Photometric and Spectrophotometric Data Required for the SUSI Programme

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1. Introduction

The Sydney University Stellar Interferometer, SUSI, a modern version of a Michelson stellar interferometer, will be capable of measuring the angular diameters of stars down to V $\approx$ 8.0, for all spectral types. The resolution of the 640 m baseline — <0.1 milliarcsec at optical wavelengths — includes reasonable sample sizes of all spectral types and luminosity classes to this magnitude limit.

The angular diameter data require complementary photometric, spectrophotometric and also spectroscopic data for the determination of fundamental parameters of single and multiple stars. This paper discusses the accuracy required of these data for some of the main problems to be tackled by SUSI. A selection of the programmes planned for this unique instrument is listed below, where the need for complementary data is also indicated.

- The measurement of the changes of angular diameters of Cepheids and other pulsating stars such as Mira variables. Comparison with the linear changes determined from radial velocity curves will enable their distances and luminosities to be determined by an essentially geometric method.

- The measurement of the angular sizes of the orbits and of one or both components of spectroscopic binary stars. This effectively makes them 'visual' binaries so that the orbital inclination, i, may be determined. When these data are combined with the velocity curve solutions which include $(mass)sin^3i$ and $(semi-majoraxis)sin\ i$, we may determine masses and linear radii of one or both components and also the distances to the systems. Also, the light curve of an eclipsing binary provides information on the ellipticities and radii of the components and on the eccentricity of the orbit — information which may be used to aid the analysis of the SUSI data. In addition, the determination of the light curve (some bright systems have not been observed for up to one or two decades) is the quickest method of finding the current phase of its orbit.

- The establishment of the total-flux-based temperature scale of all spectral types and luminosity classes from O to M. This requires accurate photometry and spectrophotometry over as wide a wavelength range as possible; it therefore also requires observations from space observatories, as was also necessary for the analysis using the Narrabri intensity interferometer data (Code *et al.*, 1976).

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- The measurement of diameters of stars with shells or extended atmospheres, such as Be and Wolf Rayet stars, at different wavelengths — in particular, in the emission lines.

It will be appreciated that the value of an angular diameter alone is of little use. To obtain the distances of Cepheids, high resolution spectra are required throughout the pulsation cycle. To obtain stellar temperatures, spectrophotometry must be obtained over as much of the spectrum as possible — especially in the UV for hot stars and in the IR for cool stars. For determining the masses, radii and distances of stars in binary systems, radial velocity and photometric data are also required. In addition, parameters such as the period and the time of maxima of variable stars are useful for reducing the number of variables for which the raw SUSI data — consisting of time variation of fringe visibility at different resolutions — has to be solved. Many of these parameters are more accurately and easily obtained by standard techniques.

The aim of the SUSI programme is to obtain angular diameters to an accuracy of $\leq 2\%$. This accuracy will be approximately equal to that to which distances of, for instance, spectroscopic binary systems can be measured by relating the angular and linear dimensions of the orbital semi-major axes. For the Cepheid programme, the distances (and therefore the luminosities) determined for individual Cepheids will necessarily have a somewhat lower accuracy. Since we relate the change in diameter during the cycle determined from the velocity curves to the change in angular diameter, the errors will certainly be greater than 2%. However, since more than 40 Cepheids are available to SUSI, the zero point of the period/luminosity relation should be well determined.

2. Requirements of Photometry and Spectrophotometry

2.1 Determination of stellar temperatures and fluxes

Davis (1985) argues that the figure of $\pm 2\%$ accuracy for angular diameters is necessary if we are to increase substantially our knowledge of the surface temperatures and emergent fluxes of stars, especially for the purpose of improving the accuracy of theoretical stellar models. Davis refers to the relation:

$$F = 4f/\theta^2 = \sigma T_e{}^4$$

where F is the flux from the star, f is the observed flux at the surface of the earth, θ the angular diameter, σ the Stefan-Boltzmann constant and T_e the effective temperature. So that errors in the diameters should not contribute significantly to the error in the derived temperatures, the fractional error in θ should therefore be less than one half of the fractional error in f, which Davis found to be of the order of 4% for well measured stars with $B - V > -0.15$. Such errors lead to 1% errors in T_e. Reversing this argument, if the angular diameters are to be determined to 2% and temperatures to 1%, then the spectrophotometric errors, including calibration errors and extrapolation to unavailable regions of the spectrum, should be no more than 4%. Thus, if the ground-based UV to infrared spectrophotometry is internally accurate to 1%, the space observations and the interpolated and extrapolated stellar flux must contribute no more than 3%.

We intend to investigate the accuracy of determining the total flux, f, from Johnson, Strömgren and/or Geneva photometry of programme stars. The catalogues of data, at least in the latter two systems, are accurate to about 1% (often less for bright stars) so that if they can be satisfactorily calibrated with respect to the absolute flux standards, the desired accuracy might be expected. That this is likely to be the case is indicated by the results of Petford *et al.* (1985). They compared their Reticon spectrophotometry with fluxes computed from integrating appropriately normalised Johnson 13-colour photometry for 216 bright stars and found agreement to a standard deviation of 0.55%.

2.2 Determination of temperature variations

Mean stellar temperatures must be determined from spectrophotometry (or many-wavelength-band photometry) over as wide a wavelength range as possible. However, small temperature *differences* may be accurately determined from *changes* in only one or two of the standard Johnson $UBVRI$ or Strömgren uvbyβ colour indices. Such temperature differences are of interest, for instance, in the study of the changes of atmospheric conditions during cycles in pulsating or eclipsing variable stars.

