A high-resolution Michelson interferometer for the Isaac Newton Telescope

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Received 1977 April 4; in original form 1977 January 27

Summary. This paper describes a Michelson interferometer capable of resolving powers over one million in the visible, at the coude focus of the Isaac Newton Telescope. The advantages of the system over conventional techniques are demonstrated, namely high resolving power plus high luminosity, an adjustable instrumental profile and very accurate wavelength calibration.

1 Introduction

The value of Fourier transform spectrometry in the infrared has been clearly demonstrated by Connes, Maillard, Pinard and Mertz (see the references). They have shown the outstanding feature of the method to be the multiplex gain in signal-to-noise ratio (Fellgett 1951). Detector noise is negligible, however, when the system is used in the visible, and so here the superiority of the method lies in the ease of attainment of high resolution, high luminosity, simultaneous observation of all spectral elements and, in particular, a unique instrumental profile which can be adjusted after observation to the form most suited to the astronomical problems.

Spectrographs and spectrometers currently in use in the visible each have certain advantages and disadvantages which make them best suited to particular problems. For example, the grating spectrograph reaches a maximum resolving power at about $2 \times 10^5$ and the luminosity is then very low because of the narrow input slit; the spectral range covered can, however, be large, and all wavelengths can be observed simultaneously. The PEPSIOS (Hobbs 1965) interferometer is capable of high resolution, which must however, be preselected, and has high luminosity, but suffers from parasitic light and has undesirably long positive wings in its instrumental profile. Wavelength calibration and compensation for scintillation are difficult, and spectral scanning is sequential. In comparison the Michelson interferometer is capable of higher resolving power and has the very desirable property of an instrumental profile which can be optimized after the observation. The wavelength observed can be changed at will over the whole visible, and resolving power chosen during the observation. All spectral elements are recorded simultaneously, but like the PEPSIOS, efficiency is equivalent to that of a sequential scanner so that the spectral bandwidth needs to be limited to the region of immediate interest. Finally, wavelength calibration is more accurate than that in any other system if path-difference is servo-controlled by a laser.
2 Specification for an astronomical instrument

2.1 Astronomical problems

There are many problems to which the properties of the Michelson interferometer are well suited, for example:

The investigation of the already-known interstellar lines and the search for new ones at resolutions higher than those used by Hobbs (1969, 1971a and b, 1972, 1973). Very accurate line profiles and velocity components would be invaluable for the comprehension of interstellar dynamics. Resolving powers greater than $5 \times 10^5$ are necessary for this work.

Accurate stellar line profile studies require resolving powers over $4 \times 10^5$, when for example the line Doppler width is only 17 mÅ, as for solar Fe atoms at $\lambda$ 3860 Å. The true or apparent continuum level may also be depressed by inadequate resolution, see Ring & Stephens (1972).

For stellar work a 10-arcsec aperture on the sky is more than adequate to make use of all the available light.

2.2 Observational feasibility

In view of the weakness of starlight, great emphasis must be placed on conserving light entering the telescope and on efficient detection. The quality of spectra to be expected from the interferometer can be calculated as follows:

If we take Allen’s (1964) value for stellar flux reaching the Earth, and assume 1 mag atmospheric absorption and 30 per cent telescope transmission, then the flux reaching the coudé slit of the Isaac Newton Telescope is $4 \times 10^6$ photon/(Å s) for a 0.0 mag star. Losses through the interferometer, grating post-monochromator, and GaAs photomultipliers reduce this to yield a count of $1.7 \times 10^5$ photoelectron/(Å s).

The interferometer has the efficiency of a sequential scanner so the output signal-to-noise ratio is given by:

$$
\frac{S}{N} = \frac{\lambda_0}{R} \cdot \left( \frac{Fr}{B} \right)^{1/2},
$$

where $\lambda_0$ is the wavelength, $R$ is the resolving power, $F$ is the photoelectron flux per Ångström per second, $t$ is the total observation time, and $B$ is the bandwidth. Fig. 1 illustrates this relationship and shows that for small bandwidths high resolution can be achieved in reasonable times, e.g. a $S/N$ ratio of 50 at $4 \times 10^5$ resolution should be achieved in 120 min on a 3-mag star for a 5 Å bandwidth at $\lambda$ 5000 Å.

