LUNAR OCCULTATION MEASUREMENTS OF STELLAR ANGULAR DIAMETERS

A. RICHICHI
Osservatorio Astrofisico di Arcetri
Largo E. Fermi, 5 – 50125 Firenze, Italy

1. Introduction

Offering an angular resolution which has remained unattained by any other technique for decades, lunar occultations have traditionally been the most productive method for the measurement of stellar angular diameters. Unlike interferometric methods, which are limited in resolution by the size of the aperture or of the baseline between apertures, in a lunar occultation the key to high angular resolution is the phenomenon of diffraction by a straight edge, that occurs at the Moon's limb in a turbulence–free environment. For the reader not familiar with the physics and technical aspects of the lunar occultation (LO) technique, it is sufficient here to show in Fig. 1 some practical examples of occultation lightcurves for sources with different angular diameters. It can be noted that the contrast of the fringes is maximum for a point–like source; it then decreases with the angular diameter, and eventually reaches the regime of a monotonic drop in the signal –as predicted by simple geometrical optics– when the angular extent of the source is large. In practice, the LO method is well suited to measure angular diameters in the range 1 to 50 milliarcseconds (mas). There is no real limitation concerning the wavelength of observation, although at present the near–IR is the region of choice for several different reasons (Richichi 1994).

Several hundred measurements have been collected so far by this method. A primary application has been the calibration of the effective temperature (T_{eff}) of the cooler spectral types, a fundamental parameter of great importance because it allows us to compare directly the theoretical models of stellar atmospheres with the observations. In order to derive T_{eff}, it is necessary to measure the bolometric flux F and the angular diameter ϕ, as

T.R. Bedding et al. (eds.),
***Fundamental Stellar Properties: The Interaction between Observation and Theory*, 45–50.**

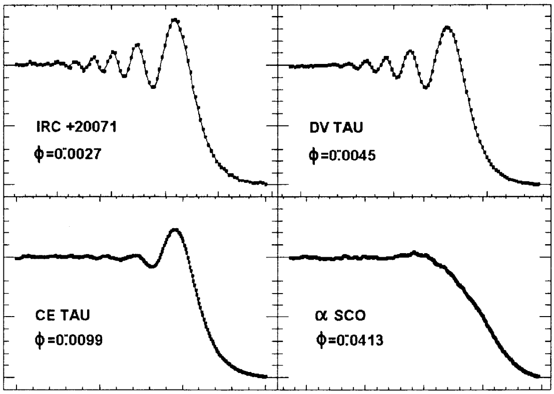

Figure 1. Occultation data (dots) and corresponding fits (solid lines) for four late–type stars with increasing angular diameter (data of the Arcetri LO group). The axes have been rescaled for each data set, bringing the time of occultation and the rate of the event to a common value and renormalizing the intensity values, in order to provide a more direct illustration of the phenomenon of fringe smoothing as a function of the angular size.

follows from the definition

$$F = \sigma \left(\frac{\phi}{2}\right)^2 \mathrm{T}_{\mathrm{eff}}^4 \tag{1}$$

Traditionally, our knowledge of $\mathrm{T}_{\mathrm{eff}}$ for cool stars has been poor, and as a result the contribution of LO in this area has been of particular interest. Lunar occultation observations have led also to important results in related areas, such as the study of surface structure, circumstellar matter, and close binaries. While there will not be sufficient space here to deal with these other applications of the method, the interested reader can find further reading in Richichi et al. (1996). Detailed accounts of the technical aspects of the method and of different aspects of data analysis are also available in the literature (see for instance Richichi 1994).

2. An overview of recent results

Ten years ago, White and Feierman (1987, WF hereafter) published a compilation of all LO angular diameters available through the end of 1986. They listed 348 determinations for 124 stars with spectral types from A to M (including several carbon stars). This large database has constituted a precious reservoir for people working in this field: both for those interested in effective temperatures, and more recently for those working with Michelson interferometry (MI) and interested in a comparison of LO versus MI

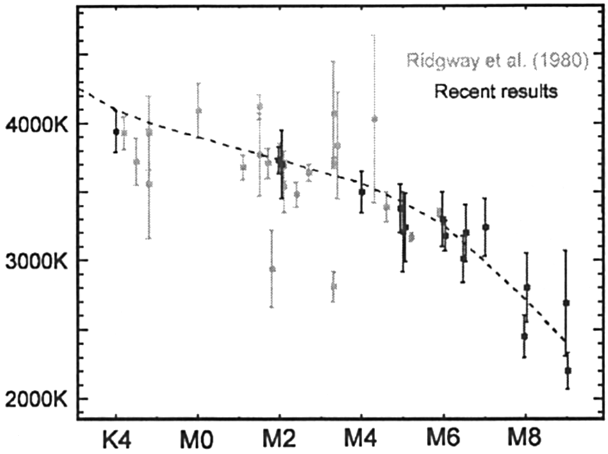

Figure 2. The data used by RJWW (shown here only below K4, in light gray), plotted as T_{eff} vs. spectral type. The dark gray points are the most recent determinations obtained by the Arcetri LO group. The dashed line is the RJWW calibration for spectra warmer than M5, and a tentative best–fit to the most recent results for spectra below M5 (see also Fabbroni and Richichi, these proceedings).