An important factor here is the sensitivity of the colour parameter used as the temperature discriminant. It is easy to show that provided the optimum discriminant is chosen (depending upon the spectral type of the star) colours should be measured to 0.003 to 0.01 mag (0.3–1%) if temperature changes of 1% are to be discerned. For instance, between F0 and K0 stars there is a temperature difference of about 2500K and a difference in $B-V$ of about 0.5 magnitude. Therefore 0.005 mag (0.5% accuracy) corresponds to 25K, or about 1% in temperature. For B stars, $(U-B)$, c_1 or $(u-b)$ are better temperature discriminants, where for a ~1.0 mag change in colour, there is a ~15,000K change in temperature. Here, 0.01 mag corresponds to 150K in temperature, or about 1% on average.

In general it may be true that the Strömgren $(b-y)$, $(u-b)$, c_1 and β values are more readily obtained to such accuracy than are the broad band indices $(U-B)$, $(B-V)$, $(V-R)$, $(R-I)$ and $(V-I)$. However, when only accurate colour *changes* are required (needing only the *slopes* of transformation equations) it is likely that observations of the broad band indices will suffice.

Usually, for bright stars at least and excepting many stars in clusters or in crowded fields, higher accuracy (<1%) is obtained by using a photometer having one or more photomultiplier tubes than by using a CCD. It is not only more accurate but also faster, both for data collection and reduction. With a computer-controlled filter wheel in front of a single photomultiplier tube, bright stars can be measured to two or three millimags in a few minutes through several filters. There are two main advantages to this system. First, fast rotation of the filter wheel enables all filters to be selected for short integration intervals (of about 1s) several times for each 'observation'. The signals through all filters are therefore measured at essentially the same time, which is important at larger air masses and at poorer sites. High precision is often maintained for the colours even through thin cloud, as long as the dwell times are short. A second advantage is that faster measurement means that more frequent observations of comparison or standard stars is feasible.

The procedure is even faster with a photomultiplier tube behind each filter, such as in the photometer used by the Danish observers at ESO (*e.g.* Grønbech & Olsen, 1976 and many later publications). In this case the analysis is more complex since it involves the sensitivity variations of several photomultipliers.

2.3 Low amplitude variable stars and 'millimag' photometry

With low amplitude variable stars such as δ Scuti stars, β Cephei stars and many ellipsoidal binaries, precision differential photometry to a limit of one to three millimag is desirable. For these stars, the variation may be no more than 0.01 to 0.1 mag, often due to more than one period. Such precision has been routinely accomplished by several observers since the δ Scuti and β Cephei work of Michel Breger and the present author independently in the late 1960s and the 1970s (see Shobbrook *et al.*, 1969, where the term 'm.mag' was first coined!).

With small telescopes on which much of the high precision work on bright stars is done, a primary consideration is starlight scintillation. On one night of fairly good seeing on the Siding Spring 16-inch telescope, extended tests showed that 100 successive one-second integrations on α Vir (with over 200,000 counts/sec) gave an r.m.s. scatter of over 0.02 mag. This indicated that integrations of 100s were required to approach 2 mmag precision. Since scintillation decreases approximately linearly with aperture, one does gain significantly by using neutral density filters with larger 1m class telescopes even on very bright stars.

It will not be possible to measure the fractional change in size and shape of variable stars to the same accuracy as that to which we measure the diameter itself. However, for those with short periods we should be able to use differential techniques over one to two hour intervals on each night. Such measurements promise to be of great interest, since the variations will not be spherically symmetric in the case of non-radial pulsations and ellipsoidal variations, and such phenomena have not been directly measured before.

Conclusion

It has been demonstrated that a precision of $\pm 2\%$ in the angular diameters determined by SUSI will require photometry and spectrophotometry of stars to an accuracy of from 1 to 10 millimag. As we can see from discussions in many papers presented at this conference, this precision is certainly attainable, provided that sufficient attention is paid to details of observational procedure and to internal (instrumental) and external (standard star) calibration.

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Discussion

M. Cohen: *Can we request that you remeasure Sirius and, if possible, Vega with SUSI? If you did so what kind of accuracy could you get on these two stars?*

Shobbrook: Sirius has been measured by the SUSI prototype and will soon be measured again by SUSI. We cannot expect a result much better than 1% for temperature, though. Vega is too far north for SUSI's declination limit of $< +30^o$.

E. Budding: *You mentioned that the actual determination of Cepheid diameters was likely to be more complicated in detail than it might, at first sight, seem. I would guess that the assigned stellar limb-darkening, for example, will have a bearing on your derived diameter values, and probably that can be well taken care of, to within your 2% target, by available model atmosphere values. However, what about the role of rotation — in relation to gravity darkening, say, or physical distortion? How will these factors affect things?*

Shobbrook: Limb and gravity darkening theory is known well enough for normal stars to be corrected for, within the 2% accuracy. We shall also be observing at a range of wavelengths, so that such effects will be able to be determined where the effects are large — this is one of SUSI's proposed programmes. Change of shape due to rotation or pulsation can be measured as the star's axis changes its orientation with respect to the baseline during a night.

T.J. Kreidl: *Have you considered that should non-radial pulsations be present in any of the target objects, the geometrical orientation of the pulsation axis will possibly have a large influence on the measured change in angular diameter?*

Shobbrook: The stars change their orientation with respect to SUSI's north/south baseline during the night. Observations over a sufficient number of cycles will enable the change in shape to be determined.

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