V}$ = 6.9 − 9.2), with a defined period of 240.9 days (Houk 1963). Schmidtke et al. (1986) plotted the LO diameter determinations for this star as a function of the photometric phase, and found that the diameter could indeed be thought to vary with the phase, although more observations were needed. Figure 4 shows the data available to Schmidtke et al. for their conclusion, as open squares. The authors chose to use partially limb–darkened diameters at H (1.65μm), using the conversion factors $\phi_{\rm UD,H}/\phi_{\rm UD,K}$ = 1.026 (as measured by them for Y Tau during a simultaneous observation at H and K), and $\phi_{\rm LD,H}/\phi_{\rm UD,H}$ = 1.04. We have then rescaled our independent determination at K accordingly, and overplotted it in Fig. 4 as a solid dot. Note that the error bar was increased to reflect the uncertainty in the above rescaling, also following Schmidtke

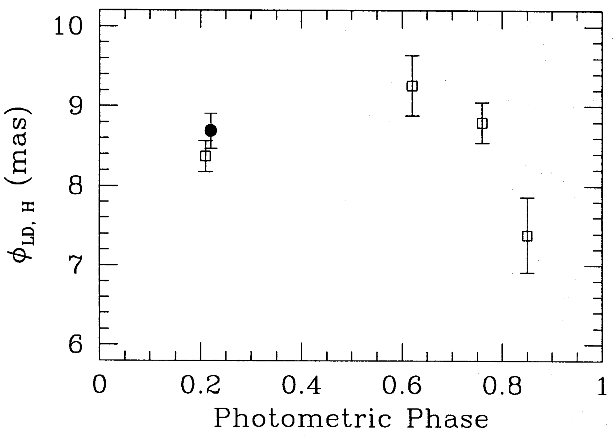

Fig. 4. Angular diameter of Y Tau as a function of photometric phase, after Schmidtke et al. (1986, squares). The solid dot represents our measurement in the K filter obtained at phase 0.22 on February 20, 1994, after the rescaling described in the text. The point at phase 0.21 was measured 28 variability periods earlier than ours

et al. Our measurements were obtained at a predicted phase of 0.22, almost coincident with a previous observation occurring at phase 0.21 on August 31, 1975. The agreement of the two independent determinations, separated by 28 variability periods, is impressive, and shows that the variations must be quite regular. In order to lend more support to the reality of such variations, we can reason that they must be accompanied by variations in the effective temperature and we note that Dominy & Wallerstein (1986) obtained a spectroscopic determination simultaneously to an occultation measurement (January 8, 1982 at phase 0.85). The spectroscopic result was $T_{\rm eff}$ = 2900 ± 250K, with the occultation giving $T_{\rm eff}$ = 2810 ± 70K. If we adopt their same assumptions on the total flux and on the limb darkening, and use the weighted average of our K and L measurements, we obtain $\phi_{\rm LD}$ = 8.46 ± 0.08 mas and $T_{\rm eff}$ = 2590 ± 30K at phase 0.22. Although the difference is only marginally significant due to the large error bar of the spectroscopic determination, it provides an independent hint that the photosphere of Y Tau might indeed experience variations of ≈300 K in its effective temperature.

5. Summary and concluding remarks

We have investigated the two carbon stars TX Psc and Y Tau by means of LO observations, which have provided sub–milliarcsecond resolution scans of these two sources at different wavelengths and position angles. Our conclusions are quite different for the two sources.

In the case of TX Psc, we find conspicuous deviations from a simple circular disc profile, which we interpret as circumstellar dust of relatively high temperature, possibly clumped and optically thin, situated in the immediate surroundings of the stellar photosphere. Also the presence of large cold spots on the photosphere could be postulated. We conclude that previous attempts to assign an angular diameter and an effective temperature to this star, based on lunar occultations and optical long–baseline interferometry data fitted by simple circular disc models, should be regarded with care. An accurate determination of the photospheric angular diameter of TX Psc must take into account the extended emission as well, which appears to be wavelength–dependent and non–circularly symmetric. We find that a good agreement between observations and recent theoretical investigations can be obtained, with a picture where the star has an angular diameter of ≈9.0 mas, and $T_{\rm eff}$ ≈ 3050 K.

In the case of Y Tau, we do not find evidence of conspicuous emission from a shell, neither at 2.2 nor at 3.6μm, and we derive a uniform–disc angular diameter of 8.21 ± 0.08 mas ($\phi_{\rm LD}$ = 8.46 ± 0.08 mas), from which $T_{\rm eff}$ = 2590 ± 30K can be inferred. It is noteworthy that this result would be consistent with the proposed diameter variations suggested first by Schmidtke et al. (1986).

An immediate consideration that emerges from this work, is that in spite of the apparent similarity of TX Psc and Y Tau when only their spectral classification ($C_{5,2}$ to $C_{7,2}$ for the first, $C_{6,4}$ for the latter) or their fluxes (2.6 × 10^{-6} erg s^{-1} cm^{-2} at ≈300 pc, and 1.1 × 10^{-6} erg s^{-1} cm^{-2} at ≈480 pc respectively) are considered, the amount of near–photosphere circumstellar emission in the two sources is very different, being rather conspicuous in the TX Psc and basically negligible in Y Tau. It is perhaps appropriate to remember that in a similar study for the $C_{4,5}$ star T Cnc (Richichi et al. 1991), a somewhat intermediate situation was found. Clearly, the individual characteristics of carbon stars are sufficiently varied that detailed studies by high angular resolution techniques of as many sources as possible are worthy and necessary.

