

## Lunar occultations in the near infrared : achievements and new challenges

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**Abstract.** A brief review of the lunar occultation program in the near infrared for high angular resolution study of bright IR sources carried out at PRL in the last decade is presented. The development of the two channel Fast IR photometer is described. Major results pertaining to circumstellar dust structures surrounding occulted objects like IRC+10216 and WR104 are outlined. The challenges for the future in observing lunar occultations in the L band and in the use of IR arrays for occultation work are discussed.

*Keywords :* Lunar occultation, infrared, late type stars, dust shells

### 1. Introduction

Even as the Physical Research Laboratory's 1.2 m telescope was coming up at Gurushikhar, Mt. Abu in the late 1980s it was clear that we had only a small telescope aperture and some innovation was required to do good science with this telescope beyond conventional photometry and spectroscopy. The lunar occultation (LO) program in the near infrared was taken up at PRL as one form of this innovative approach to study bright IR sources at high angular resolution. There are strong motivations for High Angular Resolution (HAR) studies going well below the 'seeing' limit of the atmosphere of about 1 arcsec. Binary detections at separations of tens of milliarcseconds (mas) and determination of effective temperature of late type giants from angular diameter determinations have been earlier motivations. LO provides a direct means of determining effective temperature of late type stars, without a knowledge of the distance to the source which is usually uncertain. Measuring the angular diameter ( $\varphi$ ) from LO we can determine effective temperature  $T$  from the relation  $F_{bol} = \sigma(\varphi/2)^2 T^4$  where  $F_{bol}$  is the bolometric

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flux. It is possible to estimate bolometric flux with reasonable accuracy from available multispectral observations in the literature in addition to JHK photometry carried out close to the epoch of occultation observations as in our case.

The more recent trends point to a more detailed HAR study of a few sources like Mira variables to understand their pulsational properties or study of circumstellar structures of sources heavily embedded in dust to understand mass loss mechanisms and inner zone geometry.

The difficulty of angular diameter measurements of stars can be gauged from the fact that if we hypothetically shift the Sun approximately to the distance of the nearest star, say 1 parsec then its angular diameter will be only 10 mas. At more conventional distances in the galaxy, even giant stars require milliarcsecond resolutions for angular diameter determinations. LO has the distinct advantage over the only other comparable HAR technique namely long baseline optical interferometry (LBOI) by being relatively simpler and much less expensive, while reaching angular resolution of 1 or 2 mas. LO is also not affected by atmospheric seeing unlike LBOI due to rapidity of an LO event. It must however be noted that LO provides high angular resolution in one dimension only (in the direction of occultation) and is limited to bright sources occulted by the moon. The IR advantage is in the reduction of lunar background noise by several orders of magnitude, which generally overwhelms any fringes in the visible region.

## 2. The technique

Fig 1. illustrates the Lunar occultation technique at Gurushikhar observatory. The straight edge diffraction pattern of light from a distant star produced by the sharp limb of the airless moon sweeps across the telescope aperture with speeds of  $\sim 0.5$  km/s. The telescope serves as a mere flux collector of light to record the diffraction pattern of the source. The observed LO light curve  $I(t)$  is a combination of various components - Fresnel diffraction, optical bandwidth, time response of detector electronics and the brightness profile of the source that we are attempting to recover. The time response of the system is determined carefully after the event using a fast IR LED. Details of time response measurements can be found in Anandmayee Tej (1999). The other parameters are well determined so that by an iterative process, the observed light curve can be modelled by a straight forward non-linear least squares analysis to obtain a best fit model curve and a good value of uniform disk (UD) diameter. As an LO event is essentially complete in a few hundred millisecc, a data sampling interval of 1 or 2 millisecc is essential for good definition of the fringes.

