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Near infrared occultation studies of late type stars and circumstellar regions from Gurushikhar observatory

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Abstract. High angular resolution studies of stellar sources and their circumstellar environment is being pursued in the near Infrared region at the 1.2 Gurushikhar telescope by the method of lunar occultations. Though event based and restricted to sources in the path of the moon, the technique is capable of reaching very high angular resolutions in the milliarcsec range. The method of lunar occultations is outlined and interesting results obtained on the carbon star TX Psc, the Supergiant TV Gem and other late type stars are discussed.

Key words : lunar occultations - infrared -milliarcsecond-angular size

1. Introduction

At the outset let me offer my felicitations to Prof. Ram Sagar and his colleagues at the Uttar Pradesh State Observatory, Nainital on the occasion of the silver jubilee of the 104 cm Sampurnanand telescope. It has been more than a solar cycle since I last visited Nainital and used the Sampurnanand telescope for IR observations. When I went to the Observatory last night, I found a lot of changes have taken place - all for the better. With new computing facilities and better communication facilities UPSO is very well connected to the outside world; I wish UPSO all the best in the years to come.

Coming back to the theme of this workshop - "what kind of science can be done with a 1m class telescope?", I would like to add one additional point to the discussions that have taken place yesterday and today. It has been mentioned that for effective use of a 1m class telescope it is necessary to have good backend instrumentation. I would like to add that it is necessary but not sufficient. We must be in a position to use the backend instrumentation at short notice if we are to contribute effectively. For instance in the case of novae it would be very worthwhile to catch them on the rise in the infrared. Very few novae have been caught in their rising phase. In these modern times of 'instant' communication, it should certainly be possible for us to do this kind of work, provided our instruments are primed and ready to go on the telescope at very short notice. Almost all significant contributions of 1m class telescopes in recent times have been on objects of opportunity and it is probably in this zone we could still contribute effectively with the telescopes in the country.

It is in the same spirit of doing something different with a 1m class telescope that the project which I am discussing today, namely, High Angular Resolution Studies of Stars by the method of lunar occultations was taken up at PRL. What is attractive about this technique is that one is able to achieve very high angular resolution, well beyond the diffraction limit of large telescopes, in the milliarcsecond range by relatively simpler means compared to the complexities of long base line optical interferometry. There are, ofcourse, limitations to the lunar occultation method - it is event based and restricted to the path transversed by the moon. Further it is one dimensional in the direction of occultation. Notwithstanding these limitations, the phenomenal angular resolution possible by this method in the milliarcsecond regime made it attractive enough to be taken up for serious study.

2. The lunar occultation method

The lunar occultation method is based on the fact that moon moves relative to the stars and on several occasions, which can be well predicted, it blocks the star light from reaching the earth. The airless limb of the moon serves as a sharp diffracting edge for the light coming from the distance star. Fig. 1 shows the geometry of the technique. As the diffraction fringes sweep across the earth's surface, they can be collected and recorded by telescopes in the path. The telescope

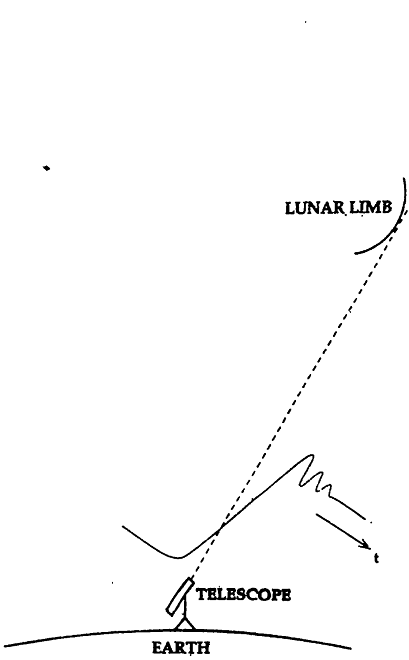

Figure 1. Geometry of lunar occultation of a stellar source.

serves as a mere light collector of the fringes without its resolution aspects being called into play. In fact, in one sense, a 1m telescope is better than a 4m telescope as it causes less smearing of the fringes due to its smaller aperture. However in actual practice the larger S/N ratio derived from larger telescopes more than compensates for the smearing effect.

