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# Infrared high angular resolution measurements of stellar sources*

## IV. Angular diameters and effective temperatures of fifteen late-type stars

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**Abstract.** We have measured the angular diameter of fifteen late-type stars in the near-infrared using the technique of lunar occultations. Included are ten giant stars in the spectral range K0–M10, three M supergiants and two carbon stars. The resulting uniform-disk angular diameters are in the range 2.5 to 10.0 milliseconds of arc (mas), and the average formal error is 0.17 mas. In one case where the same occultation has been observed from two different locations, the two diameter determinations agree well within the formal errors. Six of the sources had been resolved earlier by previous lunar occultation observations, and our results are in general agreement and show good reliability. The remaining nine sources are resolved here for the first time. In the case of one carbon star, we find a significant departure of the brightness profile from a simple uniform disk model.

In addition, we have obtained near-infrared (and partially visual) photometric observations for all the sources. Complementing this with available literature data at other wavelengths, we have computed the bolometric fluxes, and used them to derive the effective temperatures. For this purpose, we have applied a nominal limb–darkening correction to the angular diameters. The average accuracy of our angular diameter determinations is at the level of ≈4%, making it possible in principle to achieve uncertainties of 2% or ≈50 K in the effective temperatures, provided that sufficiently accurate bolometric fluxes are available. Due to problems such as scarcity of photometric data and variability, bolometric fluxes represent at present an important limitation in this field.

With this work, the set of angular diameter measurements obtained by our group comprises about 50 cool stars. This database will be used in a separate work to derive a refined calibration of the effective temperature of M giant stars.

**Key words:** occultation – stars: fundamental parameters – stars: late–type – stars: circumstellar matter

## 1. Introduction

This paper continues a series, in which we report angular diameter measurements of late-type stars obtained by the method of lunar occultations (LO). Additional results on individual stars have been published separately when appropriate, and the references can be found in the previous papers of this series. With this work, we bring the total number of stars for which we could measure the angular diameter to 51; this includes 38 giants with spectral types in the range K0 to M10, 5 supergiants, 7 carbon stars and one star which still awaits an accurate spectral classification. The main purpose of this research is to derive, from the combination of the angular diameter with the bolometric flux, the effective temperature $T_{\rm eff}$ of a star in a direct way, independently from its distance and any model-dependent assumptions. This in turn provides a fundamental test for stellar atmospheres models. This is particularly important for cool giant stars ($T_{\rm eff} \lesssim 4500$ K), since in this case the model predictions are subject to a larger uncertainty than for hotter types, and the constraint that these measurements can impose on the current theories is significant.

Although a substantial number of angular diameter measurements of this kind is available both from LO observations (the compilation by White & Feierman (1987) listed 117 giant stars with spectral class cooler than K0) and from interferometric methods of various nature (recently Davis (1997) listed 57 stars in the same category as above), our sample has the advantage of constituting a homogenous set, obtained by using a single technique with well-understood instruments, analyzed with a common method, and with a consistent error evaluation. As a result, it has been shown that these measurements are statistically more accurate than previous LO results (Richichi 1997), and have the potential to extend significatively the $T_{\rm eff}$ calibration by including spectral types cooler than those currently available.

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[*] Based on observations collected at TIRGO (Gornergrat, Switzerland) and at Calar Alto (Spain). TIRGO is operated by CNR – CAISMI Arcetri, Italy. Calar Alto is operated by the German-Spanish Astronomical Center.

**Table 1.** Summary of the occultation observations

| (1) Source | (2) Date UT | (3) Tel. | (4) PA ° | (5) D ″ | (6) Δt ms | (7) τ ms |
|---|---|---|---|---|---|---|
| IRC +20115 | 06-01-93 | C3 | 77 | 6 | 1.9 | – |
| TV Gem | 03-02-93 | T | 101 | 28 | 2.7 | 2.4 |
| Z Cnc | 06-02-93 | T | 118 | 14 | 1.9 | 1.6 |
| IRC +20155 | 21-02-94 | C1 | 174 | 17 | 2.0 | – |
| IRC +20155 | 21-02-94 | T | 122 | 28 | 3.4 | 3.0 |
| IRC −20356 | 05-03-94 | T | 327 | 28 | 2.4 | 2.0 |
| V718 Tau | 12-10-95 | T | 246 | 21 | 2.4 | 2.0 |
| DV Tau | 14-10-95 | C2 | 271 | 14 | 2.0 | – |
| DV Tau | 14-10-95 | T | 307 | 21 | 2.4 | 2.0 |
| CE Tau | 14-10-95 | T | 323 | 28 | 1.4 | 1.0 |
| CE Tau | 14-10-95 | C2 | 284 | 14 | 2.0 | – |
| IRC −20578 | 04-06-96 | C2 | 223 | 14 | 2.0 | – |
| IRC +20067 | 01-10-96 | C3 | 240 | 6 | 1.9 | – |
| IRC +20067 | 01-10-96 | T | 267 | 28 | 2.4 | 2.0 |
| RU Ari | 20-12-96 | T | 42 | 21 | 2.9 | 2.5 |
| IRC −20510 | 18-07-97 | C1 | 143 | 17 | 2.0 | – |
| IRC −20444 | 14-08-97 | C1 | 26 | 17 | 2.0 | – |
| IRC −20453 | 14-08-97 | T | 33 | 28 | 2.4 | 2.0 |
| IRC +20074 | 19-10-97 | T | 209 | 28 | 2.0 | 1.5 |

This paper aims at presenting and discussing novel angular diameter results, in a style already introduced in the previous paper of this series (see for instance Richichi et al. 1998a). Along with the angular diameters, we present also photometric data, necessary to compute the bolometric fluxes, and hence the corresponding effective temperatures. We do not discuss in great detail the implications of these results on the $T_{\rm eff}$ calibration, since this is left to a forthcoming work.