While the non linear least squares method leading to a uniform disk (UD) diameter is well suited for stellar sources it is not suitable for sources which depart from spherical symmetry in which non stellar structures like a clumpy dust shell contribute significantly to the IR flux. A particularly useful mode of analysis for sources with extended dust

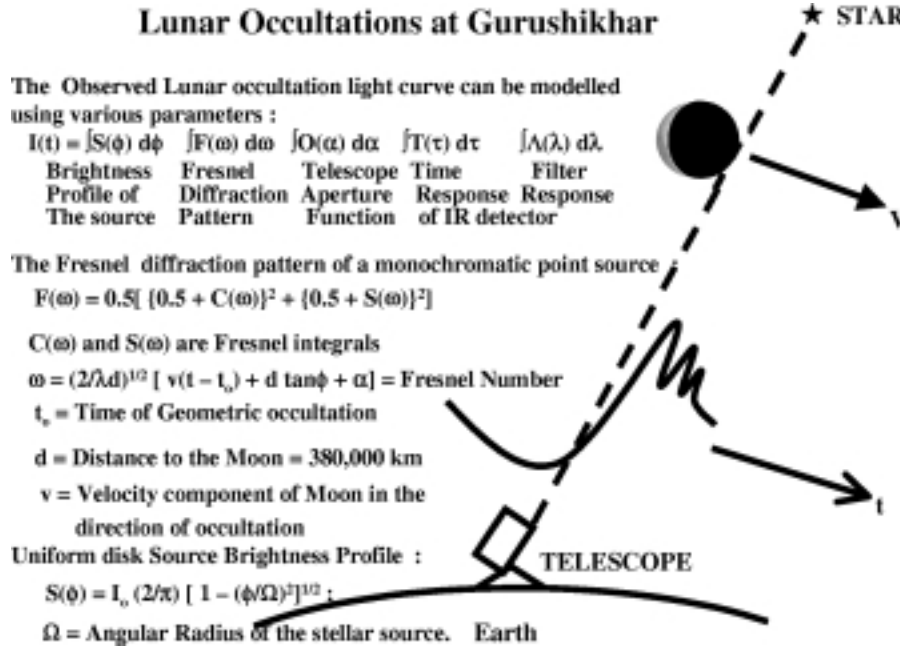


Figure 1. Schematic diagram of the lunar occultation technique.

structures like IRC+10216 or WR104 has been the Model independent method of data analysis (MIA). In this case starting from a uniform disk profile of appropriate size, the nonlinear least squares and Lucy deconvolution algorithm are used iteratively in a composite manner to arrive at the best fit to the data. The resulting brightness profile can be very different from the uniform disk (UD) profile of enshrouded sources like IRC+10216 or WR104 and signifies an asymmetry in the dust envelope.

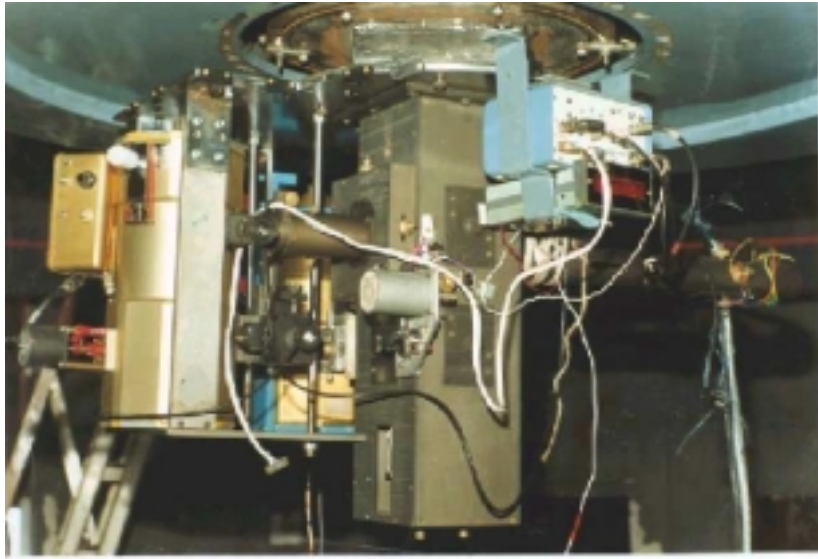
### 3. Instrumentation

Initially the lunar occultation efforts at PRL began in the visible region (Chandrasekhar et al., 1992) but the S/N advantage in the Near IR K band was compelling enough to quickly begin operation in that region with already available single element InSb detector dewars operating at 77 K. It became possible to use the 1.2 m telescope at Gurushikhar for IR occultation efforts even in its initial phase (1990-91) when the image quality was poor as the telescope was used as a flux collector only (Ashok et al., 1994).