The intensity of the occultation light curve at a given instant 't' has the form

$$\mathrm{I}(t) = \int_{\infty}^{+\infty} \int_{-A/2}^{+A/2} \int_{\lambda_1}^{\lambda_2} \int_{-\Delta\tau}^{o} S(\phi)\mathrm{F}(w)O(\alpha)T(\tau)d\phi d\alpha d\lambda d\tau + \beta(t) \tag{1}$$

where S (ϕ) is the one dimensional source function in the direction of occultation which has to be extracted. F(w) is the Fresnel diffraction pattern of a point source given by

$$\mathrm{F}(w) = 0.5\,[(0.5 + \mathrm{C}(\omega))^2 + (0.5 + \mathrm{S}(\omega))^2] \tag{2}$$

where C(ω), S(ω) are the Fresnel integrals

$$\mathrm{C}(\omega) = \int_{o}^{\omega} \mathrm{Cos}\,(\pi / {}_2t^2)\,dt;\; \mathrm{S}(\omega) = \int_{o}^{\omega} \mathrm{Sin}\,(\pi/{}_2t^2)dt \tag{3}$$

ω is the fresnel number given by

$$\omega = \left(\frac{2}{\lambda d}\right)^{1/2} [v\,(t - to) + (d\tan\phi) + \alpha] \tag{4}$$

d is the distance to the moon from the observatory, *to* is the time of Geometric occultation, λ is the wavelength of observation, α is the linear displacement term to account for the telescope averaging effect.

O(α) Δ(λ) and T (τ) refer respectively to smearing effects of telescope aperture, finite optical bandwidth and finite time constant of the detection system.

Fig. 2 shows the diffraction pattern obtainable from sources of the different angular sizes. Beyond about 20 milliarcseconds, the fringes disappear.

Table 1. Length and time scales in the lunar occultation method.

Fresnel no: (ω)	Fringe (meters)	Length Scale (V~0.5 km/s)		Time Scale (millisec)	
		0.5μm	0.5μm	0.5μm	2.2μm
1.22	Max	12.2	25.6	24	51
1.87	Min	18.7	39.2	37	78
2.35	Max	23.5	49.3	47	99
2.74	Min	27.4	57.5	55	115
3.08	Max	30.8	64.6	62	129

Table 1 gives the time and length scales of the maxima and minima of the occultation fringes for the visible region (0.5 μm) and the near infrared region (2.2 μm). The entire event is over in less than 200 milliseconds. Due to the rapidity of the event and the fact that diffraction takes place outside earth's atmosphere the fringes are not affected by 'seeing'. Fast scintillation effects can however distort the profiles and need to be taken care in the analysis.

The method of analysis in the simplest form involves a least square fit to the data involving five parameters, namely the time of occultation (to), the velocity of the moon in the direction of occultation (v), the signal level, the background level and the uniform disk angular size.

