

UBV PHOTOMETRY OF
CLOSE VISUAL DOUBLE STARS
USING AN AREA SCANNER

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To

the people of South Africa

this thesis is dedicated.

May we live together in peace

in a free and open society.

The members of binary systems may fairly be regarded as contemporaneous. Their origin was in common; their destinies are indissoluble; they are identically circumstanced; they must be similarly composed. They should then be exceptionally trustworthy guides to the unravelment of evolutionary time-relations.

Agnes Clerke (1903).

ABSTRACT

A computer-controlled area scanner designed for use on close visual double stars is described. Techniques used in making observations and in subsequent reduction of the data are given. Problems encountered are discussed. Magnitude differences and magnitudes and colours of components are given for 153 bright southern close visual doubles. Separations are given for some of the stars. Absolute magnitudes are calculated for the primaries by several methods. Individual stars are discussed where appropriate. The accuracy of the results is discussed. No significant systematic errors are evident in the results but systematic errors are present in the results of other authors. Suggestions are made for the future use of conventional photometers, scanners and other techniques in the field of visual double star photometry and astrometry.

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CHAPTER 1INTRODUCTION

For many years there has been much interest in double stars because of their bearing on theories of stellar evolution. Visual double stars are particularly useful because they offer us the opportunity of studying component stars separately thus enabling comparison of the physical properties of stars which are at approximately equal distances from the earth and which were probably formed at the same time from similar material. Many studies have been made using visual double stars. Three recent studies are those by Stephenson and Sanwal (1969), Mechler (1976) and Meisel (1968). Meisel lists many earlier studies and others are mentioned in later chapters of this thesis. There has been a decrease in activity in the field of astrometry of visual doubles and not much work is being done in spectroscopy and photometry of visual doubles. Basic data are lacking for many visual doubles, especially those in the southern hemisphere.

This thesis describes an area scanner built specifically to make (differential) photometric observations of close visual doubles (roughly in the range 0.5 - 15 arcsecs) but which can yield astrometric information also. The scanner has been used to obtain magnitude differences on the UBV system for a sample of bright stars and hence, via a knowledge of the combined light photometry, the UBV magnitudes and colours of these stars. As a by-product separations have been measured for some of the stars.

Chapter 2 reviews the methods used in the field of visual double star astrometry and photometry with particular emphasis on area scanners and on photometry obtained for close visual doubles. Chapter 3 describes the area scanner used. A key feature of the scanner is a mini-computer which is used to control the scanning action, data gathering, data display and data output. Scanning is achieved by wobbling a quartz plate in the convergent light beam just before the focus thus moving a portion of the image plane across a slit. Light passing through the slit is measured by a fast pulse-counting system. Chapter 4 describes the techniques used to make observations of double stars using the scanner. Chapter 5 gives more details about certain sections of the scanner.

Chapter 6 describes how the magnitude differences and separations were obtained from the raw data. An asymmetric fitting function derived from that given by Franz (1973) was used. Complications occurred because the shift of the image is not linearly dependent on the angle of rotation of the wobble plate. A relatively sophisticated fitting program had to be used because the fitting problem was not well-behaved. In Chapter 7 we describe how the magnitude differences and separations were analysed to obtain the final magnitudes, colours and separations given in Table I (Chapter 9). Chapter 8 describes combined light photometry which was done for stars for which no published combined light photometry was available. Chapter 9 contains Table I in which the final results are given for 145 bright stars and 8 fainter stars. Some of the stars are discussed in remarks and notes. In Chapter 10 we compare absolute magnitudes obtained for the primary stars by various methods and discuss many of the individual stars. In Chapter 11 we discuss the accuracy of

our results and of those of other authors. It appears that systematic errors are present in the magnitude differences obtained by several of the other authors.

Chapter 12 recommends improvements to our area scanner and suggests future work to be done with the scanner, with conventional photometers and by other techniques.

CHAPTER 2A SURVEY OF OBSERVATIONAL METHODS IN
VISUAL DOUBLE STAR WORK

A very brief survey of observational procedures has recently been given by Franz (1973). Visual methods used in astrometric and photometric work have been adequately described elsewhere, for example in I.A.U. Symposium 17 (Lippincott 1962) and by Wallenquist (1954). Other methods are described below with the emphasis placed on photometric methods.

Multiple exposure photography of doubles using the Hertzsprung (1920) method yields good astrometric and photometric (magnitude difference) results (Kooreman 1946, Wieth-Knudsen 1957, van Albada 1958, Thé 1970, Thé 1975, Strand 1969, Josties et al. 1974). Unfortunately almost all observations have been made in the photovisual. No extensive series of observations have been made in any other system which can be compared with photoelectric work and no reliable measures of colours have been obtained. The Hertzsprung method is used mainly on stars wider than about 2 arcsecs apart as systematic errors occur for closer stars. Strand (1969) discusses the accuracy of his and other measures of magnitude difference at some length. We discuss these measures in Chapter 11.

Electronographic cameras have been used to take multiple exposures of doubles with separations in the range 0.5 - 8.0 arcsecs. Separations, position angles and magnitude differences can be measured (Ables et al. 1970, Laques et al. 1971, Despiau and Laques 1972). The internal errors in the separations and magnitude differences obtained are 0.01 -

0.03 arcsec, $0.03^m - 0.10^m$ respectively. The separations and magnitude differences are deduced from profiles obtained from the photographs using a scanning technique with a microdensitometer. These profiles look very much like the ones we obtain (see Section 6.11). This technique seems promising although the errors in the magnitude differences may be rather high (partly due to local inhomogeneities in the photocathode) and the reduction procedure tedious. Magnitude differences can be measured in various photometric systems using suitable filters and transformations. This has been attempted by Despiau and Laques (1972) for the UBV system. We have compared their $\Delta m(V)$ results with Δm results in the catalogue of Wierzbinski (1969) and find that there is no significant systematic error and that the external errors are about equal to the internal errors quoted by Despiau and Laques. (However see Section 11.3 for comments on Wierzbinski's catalogue). Fredrick (1960) has taken short exposure photographs of doubles using an image intensifying tube.

The use of TV equipment in double star work has recently been described. Blazit et al. (1975) use an interferometric technique which can resolve stars of separations down to about 0.05 arcsecs. They hope the technique will enable interferometric observations to be made on stars down to 15^m or fainter. Dommaget (1975) uses the TV camera as a high-speed camera so as to minimize seeing effects. As the technique for data reduction should be similar to that used on electronographic camera photographs and the range of magnitudes, magnitude differences and separations also similar, and in view of the cost differential, it will be interesting to compare the accuracy and convenience of the two methods.

Interferometers have been used primarily for astrometric rather than photometric work. Construction and use of the Mount Wilson Michelson type interferometer has been described by Anderson (1920) and Jeffers (1945). For many years an eyepiece interferometer was used by Finsen (Finsen 1951, 1954, 1964, 1971) for visual observations on very close doubles. Finsen (1971) has reviewed double-star interferometry. Other interferometers have been built for use on double stars in recent years. Several different approaches have been followed. Some authors in this field are Elliot and Glass (1970), Wickes and Dicke (1973, 1974), Wickes (1975a, 1975b). Breckinridge (1974) and Currie et al. (1974) have also described instruments using amplitude interferometry. Wickes (1975b) has used his technique to obtain separations and position angles for three Hyades visual binaries and shows that the measures have small errors and are compatible with those obtained by classical visual methods. The stellar intensity interferometer at Narrabri has been used to measure the semi-major axis of γ^2 Vel (Hanbury Brown et al. 1970) and other bright stars. Twiss (1965) described work on a Michelson stellar interferometer which it was hoped would be complementary to the Narrabri instrument and would measure separations down to 0.01 arcsecs or less using a baseline of 30 - 100 metres. Labeyrie (1975) has obtained interference fringes from Vega using two small telescopes 12 metres apart.