After the mirror was removed for refiguring the IR photometer was shifted to Kavalur and several occultation in the K band were successfully observed at the 1 m telescope mainly but also at the 75 cm telescope there. When the 1.2 m mirror arrived back in

Gurushikhar in 1994 it was quickly put to use for LO observations. Ever since then all the lunar occultation work of PRL has been carried out at Gurushikhar.

Even when the primary mirror was not in place a Celestron-14 (14 inch Schmidt Cassegrain) was used with the large telescope's mount and drive to record an important LO event of the bright carbon star TX PSc in the K band in mid afternoon. Probably this is the smallest telescope aperture ever used anywhere for recording an infrared LO event!



**Figure 2.** Two channel IR Fast Photometer for K and L band lunar occultations.

Fig. 2 is a close up view of the present Two channel Fast IR photometer attached to the 1.2 m telescope. This system has evolved from the earlier single channel photometer for obtaining LO observations simultaneously in the K band (2.2 microns) and the difficult L band (3.6  $\mu\text{m}$ ) (Soumen Mondal et al., 2002). System details are shown in Fig. 3. There is provision for tertiary mirror sky chopping at 10-15 Hz for synchronous detection of sources for photometry. A specially made dichroic beamsplitter used at 45 degrees separates the K band (transmission) and L band (reflection). Two separate InSb dewars are used to separately detect the source in the K and L bands simultaneously.

#### 4. Statistics

A total of 123 lunar occultations in the K band have been successfully observed till the end of 2004. The source catalog for generating Lunar occultation predictions for the Gurushikhar site is the venerable TMSS (Two Micron Sky Survey) catalog of Neugebauer

and Leighton (1969) which has a magnitude limit of  $m_k=3.0$ . Nearly 3000 sources in this catalog lie in the path of the moon and hence can be probed by LO.