2.3 Theory

Fig. 2 illustrates a typical interferometer optical diagram in which there are catseye retroreflectors and a pair of beamsplitters. The output transmitted and reflected beam intensities are then

$$
I_t = \int_{\nu_i}^{\nu_2} S(\nu)\{A + B \cos 2\pi \nu \Delta\} d\nu
$$

and

$$
I_r = \int_{\nu_i}^{\nu_2} S(\nu)\{C - B \cos 2\pi \nu \Delta\} d\nu
$$

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Figure 1. Variation of $S/N \times$ resolving power with bandwidth as function of stellar magnitude.

Figure 2. Typical interferometer optical diagram.

where $A$, $B$ and $C$ are constants and $S(\nu)$ is the incident spectrum. To compensate for scintillation, square-wave internal modulation ('jitter') plus phase-sensitive detection is used. Each interferometer arm then gives two signals, namely

$$I_{t_1} = \alpha k \int_{\nu_i}^{\nu_2} S(\nu)\{A + B \cos 2\pi \nu(\Delta + \delta)\} d\nu, \quad I_{t_2} = \alpha k \int_{\nu_i}^{\nu_2} S(\nu)\{A + B \cos 2\pi \nu(\Delta - \delta)\} d\nu$$

$$I_{r_1} = \beta k \int_{\nu_i}^{\nu_2} S(\nu)\{C - B \cos 2\pi \nu(\Delta + \delta)\} d\nu, \quad I_{r_2} = \beta k \int_{\nu_i}^{\nu_2} S(\nu)\{C - B \cos 2\pi \nu(\Delta - \delta)\} d\nu$$
where $\delta$ is the jitter amplitude, $k$ is the atmospheric transmission factor, and $\alpha$ and $\beta$ are the photomultiplier efficiencies.

These four signal values are used to produce the interferogram which is Fourier-transformed to give the spectrum. An interferogram function which compensates for scintillation is

$$I(\Delta) = \left[ \left( \frac{\alpha}{\beta} (I_{r_1} - I_{r_2}) + (I_{t_1} + I_{t_2}) \right) \right]$$

$$= \left[ \left( 1 + \frac{\beta}{\alpha} \right) \int_{\nu_1}^{\nu_2} S(\nu) \sin 2\pi\nu\delta \sin 2\pi\nu\Delta \, d\nu \right] / \left[ (A + C) \int_{\nu_1}^{\nu_2} S(\nu) \, d\nu \right].$$

Transformation then yields a spectrum $S(\nu) \sin 2\pi\nu\delta$, where the sine term is due to the jitter. It is thus necessary to adjust the jitter amplitude to maximize this term around the wavelength of interest, i.e. $\delta = 1/4\nu$.

It can be shown that the interferogram sampling interval is given by $\Delta_0 = 1/2(\nu_2 - \nu_1)$ in accordance with the restricted sampling theorem (Connes 1966). Now the resolving power is directly proportional to the maximum path difference $\Delta_{\text{max}}$ so that for easy data handling in the on-line mini-computer it is necessary to maximize the step distance $\Delta_0$ by reducing the passband as much as possible. This condition is in agreement with the need to minimize observation time. Generally, the resolving power is taken as $R = 2\Delta_{\text{max}}/\lambda$ so that for a resolving power of one million in the visible the required path difference is 25 cm. This value is equivalent to a halfwidth of the $(\sin x)/x$ instrumental profile of 5 mA. Phase retrieval and apodization of the interferogram can be applied if necessary in the data reduction routine after the observations, to optimize the instrumental profile to a particular observation. By keeping the number of samples to less than 1024, the on-line computer can display the spectrum during the observations so that the operation, resolving power and $S/N$ ratio can be checked continuously.

The luminosity of the instrument determines the physical size of the optics. For example, if the telescope aperture is $D_T$ and the seeing disc on the sky is $\phi_T$, then the necessary interferometer aperture is given by $d = D_T(\phi_T/2)(R/2)^{1/2}$.

3 Practical Interferometer

3.1 Introduction

The specification which we have derived for a high-resolution Michelson interferometer to be used in astronomy in the visible region involves methods at the frontiers of modern technology. For example it requires accurate machining of a Meehanite optical bench, interferometric-quality optics, a high-stability laser and servo-mechanism, digital photoelectron pulse-counting circuitry, and the latest on-line digital computers for fast Fourier transforms and spectrum display. Fig. 3(a) illustrates the general layout of the whole system.