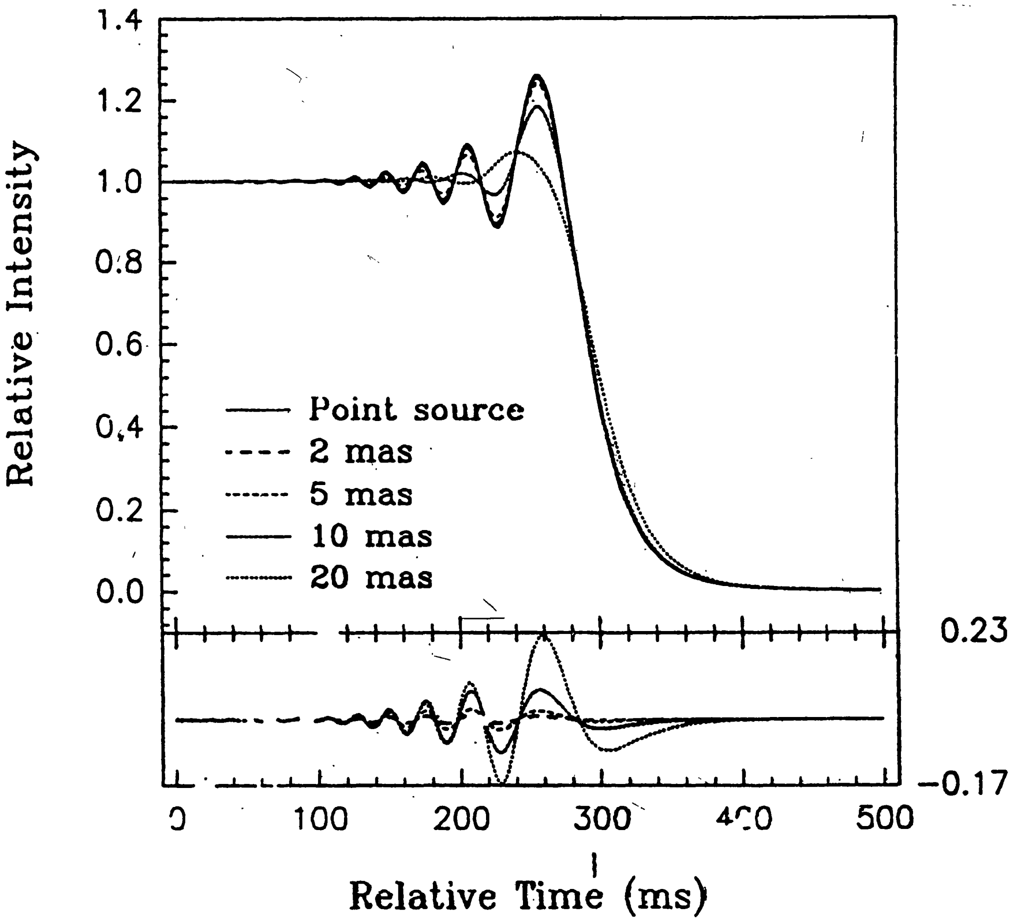

Figure 2. Observable occultation light curve from sources with different angular sizes.

The effect of finite angular size is taken into account by dividing the stellar disk into a number of vertical zones, each of which can be treated as a separate point source with relative intensity weighted according to the area of the zone and by considering the occultations of these zones to happen at slightly different times. It is also possible to introduce the effects of gradients in the sky background in the analysis. When the S/N of the fringes is good, (S/N > 100) it is possible to use a model independent method to deduce the stellar disk diameter and also detect the existence, if any, of a circumstellar shell around the star.

3. Instrumentation and observations

The initial attempts were made in the visible region using a solid state photometer employing 0.5 mm diameter silicon PIN photodiode as detector. One such attempt on Regalus (α Leo) is depicted in Fig.3. Though fringes are not seen the first fringe maximum can be clearly discerned. Further attempts were made in the optical region (Chandrasekhar et al. 1992). It however soon became clear that the noise due to scattered moonlight in the visible region was too large for any meaningful definition of diffraction fringes. At this stage it was decided to operate in the infrared K band (2.2 μm) to reduce the sky background and to enhance the S/N ratio in the fringes. This approach immediately yielded positive results.

The first successful observations in the K band were made in November 1990 at Gurushikhar with the 1.2m mirror still in its imperfect state. Since then occultation in the K band have been carried out successfully with the same instrumental system at the 1 m and 0.75 m telescopes of Kavalur and also at the 1.2m Gurushikhar telescope. The total number of successful observations in the K band (June 1997) has crossed 50. Many of the events are reappearance events, which require the telescope to be pointed exactly where the star will reappear from behind the moon.