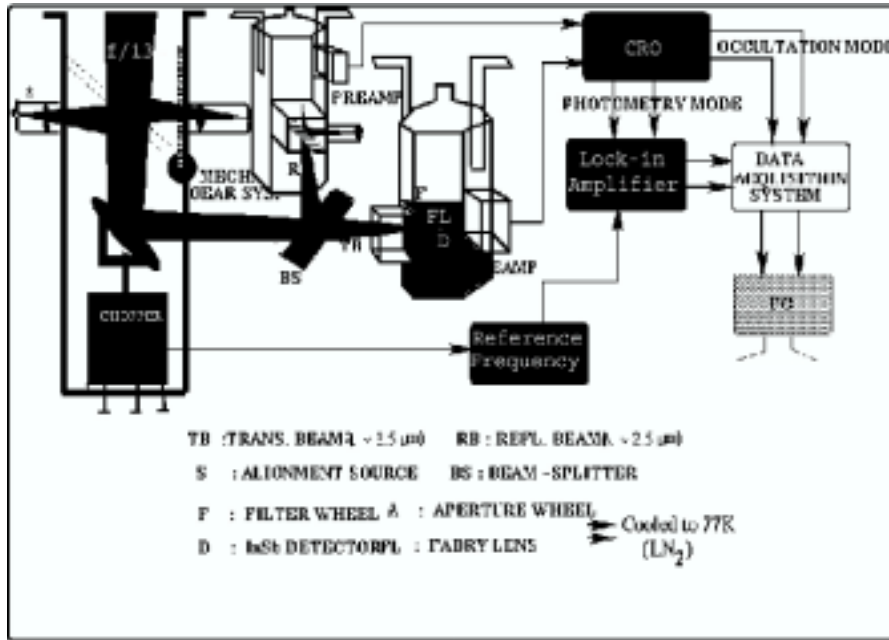
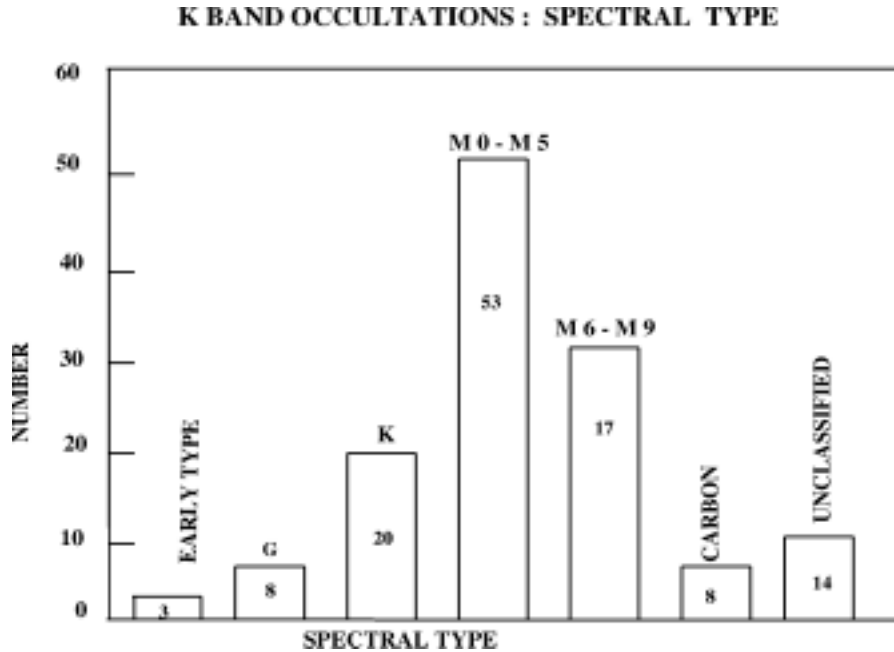


Figure 3. System details of Two Channel Fast IR Photometer.

Fig. 4 shows the histogram of the observed occultation sources in the different spectral types. Most sources are early M giants while late M types are also well represented. Carbon star events are rarer and quite a few sources remain unclassified. Only one Wolf-Rayet star (WR104) has been observed. Effective temperatures have been derived for about 40 occulted sources for which bolometric fluxes could be estimated with good accuracy. Five of these effective temperatures are first determinations for the sources. In many cases our LO observations also provided the first determinations of the angular diameter of the source.

Though LO provides high angular resolution in only one direction, by combining LO results from two different observatories it is possible to get two HAR chords across the source and hence arrive at a two dimensional HAR picture of a source which is particularly useful in probing clumpy structures in dust shells. It is also possible to obtain LO observations in two different wavelengths on the same source and to compare the results. Such efforts have been pursued in active collaboration with Dr. A. Richichi who was earlier at Arcetri Observatory, Florence and have resulted in many important results mentioned below.



**Figure 4.** Distribution of successfully observed K band lunar occultations among spectral types.

## 5. Main results

The LO program at PRL resulted in three Ph.D theses (Ragland, 1996; Anandmayee Tej, 1999; Soumen Mondal, 2004) in which the details of the work can be found. Most of the results have also been published. Hence here only a brief outline of the results is presented and the appropriate references are indicated.