3.2 Mechanical

The interferometer itself consists of a single casting in Meehanite steel which houses all the optical elements — see Fig. 3(b). A monocoque design was chosen because of its compactness, stiffness and stability. The casting is supported on spring strips which help to isolate the catseye from vibrations along its most sensitive axis.

The catseye assembly consists of two retroreflectors fixed back-to-back, in order to reduce catseye displacement and partially compensate for any aberrations caused by wobble.
This assembly moves in an oil film through a honed tube which is straight to within 0.002 in. Maximum optical path difference is 1.5 m, corresponding to a resolving power of 6 million at λ 5000 Å.

Direct-current linear motors on either side of the catseye assembly produce the driving force which, coupled with the viscous damping force, acts on the centre of gravity of the assembly in order to produce no rotational motion, and keep the mechanical response time down.

The reference laser and its detectors are mounted on the casting to eliminate differential movement.

3.3 OPTICS

The interferometer is situated immediately after the coudé slit in the f/32 divergent beam. An air-spaced doublet collimates the beam which enters the main housing, is divided and then directed towards the catseye retroreflectors by flats. The catseyes return laterally-displaced beams to the recombining mirror where interference occurs. The transmitted and reflected output beams are then reflected on to the diffraction grating for post-dispersion. Camera doublet lenses focus the chosen part of the spectrum on to the output slits. The wavelength of the passband is altered by means of a grating stepping motor, at about three steps per Ångström. The grating (PTR) has 1800 l/mm, blazed at 5000 Å, so that a typical 5-arcsec stellar image yields a triangular passband of halfwidth 5 Å. Post-dispersion means that it will be possible to add an array of detectors for multichannel operation in the future, i.e. many lines could be measured simultaneously for no additional telescope time.

Location of the required passband is achieved with the use of known line sources and accurate offsetting of the grating.

A narrow laser beam passes through the centre of the wide signal beam and is separated from it just before the grating.

All interferometric optical components, i.e. silica beamsplitters, catseyes and flats, are of high quality (λ/20) so that good fringe contrast is ensured. The catseyes are f/2.5 confocal systems with 6-in diameter paraboloid primaries of 15 in focal length, and ¾ in diameter spherical concave secondaries of 30 in radius of curvature.

Internal modulation 'jitter' is achieved by affixing one of the catseye secondary mirrors to a piezo-electric ceramic tube. A square-wave voltage applied to this produces the change

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Figure 3. (a) General flowchart of Michelson interferometer system. (b) General layout of interferometer. (c) Servo control and sampling logic module, with peripherals.
GENERAL LAYOUT OF INTERFEROMETER

Figure 3(b)
in optical path difference. The other catseye secondary mirror is mounted on a similar
device and is the active element of the auxiliary fast servo-mechanism.

A wide spectral range (4000–8600 Å) has been achieved on the basic interferometer by
using silver coatings, silica beamsplitters and GaAs photomultipliers (RCA C31034A).

3.4 ELECTRONICS

A servo-control and sampling module has been produced – see Fig. 3(c). Standard CAMAC
(Euratom 1969) modules are employed as scalers, pulse generator, interrupt request register,
preset counter, crate and controller. An interface unit, between the CAMAC system and the
original Interdata model 5 and later model 70 computer, was designed and produced
especially for the interferometer. Other instruments can be easily be run by computer via the
CAMAC crate as long as they employ CAMAC-compatible circuitry at the ports of any special
modules.

Control of the catseye movement and sampling is shared between the servo-control
module and the on-line computer.

The step-by-step mode of interferometer operation is best applied to weak signal sources
since the signal integration time needs to be much longer than the catseye movement time,
for efficiency. When a small waveband is being studied, the stepping interval – typically
several hundred laser fringes – takes about half a second to traverse.

The response time of the main second-order servo-mechanism is limited to about 10 ms
by the mass/linear-motor-force ratio. This is too long to eliminate acoustical and vibrational
pick-up effectively, so that a fast auxiliary servo, using the catseye secondary mirror on a
piezo-electric element, was developed. The third-order servo component nullifies any
constant forces, which tend to displace the catseye from the proper position.