The technique of speckle interferometry is based on the fact that seeing degraded stellar images of the order of seconds of arc wide are formed by the rapid motion of tiny images of size near the diffraction limit of the telescope. This can be seen on long focus, very short

exposure photographs (Texereau 1964, Irwin 1975). A group at Stony Brook, New York, has used an image tube camera system to take such photographs of bright stars. The photographs are optically analysed to obtain the Fourier transform. Angular diameters of single stars and separations and position angles of doubles have been published (see Labeyrie et al. 1974). Angular separations of down to $0''.049$ have been measured fairly accurately. Magnitude difference estimates are very rough. Separations of stars with magnitude differences as large as 3 or 4 magnitudes can be measured. Nisenson et al. (1974) have described a speckle interferometer which does not record the images on film. Worden (1976) has described digital reduction of speckle photographs. This seems to be a very promising technique for astrometric measures of bright stars with very close, nearly equal, components.

Instruments involving rotating wheels ('choppers') in the focal plane of the telescope have been suggested and built. Bacchus (1959) built an instrument using a rotating grill in an attempt to measure separations, position angles and magnitude differences of doubles. Villamediana and Fredrick (1971) tried a rotating Ronchi grating whereas Curott and Hegyi (1971) used radial slits on their wheel. An early result on μ Cas by Hegyi and Curott (1970) did not look very reliable but the instrument has recently been improved (Curott and Atwood 1974) and used to measure a magnitude difference and separation for Ross 614 (Atwood and Curott 1975). Image dissectors might also be used for observing double stars although they may not be very suitable. Dissectors are described by Hoag et al. (1971) and Tiffit (1972).

Various workers have used conventional photoelectric photometers to do UBV or uvby photometry of the components of visual doubles without correcting for contamination. UBV photometry has been done on components of doubles as close as 4 arcsec by Eggen (1963, 1966a). Wayman (1962) made UBV measures of the components of visual doubles, correcting for scattered light by measuring the background light in suitable places. His technique was otherwise conventional. Several of his stars have separations 7-12 arcsecs. Tolbert (1964) has made similar corrections to his UBV measures of stars of about 25 arcsec separation. Breckinridge and Kron (1964) obtained R, R-I measures of the components of close visual doubles. They measured magnitude differences using a small circular aperture, deliberately excluding the light in the wings of each image, and not correcting for scattered light. R and R-I values were deduced from these magnitude differences and combined light measures of the stars.

Smak (1966) observed CE Cas by a scanning technique using the fine motion in RA and with the edge of a circular diaphragm used as a knife-edge. Andrews and Thackeray (1973) measured the fainter components of some close visual doubles by slowly trailing the double star images across a small aperture and recording a trace on a Brown recorder. Budding and Kitamura (1974) observed the eclipsing binary YY Gem (Castor C) by scanning in declination on a 36 inch telescope.

Wallenquist (1954) tried moving double star images (in and out of focus) across small diaphragms placed in the light path, estimating magnitude differences from galvanometer readings. He suggested use of a narrow slit. Henroteau (1940a, 1940b) suggested use of a rapidly

oscillating slit in a complicated instrument designed for use on double stars. Fritze (1963) made a theoretical investigation of the likely accuracy of magnitude differences measured by moving a slit or a knife-edge over the image of a double star in the focal plane. To test his theory he made a few observations of ϵ_1 Lyrae (2.85 arcsecs, $\Delta m \approx 1.1^m$), moving the image across a knife-edge in the focal plane by rotating a plane parallel glass plate in the converging light beam. He found that the internal error of his observations agreed with his theory.

The first area scanner proper was developed by Rakos at Lowell specifically for observing eclipses of Martian satellites. This prototype scanner has been described (Rakos 1965). It used an oscillating 45° mirror to move the image across a slit of adjustable width and length. The light which passed through the slit was measured by a pulse-counting system with the output recorded on tape and displayed on an oscilloscope as a plot of intensity versus position. Franz (1966) used this instrument to test the effectiveness of the area scanning technique as applied to photometry and astrometry of double stars. Franz gives details of the simple analysis methods used to obtain magnitude differences, separations and position angles during these tests. The results were surprisingly good.

Later scanners built at Lowell (Franz 1970) and by Rakos (1970) make use of oscillating slits in the focal plane. The slit oscillations are controlled by a cam arrangement and driven by a stepping motor. Both the Franz and Rakos scanners use multi-channel analysers to sum and store the pulse counts for the channels corresponding to the various positions of the slit as the scans proceed. Høg (1971) has built a scanner which, like the one we describe (see Chapter 3), uses a mini-computer

in the data capture process and can operate in other modes as well as the area scanning mode. Høg's scanner has 3 parallel focal plane slits, 50 microns apart, each followed by a photomultiplier-pulse amplifier system. The image is oscillated across the 3 slits by rocking a double mirror in the converging light beam. The optic axis is shifted sideways by the double mirror, the amount of the shift being slightly altered during the scanning process by the rocking of the mirror.

Rakos, Franz and Høg all establish which is the first data channel of each scan by using triggers occurring at fixed positions in the scanning cycle. They add channel one of each successive scan to the sum for channel one obtained from all the preceding scans. Neglecting tracking errors this means that each channel essentially contains information on the light from a certain small area of sky whose position with respect to the components of the double varies due to motion of the stellar images. As this image motion has a frequency component similar to the scanning frequency the channels at which the centres of the images of the components are scanned will vary leading to broadening of the profiles in the summed scan. This leads to a loss of resolution. We have used (see Section 3.4.2) a cross-correlation technique for minimising the effect of image motion. Rakos (1974a) has used a different approach. He has attempted to improve the resolution of his scanner by using a compound slit. In this arrangement the two sections of the slit are perpendicular. The scanning is done with the slit alignment and motion such that the images of the two components of the double star are crossed simultaneously by one section of the slit whereas in another part of the scan the other section of the slit crosses first one and then the other component. By this

scheme the image profile corresponding to a single star is obtained simultaneously with the profile of the double star which is assumed to consist of two profiles (of different heights) of the same shape as the pseudo-single star profile. This enables reasonably accurate magnitude differences to be found, for fairly small magnitude differences at least, in cases for which the seeing disc is of size comparable to the separation of the components. For these cases scanning with an ordinary slit and analysis by the normal method (see Section 6.1), which fits parameters describing the shape of the profile simultaneously with those describing the magnitude difference and separation, would not yield reliable results. In his paper Rakos gives as an example an observation, made on a 150 cm telescope, of a 0.68 arcsec double with nearly equal components. A Fourier transform technique could be tried for estimating the magnitude difference in the analysis of the simultaneously obtained double star and pseudo-single star profiles. This method is described by Dicks and van Rooyen (1973).

The development of arrays of photosensitive cells should make possible true, two-dimensional, area photometry. Nather (1972c) has suggested a 10 x 10 array which could be used to observe double stars as well as stars in nebulosity and faint stars.