## 2. Observations and data analysis

The observational details of the events reported in this paper are summarized in Table 1, in a format very similar to that used in previous papers (see for instance Richichi et al. 1998a). In column (1) and (2) we list the source name and the date of the event. Ten of the listed events were reappearances. Column (3) lists the symbols to identify the telescope used: T denotes the 1.5 m TIRGO telescope, while C1, C2 and C3 denote the Calar Alto 1.23, 2.2 and 3.5 m telescopes respectively. In column (4) through (7) we list the predicted position angle of occultation, the aperture of the photometer, the sampling time of the lightcurve and the integration time of each data point. Table 2 lists cross-identifications of the observed sources in various catalogues, as well as some source details. All occultations were observed with fast photometers, the characteristics of which as well as of the filters used are described in Richichi et al. (1997), and references therein. In all cases, standard broad-band K filters were used, with the exceptions of the occultation of Z Cnc, recorded with an L filter, and of the Calar Alto occultation of CE Tau, recorded with a filter having $\lambda_0$=3.12$\mu$m and $\Delta\lambda$=0.14$\mu$m.

The LO observations were complemented by near-IR photometry in the JHKLM bands, and partially by visual photometry. The results are listed in Table 3. The 1.5 m telescope at TIRGO and the 1.23 m telescope at Calar Alto were used in the near-infrared, and the Loiano 60 cm telescope (code L in the table) equipped with a photometer and Johnson BVRI filters was used in the visual range. Note that the K magnitudes listed in Table 2 are taken from the literature, and there can be some difference with our determinations due most likely to intrinsic variability of the sources. In Sect. 3.8 these differences are discussed more in detail.

To analyze the occultation lightcurves and recover the high angular resolution information present in the data, we used a least squares method, based on the scheme originally proposed by Nather & McCants (1970). Our data reduction program incorporates important additions, such as the corrections for the effects of scintillation, the finite time response of the instrument and spurious frequencies. It also includes a refined error estimation. These features have been described in Richichi et al. (1992). For what concerns the issue of bolometric fluxes, we have fitted the available photometric data by a model with one or two black bodies, including extinction when necessary. More details can be found in the previous papers in this series.

## 3. Results and discussion

Our results are listed in Table 4, where we give from left to right the source name, its most accepted spectral type (see the individual discussions for alternative classifications), the angular diameter obtained from our data under the hypothesis of a uniform disk, our estimate of the bolometrix flux, and the resulting effective temperature. Note that limb–darkening, while less of a problem for cool stars in the near–infrared than at visual wavelengths, can have an effect at the level of few percents on the angular diameters. This could be comparable with the level of accuracy that is reached by the lunar occultation technique, and therefore an appropriate correction should be made. For the limited purpose of the present paper, we have chosen to show the angular diameters as uniform disk values (a standard choice in the literature), and to apply a nominal correction of 3.5% (which is typical of M stars in the 2$\mu$m spectral region, see for instance Perrin et al. 1998) for the purpose of computing the effective temperatures. A more thorough analysis is planned for a forthcoming paper devoted to the subject of the effective temperarure calibration.

Note that although some of the sources were observed twice as is detailed in Table 1, some of the poorer quality results have been excluded from Table 4. The last three columns report, when available, the temperature calibrations published by Ridgway et al. (1980b, R80 in the table), Dyck et al. (1996, D96) and Perrin et al. (1998, P98). Currently, no standard $T_{\rm eff}$ calibration is available for giants cooler than M7, as well as for carbon stars and supergiants. Dyck et al. (1992) observed that in the case of two supergiants their temperature appears 160-250 K cooler than for giants of the same spectral type. Our results seem to strengthen this conclusion.