results. However, one should not overlook the fact that the WF compilation includes results from many different groups, often obtained in an early era of LO research when data treatment was not as advanced as today (in particular with respect to the understanding of the formal errors and of the instrumental and atmospehric effects). As a result, it is inevitable that the data show a large scatter which is not, in fact, a true limitation of the method as it has sometimes been assumed. A good example of this is the T_{eff} calibration obtained by Ridgway et al. (1980, RJWW hereafter), shown in Fig. 2, where it can be appreciated how many of the stars show a much wider scatter around the mean calibration, than their formal errors would imply. Nevertheless, the RJWW calibration has proven basically correct over the range K0-M5, as shown by independent MI results (Di Benedetto and Rabbia 1987, Dyck et al. 1996).

What can be said today, looking back at these results? First of all, it can be appreciated how the research in the area is still quite active, in spite of the fact that interferometric methods have undergone a huge technical development and are now clearly the choice for the future (see the several contributions in these proceedings). In Fig. 3, it is shown how the production of papers based on LO results has remained essentially constant over the past decade. There are only few observatories where LO are observed on a regular basis, the most important ones being those at Calar Alto[1] (Spain)

[1]Run by the German–Spanish Astronomical Center, Heidelberg

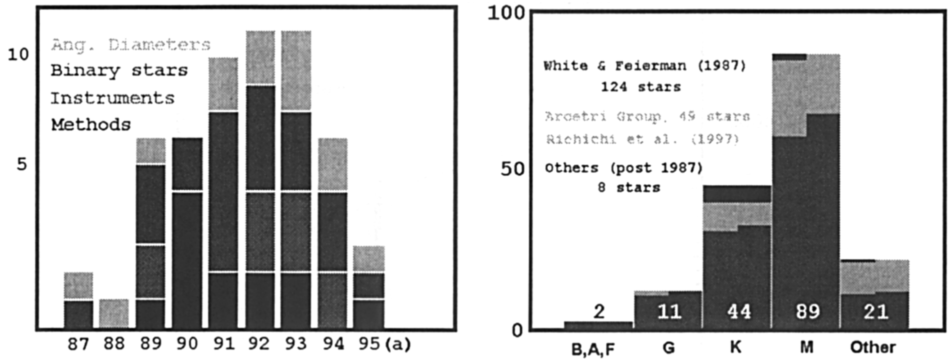

Figure 3. The graph on the left shows the yearly number of publications based on LO results, listed by field of research. On the right, the statistics of the angular diameter results is shown in detail, broken into individual spectral types. The bin *Other* includes carbon stars, and stars with unknown or uncertain spectral type.

and Mt. Gornergrat[2] (Switzerland). Activity on a smaller scale is present also at sites in the USA, Chile, India, Russia and FSU, South Africa, China, Mexico.

Almost 60 new measurements have been added in the past decade to the database of the WF compilation. Allowing for some overlap as shown in Fig. 3, angular diameters have been determined for the first time for about 50 stars. Of these, about 30 new stars belong to the M class and can be used to improve the T_{eff} calibration. At this stage, we are able to use only 17 of the stars in this sample, because for the remaining ones we are still in the process of obtaining the bolometric flux F or of assigning an accurate spectral type. While this number is only a small fraction with respect to the database already available for the M class, one should consider that the intrinsic accuracy of the results is now higher than before. Even more importantly, it should be noted that the LO–derived T_{eff} extends now from M5 to M9, in a range of temperatures for which no calibration at all was available (more recently, Dyck et al. have somewhat extended the RJWW calibration to reach M6). Figure 2 shows these more recent results, along with a tentative extension of the T_{eff} calibration. This preliminary result seems in good agreement with very recent work in the same temperature range by means of MI (Perrin et al. , this Symposium).