Both the Rakos and Franz scanners have been used to make large numbers of observations of double stars as well as various other observations. Scanners of the Rakos type have also been used by several other workers. Only scattered results have so far been published. Franz and Millis (1971) used the area scanner to search for anomalous brightening of Io after eclipse by Jupiter. Price et al. (1971, 1972) have

used the scanner for observing eclipses of the Galilean satellites. Scanning has also been used in conjunction with other techniques at Lowell. Boyce (1966) has used scanning with a spectrophotometer and Boyce and Albrecht (1973) used this scanner for observations of Mars. Hall (1968) has described a scanning polarimeter which has been used (Hall and Riley 1968, Riley and Hall 1972) for polarization work on Mars, Jupiter and the moon. Results of observations on variable visual double stars have been published by Franz's group (Franz, Millis and White 1971, Franz 1972, Franz and White 1973). Dürbeck (1972) has made various exploratory observations of double stars, a globular cluster, several galaxies and the planets. Clements and Herman (1974) have described a method of removing the blurring effects arising from seeing and from instrumental sources so as to recover the original intensity distribution of an extended source. They list other authors who have observed extended objects and illustrate their technique as applied to observations of Saturn and its rings. Rakos (1972) has shown that his scanner can give consistent results for magnitude differences and separations of visual doubles with no systematic errors. Lohsen (1975) used a Rakos scanner to observe the eclipsing binary BM Ori in the Trapezium. Three of the other bright stars in the Trapezium were included in the scans so as to be used as comparison stars. During the observations it was discovered that θ^1 Ori A is also an eclipsing binary. Rakos (1974b) has measured Sirius B using an area scanner and a special reduction technique. Rakos's result has been criticized by Lindenblad (1975) who suggests that a diffraction ray from Sirius A probably upset Rakos's estimations of the background (scattered) light. It is unfortunate that Rakos does not report the number of observations made on each of the two nights for which he

gives UBV photometry of Sirius B. Neither does he give any indication of the scatter of the observations on each of the nights. However the fact that the B magnitudes quoted for the two nights differ by 0.60^m whereas the V, U magnitudes differ by 0.29^m , 0.34^m respectively suggests that the sixth order polynomial used to describe the scattered light curve does not correctly estimate the scattered light under the profile of Sirius B, the error being worst for B because there was probably the most scattered light in this colour.

CHAPTER 3EQUIPMENT3.1 Introduction

The area scanner forms part of the U.C.T. mini-computer controlled photometry system. The system has been used for high-speed photometry (Warner 1975), observations of lunar occultations (Harwood et al. 1975) and spectrum scanning (Walker 1976a, Walker 1976b). The author did not design or construct any of the equipment except for a few minor parts.

3.2 Description of the photometer

The photometer is used at the Cassegrain focus. It is of modular construction and consists of an offset guider, a turntable, a filter box and a photomultiplier tube module. The sections are bolted together allowing rapid changing of modules. The offset guider, filter box and photomultiplier tube module are common to all configurations. The turntable can be replaced by a spacer module for high speed photometry work and a different spacer module is used in addition to the turntable for the spectrum scanner. The photometer as used in the area scanning mode is schematically illustrated in Figure 1.

The offset guider has a movable 45° mirror which reflects the incoming light towards a wide angle Erfle eyepiece. A system of baffles is used to enable this eyepiece to be moved in both horizontal and vertical directions. The horizontal travel is about 70 mm and the vertical travel about 100 mm. The eyepiece is normally set at the centre of the

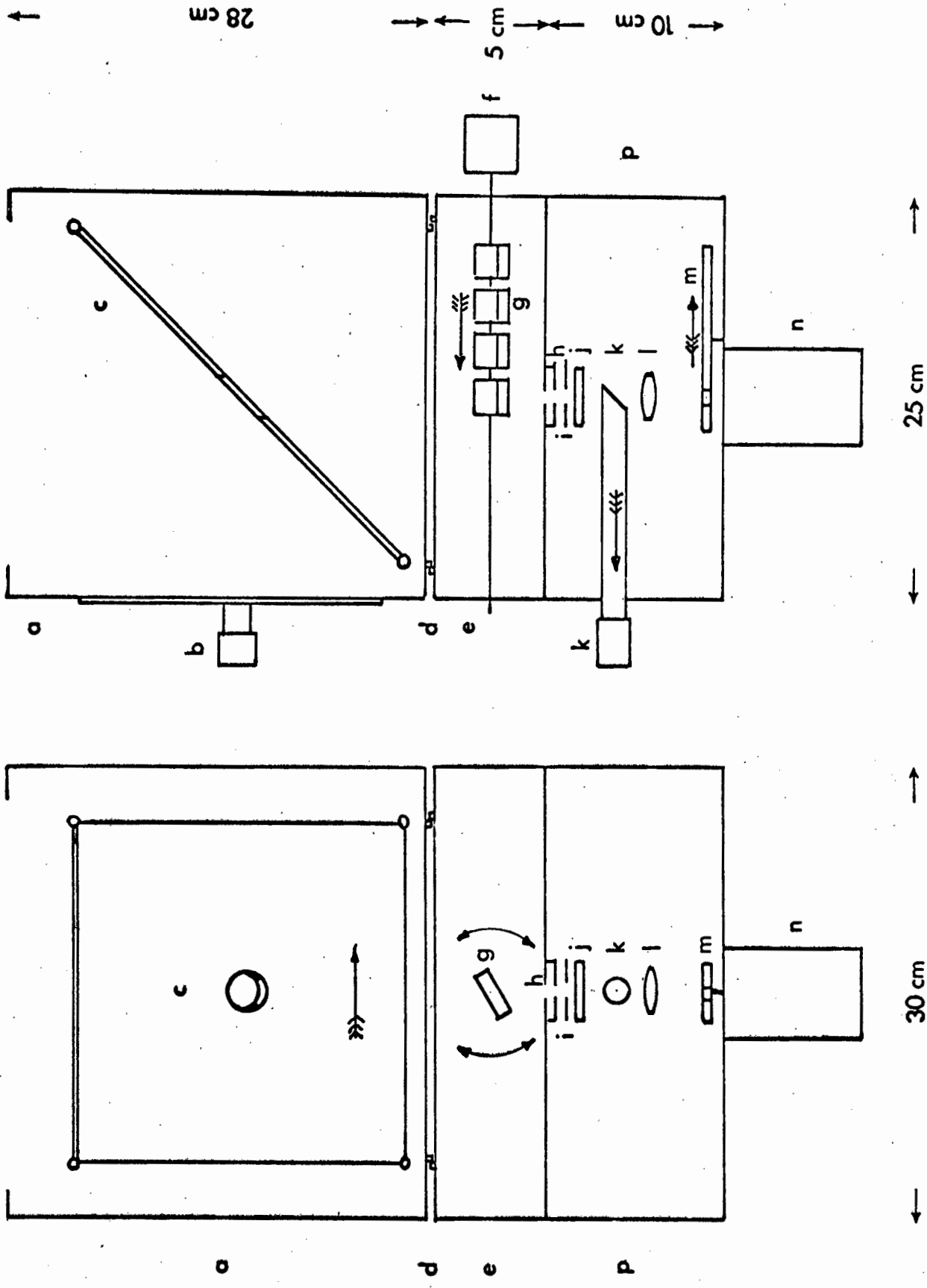


Figure 1. Schematic diagram showing front view (on the left) and side view (on the right) of the photometer as used for area scanning. Parts of the photometer are (a) offset guider (b) Erfle eyepiece (c) 45° mirror (d) bearing (e) turntable module (f) stepping motor (g) wobble plate and transmission grating (h) aperture slide (i) iris diaphragm (j) neutral filter holder (k) periscope eyepiece (l) Fabry lens (m) filter wheel (n) photomultiplier tube (p) filter box.

juel

field while operating in the area scanner mode. Once the required star has been centred in the field using the Erfle eyepiece the 45° mirror is moved so that the light from the central portion of the field passes through a hole in the mirror and into the turntable module.