**Table 2.** Cross identifications of the occulted sources and their characteristics

| Source | TMSS | IRAS | SAO | HD | Other | V | K | Sp. |
|---|---|---|---|---|---|---|---|---|
| IRC +20115 | +20115 | 05352+2247 | | | Fuen C 84 | 10.8 | 3.0 | C |
| TV Gem | +20134 | 06087+2152 | 78092 | 42475 | HR 2190 | 6.6 | 1.0 | M1Iab |
| Z Cnc | +20199 | 08196+1509 | 97768 | 70421 | | 8.3 | 1.1 | M6 |
| IRC +20155 | +20155 | | 95939 | 261164 | BD+19 1423 | 8.0 | 2.3 | M2 |
| IRC −20356 | −20356 | 17169−2140 | | | | | 2.8 | M4 |
| V718 Tau | | 04284+1732 | | | | | 2.8 | Ce |
| DV Tau | +20111 | 05281+1831 | 94604 | 36231 | AFGL 761 | 8.4 | 1.4 | M6 |
| CE Tau | +20112 | 05292+1833 | 94628 | 36389 | 119 Tau | 4.5 | −1.0 | M2Iab |
| IRC −20578 | −20578 | 19573−1641 | | | | | 2.1 | M7 |
| IRC +20067 | +20067 | 03510+1527 | 93659 | 285268 | BD+15 546 | 9.1 | 2.7 | M2 |
| RU Ari | | 02420+1206 | | | | | (2.8) | M10 |
| IRC −20510 | −20510 | 18399−1920 | 161754 | 172816 | V3879 Sgr | 6.4 | −0.6 | M4 |
| IRC −20444 | −20444 | 18090−1853 | | | AFGL 2087 | | 1.7 | M9 |
| IRC −20453 | −20453 | 18125−1856 | | 167314 | BD−18 4862 | 7.8 | 2.4 | M1/M2Ib/II |
| IRC +20074 | +20074 | 04169+1530 | 93868 | 27371 | $\gamma$ Tau | 3.65 | 1.5 | K0 III |

In this section, we shall present first a short review of some of the individual stars, in connection with earlier findings and available literature. This discussion is presented separately for the M giant stars, and for the groups of the carbon and supergiant stars. Note that in the case of two stars with a long history of previous measurements, we present a compilation in Table 5. In this latter, the column with the disk model type lists whether the value is referred to a uniform disk, a limb-darkened disk or a fully darkened disk (UD, LD, FD respectively). In the last part of this section we discuss our results, in particular in comparison with existing effective temperature calibrations. We also present some considerations on the computation of the bolometric fluxes and the implications on the effective temperatures. We have chosen not to show all LO data, since many examples of lightcurves and corresponding fits obtained through our analysis have already been given in the previous papers of this series. Instead, we show in Fig. 1 only three examples, that are intended to illustrate different situations of angular diameter.

For the giant stars, it can be seen that our results are in agreement with the existing calibrations. Three important exceptions are IRC +20067, IRC +20155 and IRC −20356. In these cases, our temperature estimate appears too low. This inconsistency could be explained by assuming that our diameter determination is wrong (specifically, too large). This hypothesis cannot be discussed directly, in the absence of independent determinations. As an indirect argument, we note that in all those other cases for which an independent determination existed, our value was in agreement either within the quoted errors, or by considerations of different wavelength or limb darkening assumptions. In cases when several other previous measurements existed (as for IRC −20510 and CE Tau, see Table 5), our determinations match very well the average of the other measurements. This indicates an overall reliability of our results. In addition, we note that the near-IR colors of the three objects above suggest a spectral type later than those quoted in the available literature (sometimes without a detailed record), or a substantial amount of extinction. This latter hypothesis would lead to considerably higher values for the bolometric fluxes, and thus explain part of the discrepancy with existing calibrations. However, we are reluctant to accept this explanation because for all three stars little interstellar extinction is expected ($<1$, $<0.5$ and $<0.5$ mag based on the work of Lucke 1978). As for what concerns the possibility of extinction due to circumstellar dust, we note that no IR excess is apparent and not much dust would be expected from early M giants. To summarize this issue, we conclude that the discrepancy in the effective temperature of these three objects could be attributed at least partially to an incorrect bolometric flux and/or spectral typing, and further photometric and spectroscopic monitoring of these sources is essential.

### *3.1. DV Tau*

DV Tau has been classified as M6 by Bidelman (1980). This source was observed earlier by Radick et al. (1982) in the visual but not resolved. Ridgway et al. (1982) observed it at 1.6$\mu$m and their derived value for the uniform disk diameter is 3.38 ± 0.19 mas.

### *3.2. IRC −20578*

The spectral classification of IRC −20578 has been reported as M7 by Hansen & Blanco (1975) and M6.9 III by Wing (1987). This source was resolved in the near-IR by Ridgway et al. (1979), and their reported value for the uniform disk angular diameter was 2.61±0.35 mas.

### *3.3. RU Ari*

Our occultation lightcurve of RU Ari is shown in Fig. 1. This star is a Mira variable of spectral type M10 (Whitelock et al. 1994). It is detected in OH (Sivagnanam et al. 1989) and $H_2O$ (Engels & Lewis 1996) maser emissions. There was no positive