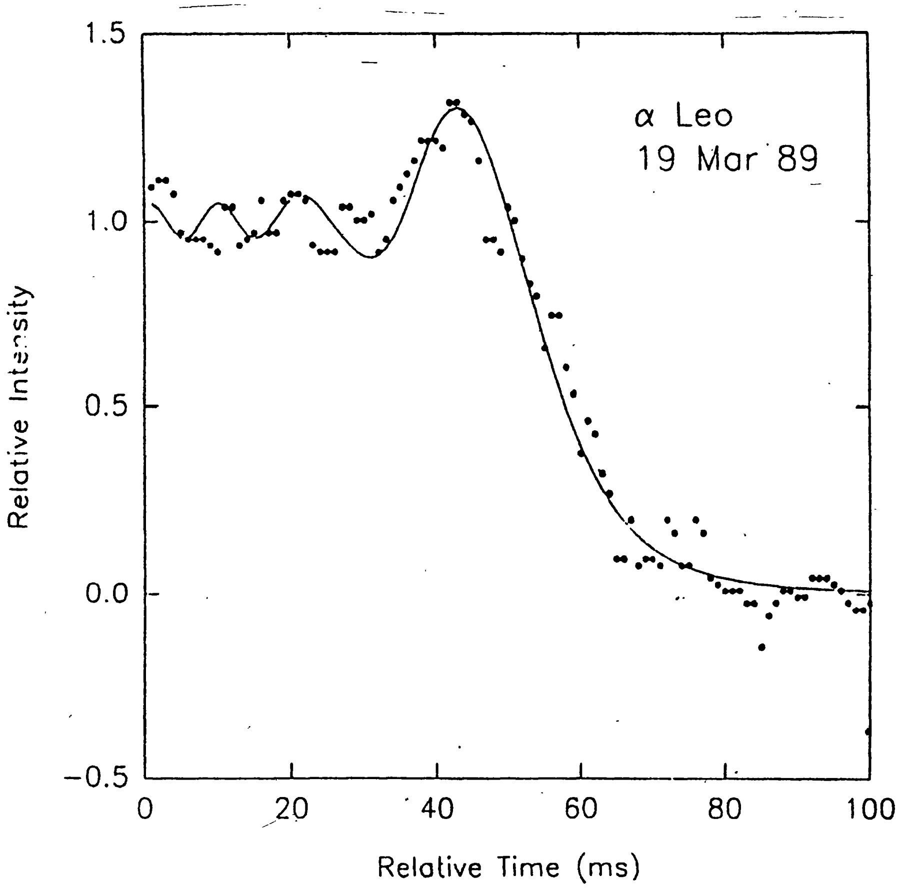

Figure 3. Lunar occultation of Regalus (α Leo) using a solid state photometer.

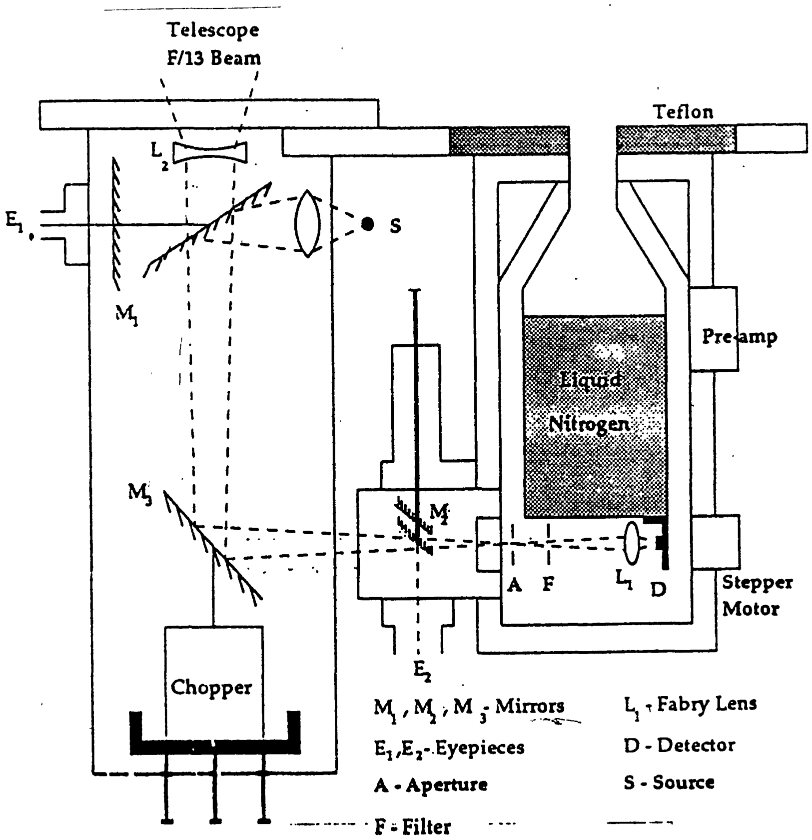

Figure 4. Near Infrared fast photometer.