The turntable module contains a transmission grating for use in the spectrum scanner mode and two "wobble plates". A "wobble plate" is a piece of optical quality quartz or fused silica with polished flat surfaces. The grating and the plates are mounted on a shaft which is at right angles to the optic axis. The desired grating or wobble plate or a clear aperture can be selected by moving a slide along the shaft. The shaft can be rotated by a Computer Devices Miniangle Motor Model 23H-05C which is geared to the shaft. This motor is driven by a Computer Devices Rapid Syn Driver Model M43020-12. 5 Volt logic pulses for the driver are supplied by the controlling mini-computer (see Section 3.3). A battery charger in parallel with a car battery forms a stabilized 12V power supply for the driver.

The light passing through a wobble plate is refracted by an amount depending on the angle of incidence on the plate, the thickness of the plate and its refractive index. The sideways displacement of the beam is non-linearly dependent on angle of incidence (see Section 6.2). The shaft, motor etcetera are in the portion of the turntable module beneath the bearings which allow the lower modules of the photometer to be rotated about the optic axis. There is a locking device so that these modules can be locked at any desired angle of rotation. There is however no circle for reading the angle of rotation. Field illumination is supplied by light diodes mounted at the bottom of the turntable module.

The focal plane aperture slide is mounted at the top of the filter box module. The distance between the wobble plate and the aperture slide is about 40 mm. On the slide there is a range of circular apertures and slits. The length of a slit can be limited using an iris diaphragm immediately below the aperture slide. In the area scanning mode the wobble plate is rotated to and fro through an angle of about 60° (30° on either side of the position where the plate is perpendicular to the light beam) thus moving a portion of the image of the field under observation to and fro across a suitable slit. The wobble plates and slits are aligned so that the motion of the image is at right angles to the slits.

Beneath the iris diaphragm there is provision for inserting a neutral filter. The apertures and slits are viewed using a periscope and a zoom eyepiece. The periscope slides in to a position underneath the neutral filter holder. A fused silica Fabry lens and a 6 position filter wheel are situated in the lower part of the module. The filter wheel can be rotated by a SLO-SYN HS25 stepping motor. In area scanner operation the filters are manually selected.

Various photomultiplier tubes can be used (see Section 5.5). Each is mounted inside a cylindrical brass or aluminium casing which is fixed onto an aluminium plate to form a module which can then be bolted onto the bottom of the filter box. A dark slide is incorporated in each case. None of our tubes are cooled. The tubes are used in a pulse counting mode with an SSR Model 1120 pulse amplifier/discriminator fixed onto the photometer very close to the tube so that the lead from the tube to the input of the amplifier is less than 100 mm long. The SSR Model 1120 has an adjustable discriminator and produces short unitized (about -1,5

Volts) pulses. The dead time is 25 ns - 50 ns in the amplifiers used by us. The pulses from the output of the amplifier are sent to the computer.

More details about certain crucial parts of the photometer are given in Chapter 5.

3.3 The mini-computer and ancillaries

The core of the photometry system is the Data General NOVA 1200 mini-computer. The use of a NOVA 1200 in a similar system has been described in a paper by Nather and Warner (1971). An interface board mounted in the computer contains two digital counters, logic to process externally supplied 1 KHz timing pulses and logic to control a CRT display. Nather (1972a, 1972b) has described the design and construction of such an interface board. The timing pulses are supplied by a Patek Philippe GN 4Z 24E quartz crystal clock. A Tektronix 604 Monitor which has a 130 x 100 mm screen is used for visual display of the data. Suitable 10 bit digital/analogue converters, mounted on the rear of the monitor, are used. A Teletype ASR 33 is used for input/output. The programs are read in on 1 inch paper tape and the data punched on 1 inch paper tape and printed on the typewriter. The keyboard is not used in the area scanning mode but it is used in other modes. The NOVA 1200 has 16 front panel sense switches which can be examined during execution of a program.

3.4 The ASHCAN program

The scanning process is controlled by the computer using a program called ASHCAN which was written in ASSEMBLER language by

R. E. Nather in 1972. Programming techniques are described by Nather and Warner (1971) and by Nather (1972b). The interrupt facility which permits parts of a program to be executed at regular intervals is central to the programming philosophy. When the interrupt is activated (by the externally supplied timing pulses) the instruction being executed is completed, the address of the next instruction stored and control transferred to another address. After the appropriate task has been performed control is transferred back to the stored address and the program continues.

During area scanning the ASHCAN program controls the stepping of the motor, the counting of the pulses from the photomultiplier tube, the visual display of the incoming data and the accumulation and storage of these data. The starting and stopping of the stepping action and of the data accumulation as well as the selection of various options in the program is done via the front panel sense switches on the computer. The ASHCAN program is described below. A description of the function of the various switches is given in the operating instructions for the program in Appendix 1. The program is used with 8K of memory.

3.4.1 The scanning action

The stepping motor (and its attached load) requires a short acceleration period before it reaches constant speed. It also requires a deceleration period and a settling time at each reversal of rotation direction. Using a step interval of 2 ms (the shortest convenient interval consistent with reliable operation of the motor) the acceleration is achieved by lengthening the interval between the first and second step by 1 ms to 3 ms. The deceleration is done similarly and 5 ms is allowed for the

motor to settle before the acceleration in the reverse direction is begun.

Before scanning is started the wobble plate is set "flat" (i. e. perpendicular to the optic axis) by the observer. Scanning begins when the correct sense switch is put up. The stepping motor is initially driven 61 steps in one direction. The motor is then accelerated in the reverse direction as previously explained and stepped 120 steps at 2 ms per step before being stopped again. The image in the focal plane is thus swept across the slit. If the data capture switch is up then the pulses arriving at the computer from the photomultiplier via the amplifier are counted by one of the digital counters during each 2 ms interval. At the end of an interval the total number of counts for the interval is transferred to an appropriate storage area. We thus obtain a 120 bin record of the intensity distribution across an area of the focal plane. After the settling time has elapsed the rotation direction of the motor is reversed and the acceleration step, 120 data-recording steps and deceleration step are made in the new direction. At each reversal of direction allowance is made for backlash in the gears between the motor and the wobble plate shaft by inserting extra steps before the 120 data-recording steps. The number of such steps is a program variable, the "backlash constant", which can be altered by the observer when necessary. The first 120 data-recording steps are called by us the "forward scan", the second 120 such steps the "return scan". The word "scan" is also loosely used to mean the total counts in each of the 120 bins corresponding to a scan. The forward and return scans continue at nearly 4 scans per second as long as the sense switch controlling the motor is up. When this sense switch is put down the motor completes the current cycle and then parks at the central position (i. e.

with the wobble plate "flat"). Data recording is stopped by putting the data-recording switch down before the motor is stopped.

3.4.2 The summing of the scans

The scans can be summed by the program in two ways. One way is bin-wise addition of the bin totals for each scan to the sums of the bin totals for the previous scans as soon as the scan is completely i. e. add total in bin 1 of latest scan to the sum of the totals in bin 1 for all previous scans etc. For several reasons this option of the program was not normally used. It was found impossible to estimate the backlash constant accurately and, furthermore, the actual backlash was not quite constant. This means that the scans do not necessarily cover the same piece of sky. Thus the bin number corresponding, for example, to the centre of a star image may vary slightly from scan to scan. If the telescope tracking is not very accurate the field being scanned will drift appreciably during an observation. The component of this motion in the direction perpendicular to the slit will cause a systematic change in the bin number corresponding to any feature in the scan. On some nights the image motion is sufficient to cause a small scan-to-scan shift in the bin number corresponding to the centre of a star image.