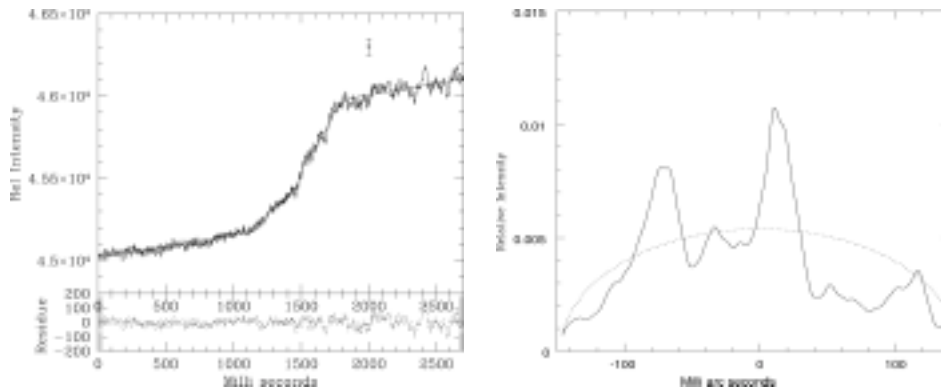
1. **Effective temperatures** of about 40 sources (K and M giants) have been determined from our angular diameter measurements. The details can be found in Ragland et al., (1997), Anandmayee Tej and Chandrasekhar (2000) and Soumen Mondal (2004).

The accuracy in temperature determinations is typically about 5%. Five of these are first determinations of effective temperature of the sources.

2. **TX PSc** : An asymmetric clumpy distribution of hot dust close to the stellar photosphere near  $2 R_*$  was the result of this collaborative investigation involving three occultation groups on the bright carbon star TX Psc (Richichi et al., 1995). It is heartening to note that Near Infrared adaptive optics imaging with COMEON+system at 3.6 m ESO-Lasilla telescope has independently confirmed on TX

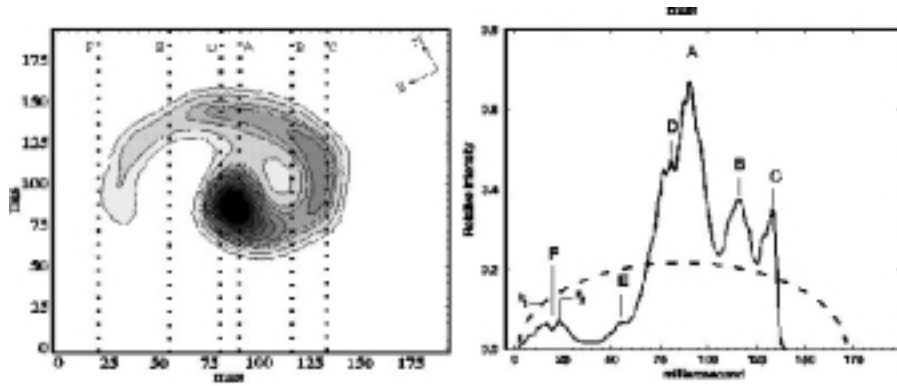
PSc the clumpy dust shell interpretation emerging from our LO data (Cruzalebes et al., 1998).

3. **TV Gem** : A circumstellar shell has been detected for the first time around this supergiant from our LO observations at  $20 \pm 5 R_*$ . A later Lunar occultation of the source has confirmed the existence of the dust shell (Ragland et al., 1997) (Soumen Mondal, 2004)
4. **R Leo** : First LO observations of this Mira variable at  $3.16 \mu\text{m}$  at Gurushikhar using narrow band circular variable filter (CVF). Linear diameter could be accurately determined. Collaborative work with Calar Alto occultation data in the K band showed the Mira variable R Leo to be an overtone pulsator. (Tej et al., 1999)