**Table 3.** Near-infrared and visual photometry

| Source | Date | Tel. | J | H | K | L | M |
|---|---|---|---|---|---|---|---|
| IRC+20115 | 18-10-97 | T | 5.32±0.01 | 3.99±0.01 | 3.19±0.01 | 2.28±0.02 | |
| | 25-09-97 | T | 5.32±0.03 | 3.88±0.02 | 3.08±0.03 | | |
| | 13-08-97 | T | 5.18±0.02 | 3.89±0.02 | 3.02±0.02 | 2.26±0.02 | |
| | 24-02-94 | C1 | 5.24±0.02 | 3.82±0.01 | 2.86±0.01 | 2.13±0.37 | |
| | 27-09-93 | C1 | 5.30±0.06 | 3.82±0.04 | 2.74±0.07 | | |
| TV Gem | 25-09-97 | T | 1.91±0.03 | 1.03±0.02 | 0.63±0.03 | | |
| | 28-01-97 | T | 2.27±0.20 | 1.21±0.02 | 0.65±0.01 | 0.35±0.05 | 0.92±0.20 |
| | 22-02-94 | C1 | 2.21±0.03 | 1.25±0.03 | 0.72±0.03 | 0.61±0.51 | |
| | 23-12-93 | C1 | | | 0.65±0.04 | 0.68±0.07 | |
| | 28-09-93 | C1 | 2.20±0.02 | 1.21±0.02 | 0.69±0.02 | | |
| | 05-02-93 | T | 2.14±0.01 | 1.21±0.01 | 0.87±0.01 | 0.58±0.01 | |
| Z Cnc | 18-10-97 | T | 2.32±0.01 | 1.33±0.01 | 0.92±0.01 | 0.80±0.02 | |
| | 25-09-97 | T | 2.29±0.03 | 1.24±0.02 | 0.83±0.03 | | |
| | 28-01-97 | T | 2.49±0.01 | 1.39±0.01 | 0.84±0.01 | 0.68±0.03 | 1.11±0.07 |
| | 24-09-96 | T | 2.62±0.02 | 1.63±0.02 | 1.28±0.03 | | |
| | 24-02-94 | C1 | 2.45±0.01 | 1.47±0.01 | | 0.71±0.31 | |
| | 18-02-94 | C1 | 2.52±0.01 | 1.37±0.01 | 1.03±0.01 | 0.87±0.01 | |
| | 23-12-93 | C1 | 2.42±0.03 | 1.42±0.03 | 0.96±0.03 | 1.17±0.06 | |
| | 05-02-93 | T | 2.31±0.01 | 1.38±0.01 | 0.98±0.01 | | |
| IRC+20155 | 25-09-97 | T | 3.55±0.03 | 2.39±0.02 | 2.27±0.03 | | |
| | 13-08-97 | T | 3.33±0.02 | 2.67±0.02 | 2.18±0.02 | 2.20±0.03 | |
| | 28-01-97 | T | 3.71±0.02 | 2.77±0.01 | 2.27±0.01 | 1.98±0.03 | 2.59±0.24 |
| | 26-01-97 | T | 4.37±0.09 | | | | |
| | 25-09-96 | T | 3.56±0.02 | 2.64±0.02 | 2.32±0.03 | | |
| | 01-03-96 | T | 3.50±0.05 | 2.66±0.09 | 2.36±0.06 | | |
| | 27-10-94 | T | 3.76±0.02 | 2.62±0.01 | 2.37±0.01 | 2.17±0.02 | 2.61±0.35 |
| | 09-03-94 | T | 3.79±0.01 | 2.85±0.01 | 2.38±0.02 | | |
| | 06-03-94 | T | 3.76±0.05 | 2.56±0.03 | 2.31±0.04 | 2.18±0.05 | |
| | 04-03-94 | T | 4.02±0.04 | 3.01±0.04 | 2.61±0.33 | 2.15±0.01 | |
| IRC−20356 | 13-08-97 | C1 | 4.43±0.08 | 3.17±0.06 | 2.66±0.07 | | |
| | 21-07-97 | C1 | 4.96±0.01 | 3.45±0.01 | 2.90±0.01 | | |
| | 03-06-96 | C1 | 4.50±0.06 | 3.20±0.05 | 2.59±0.02 | | |
| V718 Tau | 25-09-97 | T | 6.89±0.03 | 5.10±0.02 | 3.58±0.03 | | |
| | 15-08-97 | C1 | 6.21±0.23 | 4.60±0.02 | 3.12±0.02 | | |
| | 12-08-97 | T | 6.09±0.03 | 4.72±0.01 | 3.19±0.04 | 1.27±0.13 | |
| | 28-01-97 | T | 6.76±0.01 | 5.13±0.01 | 3.55±0.01 | 1.92±0.04 | 1.72±0.12 |
| | 20-12-96 | T | 6.72±0.01 | 5.15±0.03 | 3.67±0.05 | 2.16±0.03 | |
| | 24-09-96 | T | 6.19±0.02 | 4.73±0.02 | 3.38±0.03 | | |
| DV Tau | 18-10-97 | T | 2.64±0.01 | 1.59±0.01 | 1.18±0.01 | 1.11±0.02 | |
| | 25-09-97 | T | 2.46±0.03 | 1.39±0.02 | 1.08±0.03 | | |
| | 13-08-97 | T | 2.52±0.02 | 1.54±0.02 | 1.08±0.02 | 1.17±0.03 | |
| | 28-01-97 | T | 2.96±0.02 | 1.63±0.01 | 1.10±0.01 | 0.92±0.03 | 1.42±0.09 |
| | 24-09-96 | T | 2.79±0.02 | 1.79±0.02 | 1.53±0.03 | | |
| | 01-03-96 | T | 2.07±0.07 | 1.24±0.11 | 0.78±0.07 | | |
| CE Tau | 18-10-97 | T | 0.27±0.01 | −0.66±0.01 | −1.03±0.01 | −1.17±0.02 | |
| | 25-09-97 | T | 0.11±0.03 | −0.80±0.02 | −1.16±0.03 | | |
| | 13-08-97 | T | 0.03±0.02 | −0.66±0.02 | −1.13±0.02 | −1.16±0.02 | |
| | 24-09-96 | T | 0.24±0.02 | −0.65±0.02 | −1.02±0.03 | | |
| IRC−20578 | 24-10-97 | T | 3.13±0.05 | 2.36±0.04 | 1.99±0.04 | 1.51±0.05 | |
| | 18-10-97 | T | 3.56±0.02 | 2.44±0.02 | 2.07±0.02 | 1.73±0.03 | |
| | 14-08-97 | T | 3.70±0.03 | 2.37±0.03 | 2.28±0.04 | 1.71±0.04 | |
| | 11-08-97 | C1 | 3.42±0.08 | 2.45±0.06 | 2.04±0.08 | | |
| | 21-07-97 | C1 | 3.90±0.06 | 2.71±0.01 | 2.23±0.01 | | |
| IRC+20067 | 25-09-97 | T | 4.09±0.03 | 3.08±0.02 | 2.75±0.03 | | |