All the above reasons made it desirable to use the other summing method for which the program makes provision. Under this option each incoming scan is compared with the sum of all previous scans (called the "accumulated scan") before being added to it. A correlation function is calculated by multiplying the totals for like-numbered bins in the accumulated scan and in the latest scan and adding the products. The

totals (counts per bin) for the incoming scan are then shifted one bin and the correlation function is calculated again. Once the direction has been found which increases the value of the correlation function then the procedure is repeated, shifting one bin at a time, until the function value starts to decrease. The number of bins shifted in order to get the maximum value of the correlation function is stored and the bin totals for the incoming scan are shifted by this number of bins before being added to the accumulated scan. The maximum shift is set at 16 bins. For scans after the first two the search for a maximum begins with a shift equal to the last shift found. If no maximum of the correlation function is found at a shift of less than 16 bins or if no maximum is found in the time available then the scan is rejected. This implies that if the backlash constant differs by more than about 20 steps from the actual backlash then only the forward scans will be added whereas if a large tracking error occurs then none of the scans will be added until the telescope is reset. The shifting before adding means that the bins on each end of the accumulated scan will not always receive an increment when a scan is added. For example if a scan gives the maximum correlation with the accumulated scan when it is shifted so that bin 1 corresponds to bin 7 of the accumulated scan then the first 6 bins of the accumulated scan will have zero added to them when the latest scan is added. Thus 16 bins on each end of the accumulated scan are potentially deficient in counts when this option is used and they are therefore not used in calculating the correlation function.

In order to allow for scans where the total number of counts in each bin is so small that the noise in these totals makes use of the

correlation option unreliable another option is available. Under this option a constant number of forward scans and, separately, the same number of return scans are summed without correlation or shifting before being added to the accumulated scan using the correlation procedure.

3.4.3 The display

The number (say N) of scans added before correlation and the total number of scans currently accumulated are displayed alphanumerically at the top of the display screen. The rest of the screen is used to display a plot of the latest completed N forward scans (on the left) and one of the latest completed N return scans (on the right). An option allows the mean scan (the accumulated scan divided by the number of scans accumulated) to be displayed on the right hand side of the screen in place of the return scan. The display is "refreshed" often enough to avoid flickering.

On the plots of the scans a light dot is displayed for every bin, bin numbers increasing to the right on the X axis and counts per bin increasing up the Y axis. A 256 point resolution is used on the bin number axis so some space can be left between the left and the right hand plots. A 1024 ($=2^{10}$) point resolution is used on the counts/bin axis. The NOVA has 16 bit words. Ordinarily the 10 most significant bits are transferred to the 10 bit register used by the display routines in the program to determine the Y coordinates of each displayed point. However since the counts/bin totals are usually very much less than 2^{16} the plots tend to be squashed up on the X axis. An option therefore allows less significant bits to be displayed. Each on/off action of a certain sense switch causes a 1 bit shift so after 6 shifts the least significant 10 bits are being displayed.

In order to allow for a still greater multiplication of the plot size 4 more shifts are allowed, the least significant bit in the Y display register being zero filled after each shift. Thus after scaling by a factor of 2^{10} we have a $2^6 = 64$ point resolution, with 63 being the full-scale value. As the screen is marked with a half-inch grid, there being 8 intervals on the Y axis, it is easy to estimate the number of counts in a bin in the individual or accumulated scans at any stage. This is useful as it allows the observer to monitor the data accumulation fairly closely. He can, for example, estimate the number of counts in the bin corresponding to the centre of the image of the secondary and use this in deciding when to stop the data accumulation (see Section 4.3). In the bit shifting process described above a non-zero bit may be shifted out of the most significant end of the register. This is not detected so that the point concerned appears on the screen as far from the bottom of the screen as it should be above the top. This "wrap around" feature is useful as it enables greater magnification to be used to view smaller features without losing the highest points on the plot altogether.

3.4.4 Data output

Output is controlled by one of the sense switches. When this switch is put up the accumulated scan is transferred to a buffer in memory. Printing and punching of the contents of this buffer is then begun automatically. Data collection should be stopped before the output sequence is begun. However, because of the use of the buffer, a new accumulated scan can be begun while output is in progress. Output is done via the ASR33 typewriter and tape punch. The number of scans

added together before correlation, the total number of scans accumulated and then the total counts in each of the 120 bins are typed and punched. Punching is done in ASCII code. Only 7 bits are used, the parity bit being omitted so as to save time. Typewriter carriage return and line feed characters are punched. Output of one accumulated scan takes about 100 seconds. This is comparable with the minimum time needed to accumulate sufficient scans on a bright star. It is planned to output data to magnetic tape instead of using the Teletype. This will prevent the output time from influencing the time needed to make a complete observation of a star.

CHAPTER 4MAKING THE OBSERVATIONS4.1 Introduction

The ease with which the photometer can be altered from one mode of operation to another makes it possible to make observations of various types on the same night. It normally takes about 30 minutes to change modes. The scanner can therefore be used during gaps between occultations or high speed photometry mode observing. Since the scanner can give good results under non-photometric conditions provided the seeing is good (see Section 4.4) we can frequently use observing time which would be wasted by other photometric observers.

4.2 Preparing to observe

The ASHCAN program is read into the computer and execution started. One of the two wobble plates is placed in the light beam at right angles to it (i. e. angle of incidence is zero). The aligning is done by eye using marks on the visible portion of the shaft. The power to the stepping motor is then switched on thus locking the shaft.

With the aperture-viewing eyepiece in position the telescope is focussed in the ordinary way on a suitable star, usually one of the doubles on the observing list. Then one of the focal plane slits is moved into position so that the star image is on or near it. The viewing eyepiece periscope is then withdrawn, the plate is wobbled and the data recording started. Plots of the forward and return scans are displayed on the screen. It is normally found that the peaks on the plots corresponding to the

images of the stars in the focal plane can be made sharper by further small adjustments to the focus. This is probably partly due to the slits not being in exactly the same plane as the circular apertures. Focussing is discussed further in Section 5.6. Once a satisfactory focus has been obtained the backlash constant (see Section 3.4.1) must be checked. If the features on the forward and return scans are displaced relative to one another (i.e. the features appear at different bin numbers) then the backlash constant is wrong. The backlash can be most easily checked by displaying the return scan and the mean accumulated scan, alternatively in rapid succession, on the right hand side of the screen (see Section 3.4.3). Since the accumulated scan is based on the first forward scan any observed displacement of features between the reverse and mean accumulated scans indicates a displacement between the forward and reverse scans. If a displacement is evident the number of bins by which the features are displaced must be estimated. The program is then stopped and a suitably altered value of the backlash constant inserted in the correct memory location using the control switches on the front panel of the NOVA. The program is restarted and the checking procedure is repeated until no displacement is evident.

4.3 Observing a double star

The wobble plate motion is stopped during acquisition of a star. The slits are moved out of the light beam and a circular aperture inserted centrally. The star is located and roughly centred using the Erfle eyepiece of the offset guider. The lower parts of the photometer are then rotated until the line between the two components of the double, as seen

through the viewing eyepiece, is parallel to the bottom plate of the filter box. This is generally referred to as the horizontal position. There are two advantages in aligning the stars this way - the images cross the slit at the same point thus avoiding errors in the magnitude differences caused by a non-parallel sided slit and the separation of the components can be measured. The components are centred in the circular aperture before it is replaced by a slit, usually the narrowest available. The slit is usually positioned so that it lies between the images of the two components. This is easy to do as the light from all but the faintest stars can be seen through the slit. The wobbling and data recording are then started.

If the peaks due to the two stars are far from symmetrically placed with respect to the central channel of the displayed scan then the slit or telescope is moved slightly until they are reasonably symmetrically placed and data recording begun again.