3. Conclusions and a look into the future

We can conclude that the measurement of angular diameters by LO is a field which is still producing competitive results, in terms of volume of data

[2]TIRGO, run by CAISMI, Florence, Italy

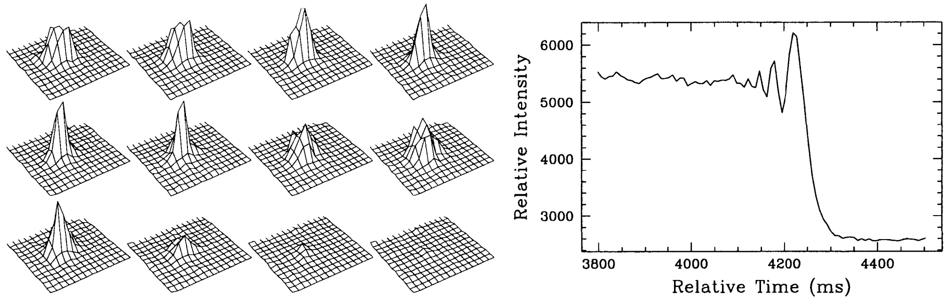

Figure 4. The disappearance of V Ari observed at TIRGO with a Nicmos3 detector operated in subarray mode. The frames on the left show a time sequence of ≈ 0.3 s in a 16X16 subarray, each representing a 7 ms integration (only a subset of frames is shown). The reconstructed lightcurve is shown to the right. An angular diameter of about 3.5 mas is measured. From Richichi et al. (1996).

and accuracy, with respect to more moderm methods such as long–baseline interferometry. If one is to look into the reasons of this prolonged vitality of LO, at least two main factors can be found:

- the method is easy. In spite of severe limitations concerning the *when* and *what* can be observed by LO, the instrumentation is relatively cheap and the data reduction simple, making the method attractive also for small observatories where the expensive technology required for other high angular resolution methods cannot be afforded. Moreover, a telescope in the 1.5m class is sufficient to observe LO at least for what concerns angular diameters.
- The improvements in the data reduction methods and in the understanding of systematic errors have been conspicuous over the past decade. This has made possible to achieve a better consistency of the results, with a much smaller scatter in the $T_{\rm eff}$ data for stars with the same spectral type (see Fig. 2).

There is one additional aspect that is worth mentioning, and it is the technological breakthrough constituted by the use of 2–D detectors used in fast mode on a subarray, to record LO events. Four years ago this author gave a talk in this same venue (Richichi 1994), in which the predicted perfomance of this novel approach was investigated and the implications discussed. Now, this has become a reality (see Fig. 4), with a fast LO mode implemented in several instruments in the near and mid–IR ranges (Richichi et al. 1996, Stecklum et al. 1996). At least 2 magnitudes can be gained, thanks to the drastic reduction in the background intensity allowed by these detectors. The advantages are expecially important for the study of fainter sources than those discussed here, but they are nevertheless considerable also for angular diameter applications.

What can we say about possible avenues for the future? What steps are necessary, to gain significantly in the the T_{eff} calibration? Maybe surprisingly, it appears that the most desirable improvements are not directly in the field of the angular diameter measurements, but rather in that of the bolometric fluxes and spectral types. In our experience, a typical relative error on the angular diameter can be $\approx 3\%$, and often at even smaller levels. If one considers the quantities that come into play in Eq. 1, it appears that in principle it is feasible to obtain direct T_{eff} estimates with accuracy of $< 1.5\%$, or < 50K for the spectral range of interest. However, to preserve this accuracy, it would be necessary to obtain bolometric fluxes with accuracies of $<$ 5-10% and in our experience this is very difficult in practice, expecially if one considers that the cooler stars are usually variable, and relatively faint in the visual bands. For the same reasons, also the spectral type can often be a non–negligible source of uncertainty. Not to mention, that the next step would be temporal studies of diameter and temperature in pulsating variable stars, where these problems are even more serious.

Therefore, it seems that LO (as well as MI) angular diameter measurements should be coupled to a systematic effort to obtain photometric coverage in a large number of bands from the visual to the IR, as close as possible to the date of the diameter determination, as well as to obtain accurate spectral types. While these measurements are simple from an experimental point of view, they require rapid and prolonged access to well equipped telescopes, and in fact the key to serious advancement in the field of direct T_{eff} determinations is probably in a coordinated effort across different astronomical disciplines.

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References

Di Benedetto, G.P., Rabbia, Y. (1987), A&A, 188, 114
Dyck, H.M., Benson, J.A., van Belle, G.T., Ridgway, S.T. (1996), AJ, 111, 1705
Perrin, G., Coude du Foresto, V., Ridgway, S.T., Mariotti, J.-M. (1996), these proceedings.
Richichi, A. (1994), IAU Symposium 158 *Very High Angular Resolution Imaging*, Tango, W.J., Robertson, J.G. (eds.), p. 71
Richichi, A., Baffa, C., Calamai, G., Lisi, F. (1996), AJ, 112, 2786
Stecklum, B., Käufl, U., Richichi, A. (1996), ESO Workshop *Science with the VLT Interferometer*, Paresce, F. (ed.)
Ridgway S.T., Joyce, R.R., White, N.M., Wing, R.F. (1980), ApJ, 235, 126
White, N.M., Feierman, B.H. (1987), AJ, 94, 751