**Table 3.** (continued)

| Source | Date | Tel. | J | H | K | L |
|---|---|---|---|---|---|---|
| RU Ari | 17-10-97 | T | 4.24±0.02 | 3.42±0.01 | 2.80±0.02 | 2.04±0.03 |
| | 25-09-97 | T | 4.22±0.03 | 3.33±0.02 | 2.79±0.03 | |
| | 14-08-97 | T | 4.27±0.02 | 3.44±0.02 | 2.73±0.02 | |
| | 12-08-97 | T | 4.28±0.03 | 3.59±0.01 | 2.86±0.04 | 2.12±0.14 |
| IRC−20510 | 14-08-97 | C1 | 0.81±0.02 | −0.22±0.02 | −0.72±0.03 | |
| | 13-08-97 | T | | −0.22±0.06 | −0.92±0.05 | |
| IRC−20444 | 15-08-97 | C1 | 3.58±0.03 | 2.41±0.03 | 1.58±0.03 | |
| IRC−20453 | 15-08-97 | C1 | 3.59±0.03 | 2.72±0.03 | 2.25±0.03 | |
| IRC+20074 | 24-10-97 | T | 2.03±0.04 | 1.57±0.03 | 1.31±0.03 | 1.39±0.04 |
| | | | B | V | R | I |
| TV Gem | 05-10-97 | L | 8.77 ± 0.27 | 6.46 ± 0.15 | 5.01 ± 0.10 | |
| Z Cnc | 05-10-97 | L | 10.38 ± 0.32 | 8.87 ± 0.19 | 6.68 ± 0.14 | |
| IRC+20155 | 04-10-97 | L | 8.38 ± 0.35 | 7.43 ± 0.23 | 6.94 ± 0.17 | 6.52 ± 0.01 |
| DV Tau | 05-10-97 | L | 10.05 ± 0.27 | 8.47 ± 0.16 | 6.48 ± 0.10 | |
| IRC+20067 | 04-10-97 | L | 10.68 ± 0.34 | 8.92 ± 0.23 | 7.48 ± 0.17 | 5.84 ± 0.01 |
| RU Ari | 04-10-97 | L | 13.28 ± 0.36 | 11.63 ± 0.23 | 9.22 ± 0.17 | 6.99 ± 0.02 |

**Table 4.** Angular diameter and effective temperature results

| Source | Sp | $\phi_{\rm UD}$ (mas) | Bolom. flux ($10^{-10}$ Wm$^{-2}$) | T$_{\rm eff}$ (K) | Calibration (K) | | |
|---|---|---|---|---|---|---|---|
| | | | | | R80 | D96 | P98 |
| IRC +20074 | K0 III | $2.69 \pm 0.18$ | $12.83 \pm 0.84$ | $4722 \pm 171$ | 4790 | | |
| IRC +20067 | M2 | $3.68 \pm 0.24$ | $1.71 \pm 0.20$ | $2439 \pm 105$ | 3730 | 3740 | |
| IRC +20155 | M2 | $3.89 \pm 0.12$ | $2.25 \pm 0.15$ | $2541 \pm 57$ | 3730 | 3740 | |
| IRC −20356 | M4 | $3.02 \pm 0.24$ | $1.44 \pm 0.20$ | $2579 \pm 134$ | 3560 | 3595 | |
| IRC −20510 | M4 | $8.09 \pm 0.27$ | $37.43 \pm 3.60$ | $3558 \pm 103$ | 3560 | 3595 | |
| Z Cnc | M6 | $4.26 \pm 0.31$ | $6.70 \pm 0.33$ | $3190 \pm 119$ | 3250 | 3380 | 3243 |
| DV Tau | M6 | $3.79 \pm 0.13$ | $5.07 \pm 0.25$ | $3154 \pm 65$ | 3250 | 3380 | 3243 |
| IRC −20578 | M7 | $3.21 \pm 0.11$ | $2.86 \pm 0.30$ | $2970 \pm 92$ | | 3210 | 2982 |
| IRC −20444 | M9 | $4.54 \pm 0.06$ | $3.55 \pm 0.70$ | $2636 \pm 132$ | | | |
| RU Ari | M10 | $4.10 \pm 0.38$ | $1.12 \pm 0.20$ | $2079 \pm 132$ | | | |
| IRC +20115 | C | $2.49 \pm 0.12$ | $1.34 \pm 0.10$ | $2790 \pm 83$ | | | |
| V718 Tau | Ce | not UD | $1.41 \pm 0.15$ | $\gtrsim 2300$ | | | |
| TV Gem | M1Iab | $4.46 \pm 0.07$ | $10.94 \pm 0.55$ | $3524 \pm 52$ | | | |
| IRC −20453 | M1/M2I | $3.24 \pm 0.16$ | $3.83 \pm 0.30$ | $3180 \pm 98$ | | | |
| CE Tau | M2Iab | $9.93 \pm 0.04$ | $55.69 \pm 3.10$ | $3547 \pm 50$ | | | |
| CE Tau | M2Iab | $9.99 \pm 0.10$ | $55.69 \pm 3.10$ | $3537 \pm 52$ | | | |