If the separation between the components is large the peaks may be too far apart on the scan. In this context too far apart means more than about 60 bins apart. If the peaks are further apart than this they will be badly defined because they will encroach on the 16 bins on either end of the scan which suffer losses (see Sections 3.4.2, 6.9 and 6.11). If the thinner of the wobble plates is being used the peaks can be brought closer together on the scan by changing to the thicker plate. Otherwise the turntable can be rotated so that the line joining the two components makes an angle with the "horizontal" and hence less than a 90° angle with the slit. The component of the separation at right angles to the slit is therefore decreased and the peaks on the scan appear closer together. The advantages of "horizontal" scanning are then lost.

It sometimes happens that the first forward scan is a very poor shape. This results in the accumulated scan having a poor shape too and, although this will eventually improve, it is worthwhile stopping and restarting the data recording, if necessary several times, until a reasonable first scan is obtained.

If the components are so faint that the individual scans do not have a recognisable hump corresponding to the position of one of the components then the option under which several scans are added before correlation is used (see Section 3.4.2), 4 or 8 scans being usually added. However the use of the option is avoided where possible as the peaks in the accumulated scan are broader than they would normally be.

Scanning is continued until a reasonably smooth plot is obtained for the accumulated scan. In most cases there is a perceptible peak due to the secondary and it is this peak that should be used in deciding when enough scans have been made. A rough calculation of the number of counts in the central bin of the secondary peak in the accumulated scan can be made since we know the total number of scans accumulated and the scale being used on the display screen and we can estimate the height of the peak on the plot of the mean scan. The scanning can be stopped when some arbitrary number (e.g. 10000 implying a noise level of about 1 per cent if noise is equal to $\sqrt{\text{counts}}$) of counts is reached in this particular bin. It has been found however that the gain in accuracy achieved by continuing the scanning after the peaks appear smooth does not justify the extra time taken. In cases where the secondary is so faint or so close to the primary that it does not show a distinct peak on the displayed plot it is advisable to estimate the number of counts in the central bin

of the secondary "peak" using an estimate of the number of counts in the central bin of the primary peak and a previous estimate of the magnitude difference.

Once sufficient scans have been made the data recording is stopped and the output started. The filter is changed and data recording begun again. This procedure is continued until an accumulated scan has been obtained using each of the three filters. Sometimes extra accumulated scans are obtained with one or more of the filters. On brighter stars with small magnitude differences sufficient scans are sometimes made before the output of the previous accumulated scan is completed. This is not a serious problem as the extra time used is less than a minute.

We record in an observing log a sequence number, the star name, the ordering of the filters used, the thickness of the wobble plate used, and whether the star was observed horizontally or not. Comments on cloud, seeing, the wind, equipment status and malfunctions and the like are also recorded. Sometimes the time, sidereal time, hour angle or zenith angle is recorded.

4.4 Observational considerations

In practice observations were only attempted when the seeing was better than about 3 arcsecs. Many of the observations were made in good seeing (1 to $1\frac{1}{2}$ arcsecs), many more in very good seeing ($\frac{1}{2}$ to 1 arcsecs), and a few in exceptionally good seeing (less than $\frac{1}{2}$ arcsec). Normally the components appeared more clearly separated as viewed through the eyepiece than they did on the displayed scans. There are at least two reasons for this. Firstly the eye sees the edge of the seeing disc at a position where the intensity is in fact still 10 or 20

per cent of the intensity at the centre of the image. Secondly the slits used in the scanner are quite wide (see Section 5.4) so the peaks in the scans are broadened relative to their separation.

It did not happen frequently that bad seeing alone prevented the use of the scanner. Records kept at Sutherland during 17 months in 1972-3 showed that about two-thirds of all usable nights had seeing less than or about two arcsecs (Harding 1974). We were able to observe through thin cloud or haze on many occasions. It frequently happened that the seeing was very good ($\frac{1}{2}$ - 1 arcsec) when there was thin cirrus in the sky. Serkowski (1970) and Honeycutt (1971) have shown that clouds are nearly neutral absorbers. Serkowski obtained $d(U-B)/dV$ and $d(B-V)/dV$ equal to -0.007 for cumulus and stratocumulus clouds with drops of about 6 microns in size and even smaller colour changes for clouds with larger drops. Honeycutt obtained smaller changes than Serkowski. These changes in colour are very small. We have assumed the components of a double to be equally affected by extinction due to cloud. This is reasonable as we essentially measure the components simultaneously through nearly identical cloud. Our magnitude differences are therefore not corrected in any way for the presence of clouds. In practice we found that we could make observations through cloud provided the seeing was good, the image motion small, and the extinction not greater than about 3 magnitudes and not too rapidly varying. Very few observations were actually made with extinction greater than about half a magnitude but many were made with extinction of one or two tenths of a magnitude.

Since we are concerned with measuring magnitude difference and separations of close (visual) double stars we do not have to be very

painstaking in our observational procedure. In particular we do not attempt to observe all doubles at equal altitude. In fact we do not usually record the zenith angle of our observations and make no corrections for atmospheric extinction. We assume that the components of a double suffer identical atmospheric extinction over the bandpass of any filter. In this case the magnitude differences in V, B, and U are not affected by extinction. There are however second order effects so that for a double consisting of stars of very different colours observed at a very large zenith angle errors of a few hundredths might occur. In practice we very seldom observed at zenith angles greater than 45 degrees.

The photomultiplier tube-pulse amplifier/discriminator system was tested at high count rates in order to determine coincidence losses. For an amplifier built by R.E. Nather losses became significant at much less than 10^6 counts per second but for the SSR Model 1120's significant losses only started at about 10^6 counts per second (see Section 5.5). In our observations the maximum count rate occurs when the image of the primary star is centred on the slit. Normally much less than all the light in the star image passes through the slit because the width of the seeing disk is greater than the slit (see Section 5.4). Thus the maximum count rate for most stars is relatively low and coincidence losses are not a problem. For very bright stars the telescope dome was used as an aperture stop in order to keep the count rate down. In future neutral filters will be used. Coincidence losses would be expected to cause relatively flat topped peaks for bright primary stars. No definite occurrence of coincidence losses has ever been detected in this way. However it should be pointed out that it would be hard to detect this effect. Coincidence losses would

depress the magnitude difference of a double below its true value. Since the magnitude difference deduced from an accumulated scan is obtained using the total counts in at least 88 of the 120 bins (see Chapter 6) and not just the bins containing the highest totals it would be in error by very much less than the error of the highest point would suggest should coincidence losses occur. So only a very small systematic decrease in the magnitude differences might be expected. This would again be hard to detect.

Almost all the observations so far have been made with the viewing eyepiece on the south side of the telescope (between east and west). This means that for most stars the turntable was always rotated in such a way that the same component appeared on the left of the scan as displayed on the screen. In the case of stars observed "non-horizontally" the same component was usually "higher" up the slit (as viewed through the eyepiece). Practical difficulties in observing with the eyepiece on the north dictated this policy. It would have been better to have observed each star twice per night, with the turntable in two positions 180° apart. This would have decreased the possibilities of systematic errors. It would have nearly halved the number of stars observed per night. However it is possible this last result would have been compensated for to some extent in that it would probably not have been necessary to observe each star on so many nights.

It was found difficult to guide the telescopes during scanning. If a tracking error occurred we frequently stopped the data recording and, if sufficient scans had not been accumulated, began again.

It was found that an observation of a star (U, B and V) normally took 12 to 15 minutes. At least 300 scans (about 4 scans per second) were usually made with each filter. Faint stars required more scans and observations on stars with a faint companion took up to about 30 minutes. Usually this was because of insufficient counts in the U band. Sometimes over 2000 scans were made with the U filter in position. An appreciable amount of time is spent setting on the star's position, locating the star and positioning it relative to a slit. As stated earlier (Section 3.4.4) slowness of output sometimes caused small delays. It is our opinion that no really worthwhile speeding up of our observations is possible in the case of bright stars. However for faint stars observations with a larger telescope would be faster.