3.5 COMPUTATION FOR CONTROL AND DATA REDUCTION

An Interdata 70 computer has been chosen for operating the interferometer under the
control of Interactive FORTRAN programs. The main merits of this system are: ease of pro-
gramming, high-speed processing for on-line spectrum display, disc and magnetic tape
storage, versatility for use with other instruments, and low cost. During development of the
interferometer when updating was a daily event, great savings in time and effort resulted
from the use of the interactive programs. Many test programs have been written for checking
the interferometer operation in detail.

After calling the programs from the disc, operation is relatively simple. For example, once
the waveband to be studied has been fixed and the catseye stepping interval computed with
the standard program, it is only necessary to call the operating program, locate the zero
path difference position, and type some factors on the teletype, namely direction and speed
of catseye, step distance, number of steps and number of photoelectrons to be integrated
per sample.

On receipt of these values the computer assumes complete control and the stepping and
sampling continue for the requisite number of times. At any instant the scan may be stopped
if a fault is evident from the current interferogram and spectrum display, or weather
conditions deteriorate. Intermittent cloud is no problem on bright stars since the system
waits until the requisite number of photons are counted before moving the catseye.

When the interferometer scan is complete the stored signal arrays are immediately put
on to magnetic tape for safe-keeping and later reduction. The program is then recalled for
another run to be added to the first. It is usually better to sum several fast scans, rather than do one slow scan, in case of unforeseen curtailment.

A typical scan consists of 512 samples which are transformed on line, by means of the Cooley–Tukey Fast Fourier Transform routine, into 256 spectral elements. This is adequate during the observations although a spectrum of 1024 or more elements may be displayed during later data reduction. The transformation may take up to 5 s on-line so that updating is done at intervals of 10 or more samples depending on the source brightness. Photoelectric events are of course being counted during the transformation and display routine.

Much work was originally done using the system without phase information so that only the power spectrum could be displayed during the recording; the phase and proper spectrum were then computed on a larger computer the next day. However, it is now possible to locate the zero path difference position under computer control and start the catsye from there, so that the sine Fourier transform spectrum with its inherent resolution is displayed on-line. The interpolated spectra for different instrumental profiles may then be drawn on an x–y plotter the next day.

4 Problems and tests

Michelson interferometry is, in general, a rather difficult though valuable technique, and when applied to the visible in an observatory environment, problems arise. Some of the methods developed for this instrument, and tests derived to confirm the theory and proper operation, will be described in the following sections.

4.1 PHASE RETRIEVAL

Phase error arises when there is no accurate way of determining the zero path difference position so that no interferogram sample coincides with this position (Connes 1970). It is then necessary to take a few samples to one side of zero path difference and the majority of samples the other side, then compute a new set of samples at the proper position before doing the sine Fourier transform. However, when observing stellar sources with a small pass-band and restricted sampling it is very difficult indeed to determine the phase error by the standard techniques because of limited S/N ratio.

We have found that it is not really necessary to know the exact phase as long as photon shot noise is the main source of spectral error. First of all, interpolation at intervals of about \( \lambda_{\text{mean}} \) is done on the measured interferogram around zero path difference where the modulation depth is much larger than the noise level. This produces an envelope containing up to 5000 points and it remains to find its effective centre of gravity, which is bound to be close to zero path difference. A level is set (say 20 per cent of the maximum value), and the number of points, \( k \), with amplitude greater than this is found. Then starting from one end, the \( k/2 \) point abscissa is taken as the approximate zero-path position. By changing the level in steps from 20 to 60 per cent, 40 different values are produced and can be averaged. The resultant abscissa is taken as being within \( \lambda/4 \) of zero path difference and the interferogram value is then calculated. Fine interpolation is then used to locate the accurate zero path difference position so that the phase error of the original samples is known. Because of photon noise in the samples, the determined phase value may lie an integral number of wavelengths from the proper value, causing the final interferogram to be incorrectly displaced by this distance. However, the net effect is to introduce a small amount of phase error which can be negligible relative to photon shot noise. By summing several fast scans this error can be reduced further.
4.2 INSTRUMENTAL PROFILE