Fig. 4 shows the infrared photometric system used to record the occultation pattern at 2.2 μm. As the event is a rapid one sky chopping is not done and the DC signal is recorded at 1 millisec intervals for a period of typically 30 sec. centered around the predicted event time. The large time range is required to accommodate errors in the predictions which can arise if the coordinates of the source are not precisely known. An important experimental problem which was overcome was the infiltration of strong 50 Hz pickup from the mains in the DC signal. After various trials, the problem was solved by electrically isolating the dewar entirely from the telescope by non conducting teflon supports.

The experimental system permits good J, H, K photometry to be done soon after or before the occultation. The chopper and Lockin Amplifiers are used in this case. In both photometry and occultation modes, data is recorded through an A/D with 16 bit resolution on a PC based data acquisition system (Ashok et al. 1994).

The limit of angular resolution that can be experimentally reached by the instrument is depicted in Fig, 5. The star IRC 20169 (ζ Gem) is just at the limit of our resolving capability at 2 milliarcseconds. The inset in Fig, 5 shows the error curve.

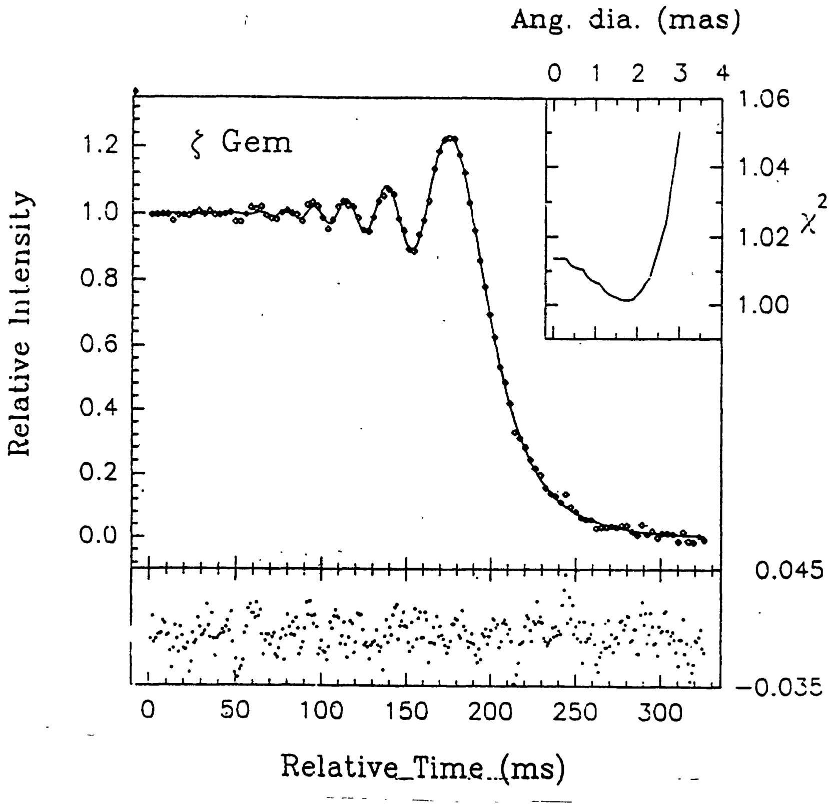

Figure 5. Limit of achievable angular resolution - IRC 20169 (ζ Gem) and its error curve.

4. Results

TX Psc

TX Psc is a bright carbon star ($m_k = -0.76$). Carbon stars are characterised by their red colours, low temperatures and presence of infrared excess indicative of circumstellar matter. High angular resolution observations of carbon stars, which can constrain theoretical models are very few. Therefore, when it became known that a bright carbon star like TX Psc was to undergo lunar occultations in 1993 - 94 it was considered important enough to organise an international campaign and of lunar occultation observations from different observatories. We participated actively in this campaign and contributed two lunar occultation light curves both in the K band, observed under very difficult conditions.

Fig. 6 shows the lunar occultation curve of TX Psc observed with a 14 inch telescope attached to the tube of the 1.2 m telescope at Gurushikhar. The occultation occurred 1430 hrs. in the afternoon and is probably the only successful K band occultation observed anywhere with such a small aperture. Analysis of the occultation light curve has yielded a value of 7.5 ± 0.5 milli arcsecond for the uniform disk angular size of the star. Table 2 gives the results from other occultations of TX Psc during the campaign period.