4.5 Comments on seeing

The use of the area scanner is of course very dependent on the seeing. Scanners make good seeing monitors and it has been suggested that they be used in studies of seeing. In our system the visual display of every scan (or every second scan) enables us to maintain a close watch on seeing conditions. However we have not attempted any analysis of the seeing. We therefore confine our comments to a few general remarks.

Since we used our scanner on intermediate size telescopes we suffered from the effects of seeing proper (the size of the seeing disc) as well as image motion and scintillation. Changes in transmission were also noticeable. We found that the size of the seeing disc was often highly variable during a single night. Seeing was sometimes very patchy over

the sky but usually was worse at greater zenith angles. We also found that the seeing disc tended to be larger for U than for B or V. We sometimes had to stop scanning a star because of a sudden change in the size of the image discs. We often noticed apparently coherent image motion for our program stars whereas we seldom suspected appreciable differential motion. This is not surprising since most of our stars had separations of 2-10 arcsecs. Rakos (see Franz 1971) had tried scanning at 20 scans per second (as opposed to our 4 scans per second) and finds that the image motion between scans is then negligible.

Scintillation is very noticeable on our displayed scans because counts are recorded for only 2 ms in each bin with the whole scan taking only $\frac{1}{4}$ second. The scintillation and scintillation frequencies seemed to be highly variable. Unfortunately we did not take any photographs of scans displayed on our screen so we cannot illustrate typical cases of scintillation. A very poor picture of successive individual scans which shows the effects of image motion and scintillation is given by Rakos (1970). Scintillation was very occasionally a serious problem in that there would not always be a peak on the scan and we could therefore not trust our correlation process (see Section 3.4.2).

We frequently find that the successive individual scans show great variations in appearance due to scintillation, image motion and rapid changes in the size of the seeing disc. It would therefore seem possible to greatly improve the resolution of an area scanner by using only a suitable selection of the scans made. This has been previously suggested (see Franz 1971). It is however very difficult to know how to select the "best" scans especially for stars with large magnitude difference. We have

seen scans where a companion several magnitudes fainter than the primary has given a peak of nearly equal height. There is a great danger of introducing a systematic error when rejecting the apparently poorer scans. One might expect the separations to be measured too small and the magnitude differences either too large or too small depending on the criterion used for selecting/rejecting scans. After the observations here published (Chapter 9) were completed experiments were started (by others) to develop criteria for on-line selection of scans by our scanner. These experiments have not yet been concluded.

CHAPTER 5HARDWARE DETAILS AND CALIBRATIONS5.1 The wobble plates and their gearing to the motor

Originally only a 3.00 mm thick, 30 mm diameter, quartz wobble plate was used. This was mounted alone on a shaft to which the stepping motor was connected by a 4:1 gearing. The gears used were of the pick band type. Later a 5.00 mm thick, 25 mm diameter, fused silica plate was obtained and the two plates and a transmission grating (see Section 3.2) were mounted on a shaft to which the motor was connected by a 4.032:1 gearing. Here the gearing consisted of a worm and toothed wheels. Both the original and the later gear systems had backlash.

The stepping motor used to wobble the plates made 200 steps per revolution. The rotation of the wobble plate shaft was thus 0.45 degrees per step for the 4:1 gearing and slightly less for the 4.032:1 gearings and the maximum rotation was about 27 degrees.

In order to calculate the bin positions (see Section 6.2) for the passbands corresponding to the various filters, values of the refractive index n were required. It was assumed that the effective wavelengths of the filters were as follows:

U	3600	Angstroms
B	4400	Angstroms
V	5500	Angstroms

Values of n were found by interpolation in tables given by Allen (1963).

The positions of the bins were then calculated (using formula [6.2]) in arbitrary units as explained in Section 6.2. In the fitting program only the positions for the 3.00 mm wobble plate and the 4:1 gearing were used (see Section 6.2).

5.2 The scale factors

The fitting program gives the separation between the components of a star in the arbitrary units. The scale factor needed to convert these units into arcsecs depends on the wobble plate and gearing used and on the image scale of the telescope used. The scale factor should depend very little on the filter used as an attempt has been made to remove this dependence by using different bin positions for the fitting of the scans made with the various filters. Tests showed that for the 3 mm plate with 4:1 gearing any dependence of the scale factor on the filter was entirely negligible and for the 3 and 5 mm plates with 4.032:1 gearing it was very small, less than 0.5%. (These tests were done by summing, separately for each filter, the fitted separations in arbitrary units for a number of observations). The residual dependence found for the 4.032:1 gearing probably occurs because the way the positions of the bins for this gearing change from filter to filter is actually slightly different from that in which the positions change for the 3 mm plate with 4:1 gearing.

In practice the same scale factor was used for all filters for a particular wobble plate, gearing and telescope (see Section 7.5). There are two methods by which this factor can be obtained.

One method is to observe stars of known separation. The scale factor is then obtained by comparing the known separation in arcsecs with the fitted separation in arbitrary units. This was in fact done. Stars whose separations had been measured photographically at Lembang (van Albada 1958, Thé 1970) or by Luck (1972) were chosen as standard stars for this purpose. 32 stars were actually used. These were well scattered in right ascension and declination. Care was taken to ensure that none

of the stars used had separations which were changing appreciably. 12 of the stars were common to the lists of van Albada and Luck, the differences between the results of the two authors being negligible. Many of the standard stars were bright stars already on the observing list so large numbers of additional observations were not necessary. Those present in Table I are marked by an asterisk.

The second method involves establishing the image scale of each telescope by some other method and using the relation between our arbitrary units and the image motion in mm. (This relation is 1 unit = 0.00300 mm for the 3 mm wobble plate and 4:1 gearing). This method was tried. With the telescope drive stopped the time taken for a star image to pass across a large circular focal-plane aperture of known diameter was accurately measured using another program available in the photometry system. This was done at various declinations using the 50 cm telescope. The result obtained agreed well with the appropriate factor as obtained by the first method. This method was awkward and time-consuming and it was felt that it would be safer to use factors determined in the scanner program itself rather than externally to it. The first method was therefore used in practice. This also meant that the scale factor was in fact continuously monitored during observations. This was fortuitous as it enabled us to detect malfunctioning of the equipment (see Section 7.4). The program used to calculate the scale factors is described in Section 7.2.

5.3 The slits

For a large proportion of the observations a slit constructed from two razor blades was used. This was easy to make and long-lasting.

The width of this slit was varied several times. Most of the time it was about 35 microns wide. Two disadvantages of using a razor blade slit are the difficulty in making the edges exactly parallel and the small bumps on the edges. The slit was examined under a microscope from time to time to ensure that no gross non-uniformities in the width occurred.

For several hundred observations slits made by depositing aluminium on a piece of fused silica were used. A number of pieces of fine nylon of different thicknesses were stretched across the silica plate. Aluminium was deposited on the plate in a vacuum chamber in such a way that the nylon shielded the surface underneath it. The narrow slits produced in this way were of very uniform width but slits of about 100 microns were not very good. Slits of width in the range 20-35 microns were used in practice. Unfortunately these "aluminized" slits deteriorated rapidly. They were also relatively hard to make. Franz (1970) used slits made in a similar way using tungsten wire.