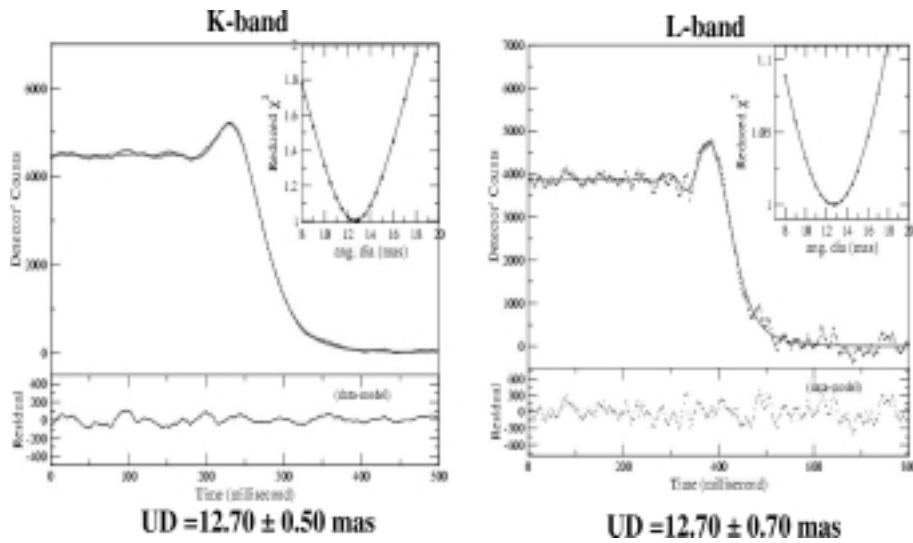


**Figure 5.** Observed occultation light curve in K band (left). Derived brightness profile. Solid line shows the final MIA profile obtained from the initial UD profile (dotted line) (right).

5. **IRC+10216** : Reappearance occultation in the K band yielded a highly structured MIA brightness profile showing the presence of distinct clumps in the thick circumstellar dust enshrouding this highly evolved carbon star (Fig. 5). Lower resolution speckle images taken elsewhere are in conformity with this work. Analysis of an earlier LO taken at Calar Alto provided new perspectives on source location and angular size of the embedded central source. (Chandrasekhar and Mondal, 2001) (Richichi et al., 2003)
6. **WR 104** : A rare LO event of a Wolf-Rayet star surrounded by a thick shell resulted on MIA analysis in a structured brightness profile which could be well compared with a rotating spiral dust structure deduced from aperture interferometry carried out on the 10 m Keck telescope. Several finer features not seen in Keck data exist in our observations which has a higher 1D resolution (Fig. 6) (Mondal and Chandrasekhar, 2002)



**Figure 6.** Keck I Aperture Interferometry Image of WR 104 (left). Brightness profile derived from our LO observations. Solid line is the MIA profile and dotted line the initial UD profile (right).



**Figure 7.** K and L band lunar occultation light curves of  $\eta$  Gem obtained with the Two Channel Photometer.

7. **U Ori** : Spatial asymmetry in a Mira atmosphere detected. More details are given in the article by S. Mondal in this volume.  
(Mondal and Chandrasekhar, 2004)



## 6. Challenges for the future

- **LO with IR arrays**

With the advent of two dimensional IR detector arrays like NICMOS, HAWAII etc. in the 1-2.5  $\mu\text{m}$  region, single element detectors are being phased out. The smaller pixel size of an array detector will reduce the background noise compared to a single element detector. It has been estimated (Richichi, 1994) that with a 1.5 m telescope one can reach  $m_k=6.5$  for LO studies. Presently the main draw back in using IR arrays for LO is in the sampling rate of arrays. Even in a area of interest (AOI) subarray mode it has not been possible anywhere to reach 1 to 2 millisecc sampling time required for LO operations. Our attempts with the software of NICMOS array have yielded so far about 16 ms sampling time for a  $20 \times 20$  pixel subarray. Three LO events have been successfully recorded in this mode (Chandrasekhar et al., 2003).

More efforts are on to reduce sampling time to less than 5 millisecc so that fainter sources with extended dust shells like IRC+10216 sources can be studied using LO with IR arrays.

- **LO in the L band**

The large thermal background in the L band has so far permitted only a few bright sources like  $\eta$  Gem,  $\mu$  Gem to be studied. They yield L band UD values consistent with K band values (Fig. 7). LO of a few other sources like U Ari and  $\nu$  Vir have been attempted but the light curves are noisy. A new small element array for the 3-5  $\mu\text{m}$  region can be explored for LO work in this region.

## 7. Conclusion

Inspite of the impressive advances in Optical/IR long baseline interferometry, Lunar occultations in the NIR 1-5  $\mu\text{m}$  region remains a viable and cost effective alternative for high angular resolution studies of late type enshrouded sources at 1 m class telescopes. Usage of IR arrays for LO work needs to be pursued vigorously.

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