detection of SiO maser emission by Benson & Little-Marenin (1996). The distance to this source is estimated to be 1.2 kpc (Jura & Kleinmann 1992). Alternative estimations are 1.73 kpc by Sivagnanam et al. (1989) and 2.09 kpc by Nguyen-Q-Rieu et al. (1979). The amplitude of variability in the visual is $\gtrsim 3.8$ (Jura & Kleinmann 1992), and in the K band is $\sim 1.2$ magnitudes (Whitelock et al. 1994). The period is 353.5 days (Smak & Preston 1965), and our LO measurement took place at phase 0.2 from maximum. We note that our photometric measurements were obtained also around the time of maximum light, in the following cycle.

### *3.4. IRC −20510*

IRC −20510 has been classified as M5.2III by Ridgway et al. (1980a). An alternative classification of M4 III can be found in the literature (Eggen 1992). This source shows variability in the visual range of amplitude $\sim$ 0.5 mag with a period of $\sim$ 50 days. Several LO events of IRC −20510 have been previously observed, and we list the results in Table 5. While it is difficult to combine together these measurements without a thorough discussion of the role of limb-darkening and its wavelength-dependence, we note that our value $\phi$ =8.09±0.27 mas (uniform disk at 2.2$\mu$m) is in good agreement with the average of the three near–IR determinations by Ridgway and his collabo-

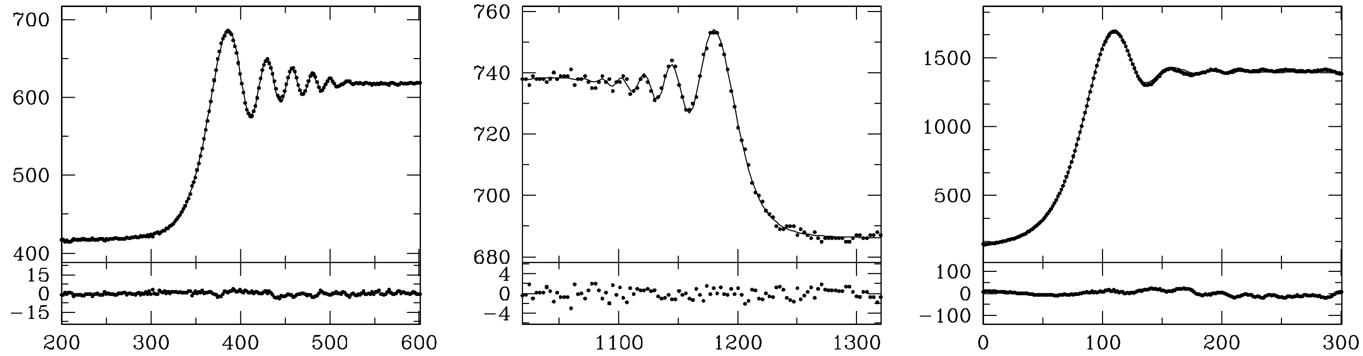

**Fig. 1.** Selected occultation lightcurves. The data and our model fits are shown in the upper panels (dots and solid line respectively), while the fit residuals are shown in the lower panels on a scale enlarged by a factor of two. The horizontal axes are marked in ms, the vertical ones in arbitrary detector counts units. From left to right, the stars are the K0 giant IRC +20074, the M10 giant RU Ari, and the M2 supergiant CE Tau (one of two available lightcurves). It can be noted how the fringe contrast decreases steadily in this sequence, an indication of the increasingly larger associated angular diameter (see Table 4).

rators. Radick & Lien (1982) derived a uniform disk diameter of 4.9±0.76 mas for this source, which is much smaller than the above values. These authors claim to have detected a secondary component in this source from their observations. No evidence for binarity is quoted in the other observations reported above, nor is found in our data. The effective temperature has been derived by Ridgway et al. (1980a) at 3170±30 K, somewhat lower than our estimate probably because of differences in the estimate of the bolometric flux. Using the infrared flux method, Tsuji (1981) derived the value 3320 K, which agrees well with our determination.

### 3.5. *IRC +20074*

Our occultation lightcurve for IRC +20074 is shown in Fig. 1. This source was previously resolved by LO by Ridgway et al. (1980a), who reported $\phi$ =2.84±0.16 mas at 2.17$\mu$m. Radick et al. (1982) and Evans & Edwards (1981) also observed LO events at visual wavelengths, but in their case the source could not be resolved. A determination of the angular diameter and effective temperature of this source by the infrared flux method was made by Blackwell & Lynas-Gray (1994), who obtained $\phi$ =2.375 mas and $T_{\rm eff}$=4965 K. IRC +20074 was reported to be a speckle binary with an angular separation of $0\farcs395$ (Morgan et al. 1982). Later observations by Mason et al. (1993), as well as our own, did not confirm this finding.