After the interferogram has been phase-corrected, if necessary, it is possible to apply various types of apodization to optimize the instrumental profile for the particular spectrum in hand. The unique feature of the Michelson interferometer is the natural \((\sin x) / x\) instrumental profile with its alternating negative and positive side-lobes. Ring & Stephens (1972) computed that this causes much less filling-in of absorption lines than the profile of a grating, and we have since confirmed it on astronomical and test source data. This effect is directly equivalent to a substantial increase in resolution for no extra cost in observing time, in comparison with sequential scanners of the grating or PEPSIOS interferometric types. For instance, let a Gaussian absorption line of zero residual intensity be convolved with a Gaussian grating profile, a PEPSIOS (Airy function)\(^3\) profile, and a \((\sin x / x)\) profile, each being on the same half-width as the absorption line: then the line centre will be filled in to a depth of 31, 42 and 9 per cent respectively. Thus the spectral line is much less distorted by the \((\sin x / x)\) profile and therefore, to produce a similar amount of distortion the grating and PEPSIOS resolving powers would have to be increased by a factor of 3 or 4 at least.

4.3 WAVELENGTH CALIBRATION

The interferogram sampling interval is very accurately determined by the laser-controlled servo-mechanism so that the passband extremities are given by \(\lambda_1 = (2m \lambda_L) / (2p + 1)\), and \(\lambda_2 = (m \lambda_L) / p\), where \(m\) is the number of laser fringes per step, \(\lambda_L\) is the laser wavelength and \(p\) is an integer called the alias number. Hence all spectral wavelengths are directly referred to the laser wavelength which can be known to 1 part in \(10^7\). Correction for dispersion by the air in the interferometer is necessary at present, so it may be more accurate in the future to add a known absorption line to one end of the spectrum during the observations.

4.4 CHOICE OF INTERFEROGRAM

The interferogram formula quoted in Section 2.3 can be used to compensate for scintillation when the detector efficiencies are constant and the two output passbands are identical. However, for the times that this is not the case there is another interferogram formula which

![Figure 4. Stellar image diffuser, showing caustic curves due to a particular part of the input image. Adequate diffusion when pipe length is greater than 'image f/No x pipe width x 2/3'.](image-url)
compensates for detector drift as well as scintillation, and treats the passbands separately, namely

\[ I_t(\Delta) = \frac{(I_{t_1} - I_{t_2})}{(I_{t_1} + I_{t_2})} = \left[ -\int_{\nu_1}^{\nu_2} S(\nu) \sin 2\pi\nu\delta \sin 2\pi\nu\Delta \, d\nu \right] / \left[ A \int_{\nu_1}^{\nu_2} S(\nu) \, d\nu \right] \]

\[ I_r(\Delta) = \frac{(I_{r_1} - I_{r_2})}{(I_{r_1} + I_{r_2})} = \left[ \int_{\nu_1}^{\nu_2} S(\nu) \sin 2\pi\nu\delta \sin 2\pi\nu\Delta \, d\nu \right] / \left[ C \int_{\nu_1}^{\nu_2} S(\nu) \, d\nu \right] . \]

Figure 5. (a) (i) $^{198}$Hg isotope lamp at $\lambda$ 5461 A; resolving power = 10^4. (ii) Cd lamp at $\lambda$ 5086 A; resolving power = 5 x 10^4. (b) Test for repeatability. $I_r$ absorption cell at resolving power of 250 000. (c) White-light interferograms at $\lambda$ 5890 A for sampling intervals of 8 and 12 laser fringes.
There is no occurrence of detector efficiencies in these formulae as long as the internal modulation amplitude is accurately set equal to a quarter of the mean passband wavelength. Spectra resulting from these independent interferograms can be summed, after allowing for different noise levels, by weighting according to the individual S/N ratios, i.e.

\[ S(\nu) = S_r(\nu) \times (S/N)_r^2 + S_t(\nu) \times (S/N)_t^2 \]

where

\[ S_r(\nu) = F.T. [I_r(\Delta)] \quad \text{and} \quad S_t(\nu) = F.T. [-I_t(\Delta)]. \]

F.T. = Fourier Transform.

![Figure 6. Playback of summed spectra of ε Cyg around λ 5195 Å, to show increase in resolving power up to 250,000 as a function of number of samples. Sample number: (a) 8, (b) 16, (c) 32, (d) 64, (e) 128, (f) 256, (g) 512. The final spectrum after normalization is shown in (h).](https://academic.oup.com/mnras/article-abstract/181/2/131/988740)
4.5 System Noise

Besides needing the on-line computer for immediate spectrum display, we have found it invaluable for general diagnosis of faults. For example, by sampling a white-light-source interferogram at large optical path difference where only photon shot noise prevails, the detector system can be checked by standard deviation calculations. Similarly, phase changes in the interferometer due to air turbulence within the catseyes can be measured by sampling a white-light interferogram around zero path difference. We found that this air movement
made the spectrum unacceptably noisy if the optical path length of the servo laser beam slowly varied by only a few Ångströms from the optical path length of the signal beam. Enclosing the interferometer in a sealed box and keeping the air and box at a slightly higher temperature than the interferometer effectively removed this source of noise.