Table 2. TX Psc lunar occultations observed at different observatories.

Observatory	Date	Filter	Pos. Ang.	Derived Ang. Size (f) (milliarcsec)
Calern, France	12 Mar. 92	V	98	9.5 ± 1.1
Calern, France	12 Mar. 92	R	98	8.8 ± 0.7
Tirgo, Switzerland	12 Mar. 92	K	92	9.82 ± 0.10
Gurushikhar, India	27 Jan. 93	K	76	7.5 ± 0.5
Wyoming IR Observatory, USA	20 Oct. 93	K	5	7.72 ± 0.06
Calar Alto, Spain	20 Dec. 95	L	50	9.7 ± 0.2
Kavalur, India	13 Dec. 94	K	40	9.3 ± 0.5

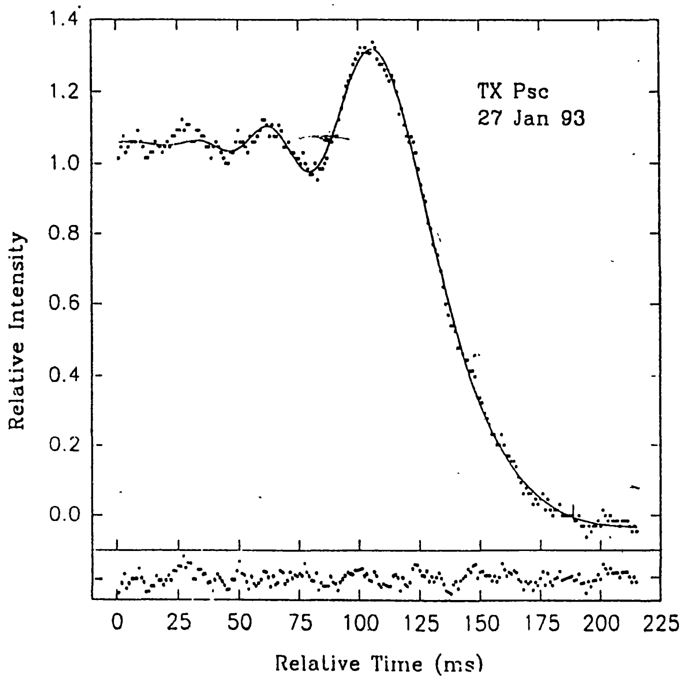

Figure 6. Occultation light curve of TX Psc obtained with a 14 inch telescope at Gurushikhar.

The recovered brightness profiles from occultation light curves are shown in Fig. 7. The departure from circular symmetry is clearly apparent in all six profiles. As one moves to IR wavelengths from optical, the brightness profiles get more complex. Side peaks are seen on either side of the central compact source suggesting a shell like structure which is particularly dominant in the L band. The observed profiles can be satisfactorily explained by a model of the source consisting of the central star and an asymmetric circumstellar dust shell with an inner radius of $\leq 2\ R_*$. The dust temperature in the shell can be constrained to < 1300 K from the relative strengths of the side peaks in K and L bands. The detected presence of asymmetric dust shell close to the photospheric of a hot carbon star like TX Psc indicates that models of carbon stars which predict only shells around cooler carbon stars require substantial revision (Richichi et al. 1995).