### 3.6. *Carbon stars*

Two carbon stars, namely IRC +20115 and V718 Tau, are among the results of Table 4. We note that at present there is no generally accepted temperature calibration for carbon stars, partly because of the scarcity of data, partly because these objects are intrinsically subject to marked flux variations. Therefore there is no reliable comparison provided in the table in these two cases. While a uniform disk model fits the IRC +20115 LO data well, the same is inadequate in the case of V718 Tau. An analysis of these latter data by means of the CAL algorithm (Richichi 1989) revealed a brightness profile composed by a central core with FWHM ≈4.2 mas, surrounded by extended wings. These can be traced out to ≈15–20 mas and are not completely symmetric, the emission on the NE side being more pronounced than that on the SW side. We interpret this wing-like structure as due to the presence of warm dust close to the photosphere as in the case of another carbon star, TX Psc (Richichi et al. 1995). The presence of dust is confirmed also by the strong extinction which is evident from our photometry (see Table 3, and also Fig. 2). We have obtained also some preliminary visual photometry for this star. While these data are not accurate enough for publication, they indicate a B–V of ≈3.5 mag and V–K $\lesssim$ 12 mag. Our fit of the bolometric flux for this star indicates an extinction of $A_{\rm V}$ ≈5 mag. We note that recently we have observed another carbon star, namely IRAS 06088+1909 (Richichi et al. 1998b), with similar characteristics of strong extinction and compact circumstellar dust.

Under these conditions, the estimate of effective temperature could be highly biased. If the characteristic size of the central emission is interpreted as the angular diameter of the underlying star, it would result in $T_{\rm eff}$ ≈2300 K, but this should be regarded only as a lower limit. While in the cases of TX Psc and IRAS 06088+1909 we have been able to record several LO along different scan angles, as well as complementary information by other techniques, in the case of V718 Tau an estimate of the effective temperature must be postponed until more data can be collected.

### 3.7. *Supergiants*

We report also on three stars in the supergiant luminosity class, namely TV Gem, IRC −20453 and CE Tau. For this latter, two independent lightcurves have been recorded at different wavelengths (2.2 and 3.1$\mu$m), but the resulting angular diameters agree well within their errors (see Table 4). One of the two occultation lightcurves obtained for CE Tau is shown in Fig. 1. CE Tau has been extensively observed by LO in the wavelength range 0.548$\mu$m to 1.62$\mu$m, and in one case by interferometry. A

**Table 5.** Previous measurements for two stars

| $\lambda$ ($\mu$m) | $\phi$ (mas) | Disk Model | Reference |
|---|---|---|---|
| | IRC −20510 | | |
| 0.68 | 11.7±1.4 | LD | Evans & Edwards (1981) |
| 0.76 | 10.3±1 | UD | Beavers et al. (1982) |
| 0.82 | 8.5±1.5 | LD | Africano et al. (1977) |
| 0.86 | 4.9±0.76 | UD | Radick & Lien (1982) |
| 1.62 | 8.69±0.16 | UD | Ridgway et al. (1979) |
| 1.62 | 7.53±0.17 | UD | Ridgway et al. (1980a) |
| 1.62 | 7.74±0.38 | UD | Ridgway et al. (1982) |
| | CE Tau | | |
| 0.54 | 10.3±2.3 | UD | White (1980) |
| 0.54 | 10.4±1.6 | UD | White (1980) |
| 0.54 | 10.3±3.0 | UD | White (1980) |
| 0.57 | 9.2±1.4 | LD | Beavers et al. (1982) |
| 0.62 | 9.0±2.0 | UD | White (1980) |
| 0.71 | 11.47±0.33 | UD | Quirrenbach et al. (1993) |
| 0.72 | 8.9±0.3 | UD | White (1980) |
| 0.75 | 9.98±0.20 | UD | Quirrenbach et al. (1993) |
| 0.76 | 9.1±1.0 | LD | Beavers et al. (1982) |
| $H_\alpha$ | 14±1 | UD | White et al. (1982) |
| 0.66 | 9.0±0.2 | UD | White et al. (1982) |
| 1.62 | 9.48±0.07 | UD | Ridgway et al. (1980b) |

compilation of the previous angular diameter determinations for this star is given in Table 5. Also in this case, as before for IRC −20510, a detailed comparison would require a discussion of the wavelength dependence and limb-darkening effects, which is beyond the aim of the present paper. We note that a simple average of all results which can be assumed to have been obtained in the continuum, produces a value which agrees very well with our results listed in Table 4. Also TV Gem has been previously studied by LO: Radick et al. (1984) reported $\phi$ =5.31±0.91 mas while more recently Ragland et al. (1997) derived $\phi$ =4.9±0.3 mas and $T_{\rm eff}$=3670±125 K. These latter authors reported a circumstellar dust envelope around TV Gem with an angular extent $\approx$ 20 $R_\star$ and a shell-to-star flux ratio $\approx$3% at 2.2$\mu$m. It is difficult to make a definitive statement in this sense in the case of our data, since they have been marginally affected by scintillation. While this had no significant influence on the fringe contrast and hence on the angular diameter determination, it might have hindered the detection of a possible extended component with the characteristics quoted above.