Noise is also introduced by variation in the shape of the stellar image on the input aperture, since a constant optical passband is essential for the interferometer and that of the post-monochromator is governed by the input and output slit profiles. A simple light pipe was therefore introduced to smear the image into a more uniform patch of constant size and the same focal ratio. Fig. 4 illustrates this image diffuser, designed such that any point of the input image is smeared to cover a patch of up to 5-arcsec square at the output aperture. Silvered internal walls ensure efficient reflection at near grazing incidence. It is still
important to keep the stellar image on the centre of the input aperture by accurate guiding, for complete effectiveness. An autoguider has been developed which detects the stellar image on the TV slit viewing system monitor and then corrects the telescope to better than ±0.2 arcsec.

4.6 STANDARD TESTS

Full-length scans of test sources are made before and after a night's observation, to confirm correct operation of the whole system. Fig. 5(a) illustrates the λ 5461Å line of a ¹⁹⁸Hg
isotope lamp at a resolving power of one million and the λ 5086 Å line of a Cd lamp at half a million resolving power. After making this type of scan the post-monochromator is stepped to the waveband of interest, then two consecutive scans of an absorption cell are done to check repeatability, see Fig. 5(b) for example. A final test which may reveal optical misalignment and systematic noise involves the oversampling of the white light source to produce a lissajou pattern representing an anti-symmetrical interferograms, see Fig. 5(c).

5 Astronomy

Use of the interferometer has been confined to problems in astronomy which cannot be done better or at all by other types of instruments. Much effort has been spent on achieving the proper instrumental profile, and efficient operation, in view of the cost of telescope time. Typical investigations are outlined in Section 2.1 and others could easily be proposed.

The increase in resolving power with sample number is illustrated in Fig. 6 for e Cyg around λ 5195 Å. This series of spectra is an average of seven faster scans which were individually √7 times noisier, but it is otherwise the same as is seen on-line during the observation. By recording a white-light spectrum or better still an early-type stellar spectrum before and after the observations, the effect of the gratings profile can be removed. Fig. 7 shows the resultant normalized spectrum of e Cyg in greater detail, compared with Griffin’s Arcturus Atlas (Griffin 1968). Total observing time for this 10 Å passband was 6 hr on a night of 2.5 m_0 absorption. A similar passband of day sky spectrum is illustrated in Fig. 8, where the Solar Atlas by Delbouille, Roland & Neven (1973) is shown also for comparison. Total observing time for this 10 Å passband of 5 (arcsec)^2 of sky was 4 hr.

A high-resolution spectrum of Arcturus at λ 5890 Å is shown in Fig. 9 (total observing time 2 hr for 10 Å passband). The saturated telluric water vapour lines, completely resolved with a typical FWHM of 0.05 Å, serve as excellent confirmation of system performance for radial velocity measurement. Finally, Fig. 10 depicts the [OIII] line at λ 5007 Å of two planetary nebulae for which only medium resolving power is required.

Acknowledgments

The authors would like to thank the Science Research Council for their continued support of this project; in particular, RCW is very grateful for the Research Fellowship and Research Assistantship appointments which have made this work possible. Several discussions with Professor P. Connes at Laboratoire Aimé-Cotton were very productive and greatly appreciated. On the computing side, the assistance of C. Stephens, J. Truch, A. Begg, N. Vine and I. Wynne-Jones at Imperial College, and Drs K. Hartley, D. King and C. Amos at the Royal Greenwich Observatory is gratefully acknowledged. Considerable workshop support from J. Crabtree is recorded with thanks. In addition, we thank the Director of the RGO (Professor F. G. Smith) and the Isaac Newton Telescope manager (P. Willmoth) for their support.

Finally, it is with great pleasure that RCW acknowledges advice from Professor W. H. McCrea and Dr R. H. C. Newton, who originally directed him towards a career in astronomy.

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