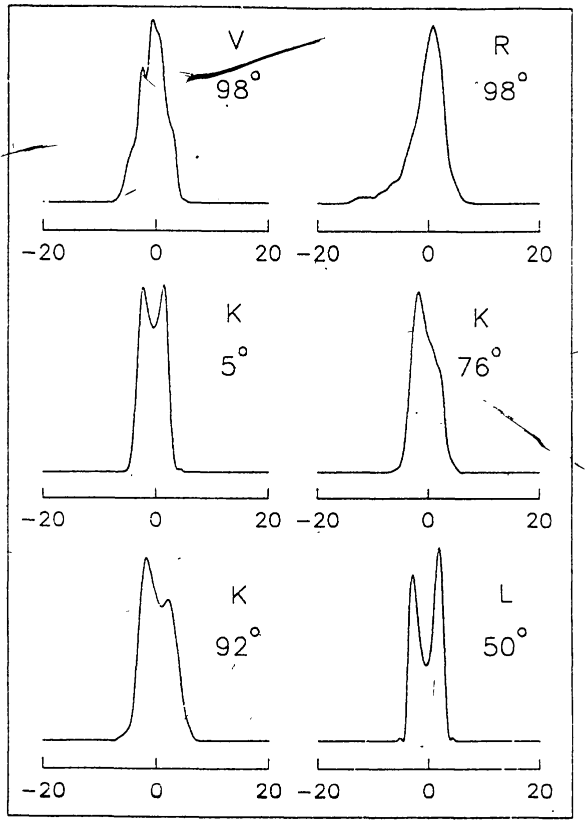

Figure 7. Brightness profiles of TX Psc recovered from occultations of TX Psc observed at different observatories.

TV Gem

TV Gem is a distant (d = 1200 pc) oxygen rich supergiant classified as M1 Iab. From IRAS observations it is known to have a strong silicate feature at 9.7 μm. The lunar occultation of TV Gem was successfully observed by us with a 0.75m telescope at Kavalur on 30 March 1993. A careful analysis of the data showed that in addition to a compact source, for best fit to the data, a circumstellar shell at a distance of 20 ± 5 R_{star} with (F_{star} / F_{shell}) = 35 needs to be invoked. The presence of such a shell is also consistent with 9.7 μm silicate signature which can arise from the same region. The star is resolved with a uniform brightness disk of angular diameter 4.9 ± 0.3 milliarcseconds. The circumstellar shell therefore exists at ~ 100 mas. The recovered one dimensional brightness profile of the extended component is shown in Fig. 8. It is seen that the 60 μm and 100 μm data of IRAS require the presence of an outer shell due to cooler dust at ~ 500 R_{star}. The picture of the supergiant that emerges is that of a star surrounded by two shells with void in between. Such a picture is very similar to that of the well known supergiant α Ori which has also two shells at 25 R_{star} and 50 R_{star}. We have suggested that sporadic mass loss resulting in dust condensation with a time scale of a few decades must be operating in the two supergiants. Such sporadic mass loss could well be a general phenomena in early M Supergiants (Sam Ragland et al. 1997).

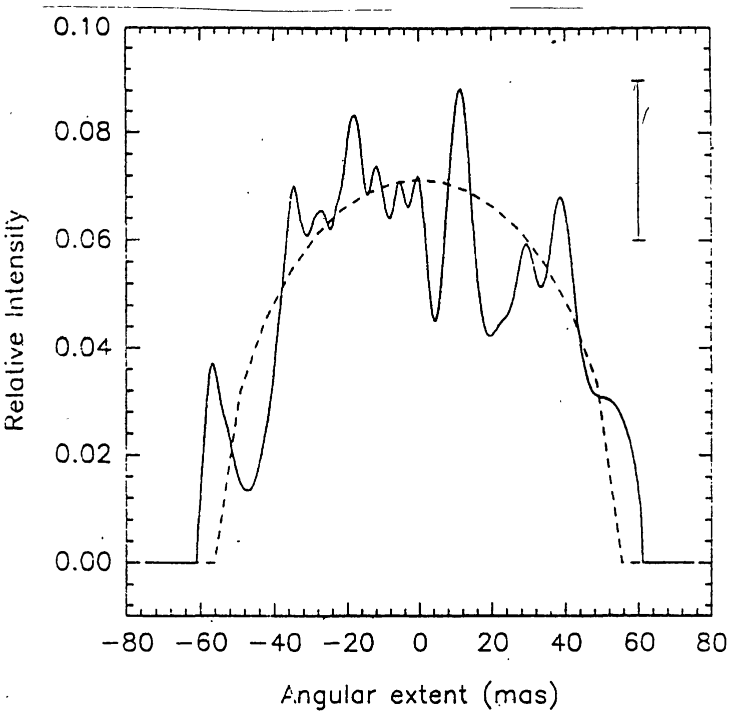

Figure 8. The shell around TV Gem.