Modern techniques such as long baseline interferometry are exciting and promising, expecially when it will be possible to reach better SNR and fainter sources than at present. Here we would also like to stress that lunar occultations are relatively simple to observe, accurate in their result (note that the average of three measurements of TX Psc in the years 1971–1975 gave a weighted average $\phi_{\rm UD}$ = 8.6 ± 0.7 mas, while the seven occultations of this work would yield $\phi_{\rm UD}$ = 8.38 ± 0.05 mas if extended emission is ignored) and offer the best angular resolution ever achieved in the near–IR. Coordinated observations from several different sites, as was the case in the present work, can effectively remove some of the intrinsic limitations of the technique and are highly encouraged. An average of about 30 carbon star occultation events are available every year to telescopes of the 1.5 m class equipped with a fast infrared photometer. Among the most noteworthy occultation series of carbon stars to begin in 1995 are those of TW Oph and V Ari.

Acknowledgements. Lunar occultations are elusive events, and trying to coordinate their observation from several continents involved a good deal of patience and the efforts of many persons. We should like to express our gratitude here to all those who helped us in establishing a network of attempts, many of which were frustrated by bad weather. In particular, our thanks go to B. Stecklum, H.–U. Käufl, M. Simon and N. White. Also, we should like to thank the director of the Vainu Bappu Observatory for special time allocation. This research has made use of the *Simbad* database, operated at CDS, Strasbourg (France).

References

Ashok, N.M., Chandrasekhar, T., Ragland, S., Bhatt, H.C. 1994, Experim. Astron., 4, 177

Bergeat, J., Lunel, M., Sibille, F., Lefevre, J. 1976, A&A, 52, 263

Bergeat, J., Sibille, F., Lunel, M. 1978, A&A, 64, 423

Blow, G.L., Chen, P.C., Edwards, D.A., Evans, D.S., Frueh, M. 1982, AJ, 87, 1571

Bogdanov, M.B. 1979, Sov. Astron., 23, 577

De Vegt, Ch. 1974, A&A 34, 457

Dominy, J.F., Wallerstein, G. 1986, PASP, 98, 1193

Dunham, D.W., Evans, D.S., Silverberg, E.C., Wiant, J.R. 1975, MNRAS 173, 61

Eriksson, K., Gustafsson, B., Johnson, H.R., Querci, F., Querci, M., Baumert, J.H., Carlsson, M., Olofsson, H. 1986, A&A 161, 305

Fleischer, A.J., Gauger, A., Sedlmayr, E. 1992, A&A, 266, 321

Griffin, R.F., Redman, R.O. 1960, MNRAS, 120, 287

Heske, A., Te Lintel Hekkert, P., Maloney, P.R. 1989, A&A, 218, L5

Houk, N. 1963, AJ, 68, 253

Jørgensen. U.G. 1989, ApJ, 344, 901

Kholopov, P.N. 1985, *The General Catalogue of Variable Stars*, 4th ed (Moscow, Nauka)

Knoechel, G., von der Heide, K. 1978, A&A, 67, 209

Lambert, D.L., Gustafsson, B., Eriksson, K., Hinkle, K.H. 1986, ApJSS, 62, 373

Lasker, B.M., Bracker, S.B., Kunkel, W.E., 1973, PASP, 85, 109

Loup C., Forveille T., Omont, A., Paul, J.F. 1993, A&ASS, 99, 291

Lucy L. 1974, AJ, 79, 745

Manduca, A. 1979, A&AS, 36, 411

Mauron, N., Caux, E. 1992, A&A 265, 711

Meyer, C., Rabbia, Y., Froeschle, M., Helmer, G., Amieux, G. 1994, A&ASS, in press

Nather R.E., McCants M.M. 1970, AJ, 75, 963

Olofsson, H., Eriksson, K., Gustafsson, B. 1987, A&A, 183, L13

Olofsson, H., Eriksson, K., Gustafsson, B. 1988, A&A, 196, L1

Quirrenbach, A., Mozurkevich, D., Hummel, C.A., Buscher, D.F., Armstrong, J.T. 1994, A&A, 285, 541

Richer, H.B. 1971, ApJ, 167, 521

Richichi, A. 1987, Mem. Soc. Astron. Ital., 58, 431

Richichi, A. 1989, A&A, 226, 366

Richichi, A., Lisi, F., Calamai, G. 1991, A&A, 241, 131

Richichi, A., Lisi, F., Di Giacomo, A. 1992, A&A, 254, 149

Ridgway, S.T., Wells, D.C., Joyce, R.R., 1977, AJ, 82, 414

Ridgway, S.T., Keady, J.J. 1988, ApJ, 326, 843

Scargle, J.D., Strecker, D.W. 1979, ApJ, 228, 838

Schmidtke, P.C., Africano, J.L., Jacoby, G.H., Joyce, R.R., Ridgway, S.T. 1986, AJ, 91, 961

Stecklum, B., Howell, R.R., Eckart, A., Richichi, A., 1994, *Very High Angular Resolution Imaging*, W.J. Tango, J.G. Robertson (eds.), p. 364

Toombs, R.I., Becklin, E.E., Frogel, J.A., Law, S.K., Porter, F.C., Westphal, J.A. 1971, ApJL, 173, L71

Tsuji, T. 1986, ARA&A, 24, 89

Volk, K., Cohen, M. 1989, AJ, 98, 931

White, N.M., Feierman, B.H., 1987, AJ, 94, 751

Willson, L.A. 1987, in *Late Stages of Stellar Evolution*, Kwok, S., Pottasch, S.R. (eds.), Reidel, Dordrecht, p. 253

Wirsich, J. 1991, ApJ, 377, 285

Young, K., Phillips, T.G., Knapp, G.R. 1993, ApJ, 409, 725

Zuckerman B. 1993, A&A, 276, 367

Zuckerman B., Dyck H.M. 1986, ApJ, 311, 345

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.