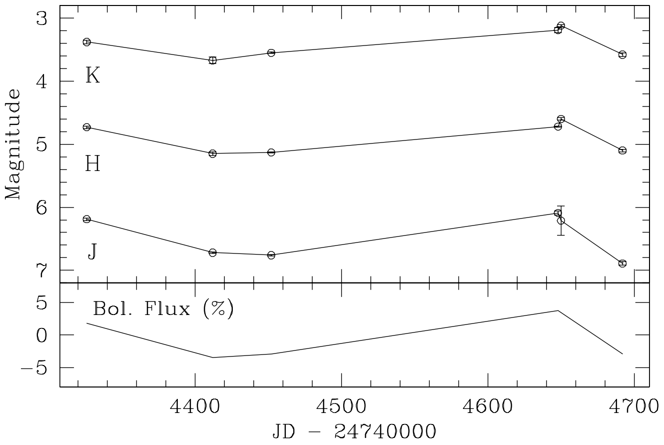

**Fig. 2.** Example of photometric variations in one of the stars in our list. The plot shows our near–IR measurements of the carbon star V718 Tau over a period of one year starting from September 1996. The lower panel shows the changes in the bolometric flux, based on the near-IR variations only.

### *3.8. Bolometric fluxes and variability*

From the discussion presented at the beginning of this section, we conclude that in order to obtain a reliable $T_{\rm eff}$ calibration, it is necessary to inspect carefully not only the accuracy of the angular diameters, but also of the bolometric flux and of the spectral types. Indeed, these latter can be difficult to obtain for late-type stars. In our work, we find that in about 50% of the sample, the uncertainty in the bolometric flux accounts for the major part of the error in the derived effective temperature (similar conclusions were reached in Richichi et al. (1998a)). For most M giants, but particularly so for spectra cooler than M5, variability of both flux and spectrum can bias the temperature estimates. So far, works in the field of temperature calibrations have not included this problem, and have relied on pre–existing determinations of spectra and fluxes, or have measured the fluxes at one epoch only and in a restricted range of wavelengths. In some cases, the presence of dust causes not only an IR-excess, but also a substantial extinction. This is difficult to detect if only near-IR photometry is used, but can affect very significatively the overall determination of the bolometric flux. Among the sources listed in this paper, in seven cases (namely IRC +20115, TV Gem, Z Cnc, V718 Tau, IRC −20578, RU Ari and IRC −20444) there is evidence of an infrared excess and we included in our fits to their spectral energy distribution both dust extinction and a corresponding dust emission. We point out that an occultation of Z Cnc observed in the thermal IR has revealed directly the dust emission: this result is being analyzed in detail and will be presented elsewhere.

We have an ongoing program to obtain a good visual and near-IR photometric coverage of our LO targets, with an emphasis to obtain these measurements as close as possible to the date of the LO events. Photometric monitoring such as that listed in Table 3, when sufficiently extended, should allow us to investigate the role of variability on the estimation of bolometric flux. An example is given in Fig. 2, where we plot the near-IR variability of the carbon star V718 Tau, and the estimated influence of this variability alone on the bolometric flux. It can be noted that a random single-epoch flux determination could have an error of ±5%. Our plot confirms a variability with a period of $\approx$400 days (Kukarkin et al. (1958)), but since it is not continuous we must conclude that larger variations in the bolometric flux might also be possible. We remind that an error of 10% in the flux is equivalent to an error of ≈100 K for M stars.

## 4. Conclusions

We have presented angular diameter determinations and photometry of fifteen late type stars in the spectral range K0-M10 (including three M supergiants and two carbon stars). Nine sources are resolved for the first time. In one case, namely the carbon star V718 Tau, we find a significant departure from a simple uniform disk model. Detailed analysis of the light curve of V718 Tau shows emission extending up to ≈20 mas from the central star, that we interpret as warm circumstellar dust close to the stellar photosphere. In the case of TV Gem, where circumstellar dust detection has been reported by Ragland et al. (1997), we cannot confirm the finding but the detection reported by these authors is just at the limit of our measurement. There is evidence of some IR excess in the spectral energy distributions of Z Cnc, IRC+20115, IRC-20578, RU Ari and IRC+20444, but we do not detect extended emission at $2\mu$m in our data. We note however that in the case of Z Cnc a lunar occultation recorded in the thermal IR has succeeded in detecting the circumstellar dust. This result is to be presented elsewhere.

We have used the angular diameters (including a nominal correction for limb–darkening) and the bolometric fluxes to derive effective temperatures, and compare them with existing temperature calibrations. Our results are in good agreement with the latter, and show the potential of the lunar occultation technique to refine the existing calibrations and extend them to the coolest spectral types. A discrepancy is evident only in three cases, for which however we find some conflict also between the spectral type and the observed colors. The angular diameter measurements presented here have the potential to provide an accuracy of ≈ 2% in $T_{\rm eff}$. In practice however the accuracy is limited in several cases by the uncertainty in the bolometric fluxes, an issue which is relevant to all current efforts by different techniques in this field. The role of near-IR variability on the estimation of the bolometric flux for M giants is discussed. A program of photometric monitoring of these sources in the near-IR and visual is in progress with the aim of improving the estimation of bolometric flux in near future.

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