In addition to TX Psc and TV Gem, a number of M giants namely IRC + 20190, NSV 1529, IRC + 00198, BQ Ori, IRC + 10194 and IRC + 10024 in the spectral range M2-M7 which underwent lunar occultations were observed in the K band. When the source is resolved, knowing the bolometric luminosity F_{bol} one can also deduce the effective temperature T_{eff} without a knowledge of the distance

$$F_{bol} = (\phi / 2)^2 \sigma T^4_{eff} \tag{5}$$

Table 3 gives the effective temperature and angular sizes deduced from our occultation data of a few M giants. Fig. 9 shows the data model and error curve of a recent observation from Gurushikhar.

Table 3. Lunar occultations of M giants

Source	Sp. Class	(φ mas)	T_{eff}
IRC + 20190	M2 III	≤ 2	
NSV 1529	M2 - M7 III	3.3 ± 0.3	3380 ± 160
IRC + 00198	M2 III	≤ 22	
BQ Ori	M5 III	4.2 ± 0.2	3460 ± 100
IRC + 10194	M3.3 III	4.2 ± 0.5	2760 ± 170
IRC + 10024	M2 III	3.2 ± 0.2	3650 ± 100

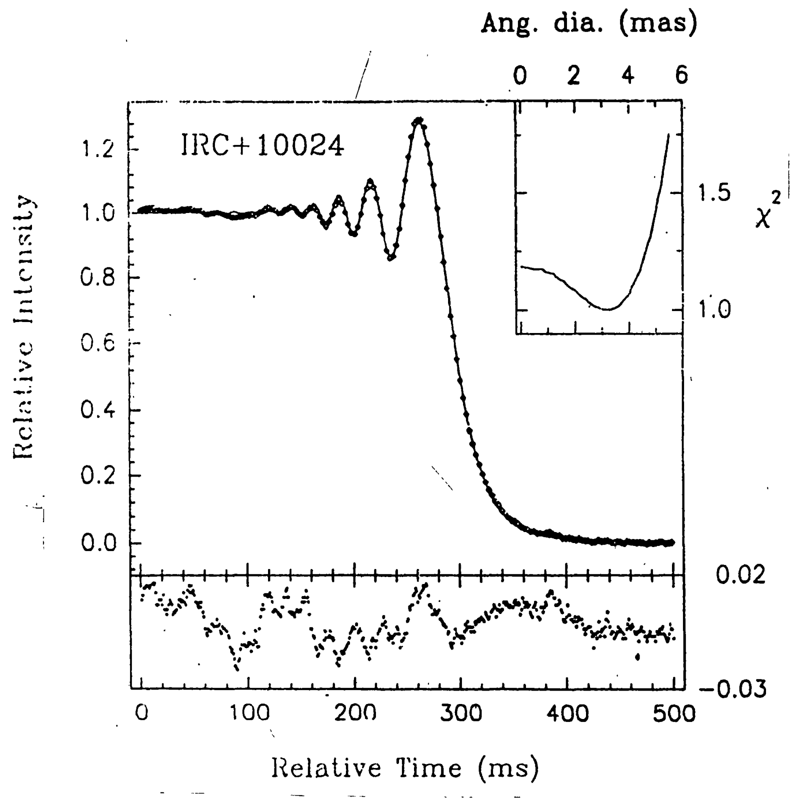

Figure 9. Observed light curve, model fit, residuals and error curve of IRC + 10024. Derived uniform disk diameter $\phi = 3.2 \pm 0.2$ mas. $T_{eff} = 3650 \pm 100$K

5. Future

1. The TX Psc campaign has shown that L band occultation light curves are particularly suited for probing the circumstellar region of late type stars. If in addition, a K band occultation data is also available then the contributions of the star and shell, if any, can be clearly determined. With this end in view a two channel IR fast photometer for recording Lunar occultations simultaneously in K and L bands has been constructed at PRL and is undergoing pretelescopic test at Gurushikhar.

2. The infrared array with its smaller pixel size (~ 40 microns) compared to photometric diaphragms (2 mm typically) can lead to a large reduction in background noise when used for lunar occultations. Further, possibilities of observing lunar occultations on a bright limb can be explored. The problem to be overcome if IR arrays are to be used for occultations is the rapid readout times (milliseconds) required even for small portions of the array (10 × 10 pixels).

3. With the growing number of long base line optical interferometers, it would be extremely useful if there is a concerted move to compare occultation diameters with these derived from LBOI.

Acknowledgements

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