Exhaustive tests to determine whether magnitude differences were significantly affected by the use of slits whose sides were possibly not quite parallel were not conducted. Such tests would have been very difficult to conduct as there were so many other possible sources of error. However most of the stars were scanned in the "horizontal" position (see Section 4.3) in which the images of the components cross the slit at the same point. For stars whose separation was too great to allow horizontal observation the separation between the points where the star images crossed the slit was not very great so large differences in effective slit width should not have occurred. However, since the observations on a given double were usually made with the components in roughly the same

orientation, there is a possibility of small errors (a few hundredths of a magnitude) occurring in the measured magnitude differences of some of the wider stars. It is unlikely that these errors would cause a significant error in the V magnitude difference result for a particular star as most stars were observed using several different slits. The colours of the components would not be affected at all. A systematic error in the V magnitude differences as a whole is even more unlikely as the errors would be randomly positive and negative.

5.4 The relation between slit width, bin spacing and seeing

Our slits were between 1.5 and 4 times as wide as the bin spacing depending on the wobble plate and slit used. The slit width in arcsecs depends on the telescope image scale as well as the slit width in microns and varied from ~ 0.3 to ~ 0.8 arcsecs for the slits used. The bin spacing in arcsecs depends on the telescope image scale, the wobble plate thickness and refractive index and the step size (see Section 6.2). Our bin spacings varied from ~ 0.10 to ~ 0.25 arcsecs. Thus except in very good seeing the full width at half intensity of the image of a star was greater than the slit width which in turn was greater than the bin spacing. The peaks in the plots of the scan were very narrow with FWHM as little as 5 bins in the case of exceptionally good seeing. See, for example, Figure 8.

If we had used wider slits we would have made more efficient use of the light and cut the time needed for each observation slightly (perhaps considerably in the case of faint stars). However the resolution of the instrument would have suffered. Wider slits result in more overlapping

in the profiles and consequently larger errors in the fitted magnitude differences and more cases in which a reliable fit cannot be obtained. For wide faint stars of small magnitude difference wider slits would be an advantage. On some occasions of very good seeing we would have preferred to use a narrower slit than the narrowest available at the time in order to obtain better resolution of very close stars. We had difficulty in making good slits narrower than about 20 microns. The size of the image formed by the telescope at best focus and the impracticability of achieving this best focus with our instrument will limit the usefulness of really narrow slits.

In order to make the best use of the instrument we planned to have a choice of several slit widths available at any time. In practice however this was not often the case. It should be mentioned that using different slit widths on the same night causes complications in the analysis of the relative magnitudes (see Sections 6.6 and 7.2).

5.5 The filters, photomultiplier tubes and pulse-amplifiers

Two different sets of UBV filters were used. For the first few observations (only about 35) a set of filters as specified by Johnson and Morgan (1951) was used. For the overwhelming majority of the observations Schott filters supplied by Dr. A.W.J. Cousins were used. The U filter is Schott UG2 glass.

Three different photomultiplier tubes were used. These were an Amperex 56 DVP (S11 photocathode), an RCA 4516 (S11 photocathode) and an RCA 8644. The RCA 8644 is a red-sensitive tube (S20 photocathode) and was used by way of experiment and very few observations were made with it.

It was found that using the 8644 magnitude differences in R could be obtained but that the red leak in U made it impossible to obtain magnitude differences in U. Differences in U could probably be obtained using a suitable blocking filter. All the tubes used have quartz windows.

The tubes were not cooled but had low dark counts (of order 100 per sec), the 56 DVP being particularly good in this respect. Ambient temperatures were mostly in the range 0-15°C. Low dark counts are not critically important for the area scanner because the dark count merely contributes to the background which is usually dominated by the contribution from background light in the sky (particularly if there is a bright moon).

Standard stars were observed in the conventional way in order to obtain the colour equations for the various combinations of filters and tubes. It was noted that the quartz and fused silica wobble plates were nearly neutral. The 4516 tube was run at two different voltages. No account was taken of possible minor variations of the colour equations with time or with telescope used. Five different sets of colour equations were obtained. Using U, B and V for the UBV system and u, b and y for the instrumental system the colour equations were:

Combination 1: Johnson filters and 56 DVP tube at 1800 Volts.

$$V = y - 0.11 (b - y)$$

$$B - V = 1.17 (b - y)$$

$$U - B = (u - b) - 0.08 (b - y)$$

Combination 2: Schott filters and 56 DVP tube at 1800 Volts.

$$V = y - 0.03 (b - y)$$

$$B - V = 1.025 (b - y)$$

$$U - B = u - b$$

Combination 3: Schott filters and 4516 tube at 1500 Volts.

$$V = y - 0.05 (b - y)$$

$$B - V = 0.99 (b - y)$$

$$U - B = (u - b) + 0.04 (b - y)$$

Combination 4: Schott filters and 4516 tube at 1800 Volts.

$$V = y - 0.04 (b - y)$$

$$B - V = 0.98 (b - y)$$

$$U - B = (u - b) + 0.08 (b - y)$$

Combination 5: Schott filters and 8644 tube at 1800 Volts.

$$V = y + 0.175 (b - y)$$

$$B - V = 0.81 (b - y)$$

A very high proportion of the observations were made using Combination 2 i.e. the Cousins-recommended filters and the 56 DVP tube at -1800V supplied EHT (-1700 Volts at photocathode). The colour equations were not frequently checked. There is thus the possibility that changes in the colour equations caused significant errors in the corrected magnitude differences for stars with components of very different colours (see Section 7.6).

During a single scan the count rate may change by a factor of 1000 in less than 100 ms. The tubes were not specifically checked for linearity over a wide range of count rates or for possible spurious pulses occurring after the maximum irradiation of the photocathode. However it seems very unlikely that any abnormal tube response occurred.

A pulse-amplifier built by R.E. Nather was used on only 3 nights. An SSR Model 1120 amplifier/discriminator (see Section 3.2) was used on all other nights. Several different 1120's were actually used. For the amplifier built by Nather coincidence losses occurred at a rather low

count rate whereas for the Model 1120's losses only became significant at about 10^6 Hz.

5.6 Some consequences of the use of a wobble plate

The telescopes used by us have a focal ratio of about $f/15$. Consequently the converging light cone near the focus has a small semi-angle and the defocussing caused by the passage of the light through the wobble plate is slight. In addition the displacement of the position of best focus which occurs when the wobble plate is inserted is small. Dispersion due to the wide range of wavelengths of the light passed by any of the filters is also small. Taken together these effects result in a slight widening of the peaks in the profiles. This widening is undetectable because it is equivalent to a slight deterioration in seeing.

The surfaces of the wobble plates should be kept clean so as to minimize reflection. Light losses are obviously undesirable but internal reflections are a serious problem. Light which undergoes an even number of internal reflections before emerging from the wobble plate parallel to the main beam results in further images of the components of the doubles. These images cross the slit during the scanning process. The first of these internal reflection images has been noticed on rare occasions, between 6 and 10 magnitudes fainter than the corresponding normal image. Second and higher order internal reflection images should be extremely faint and have not been detected. The internal reflection images fall on top of the normal image for stars which cross the slit when the wobble plate is horizontal but for other stars the first internal reflection images appear near the centres of the profiles on the opposite side to the star. If the

first internal reflection image of the primary should happen to cross the slit very close to the secondary then errors in the magnitude difference will occur. More usually the only effect of the internal reflection image would be a worsening of the fit obtained. Assuming a first internal reflection image 7 magnitudes fainter than the main image we could get serious errors for stars with magnitude difference greater than about 3.5^m . This is discussed further in Section 7.6. An internal reflection is visible close to the secondary in the profile of Antares shown in Figure 8.

CHAPTER 6COMPUTATION OF THE MAGNITUDE DIFFERENCES
AND SEPARATIONS FROM THE RAW DATA6.1 The fitting function

Extraction of magnitude differences and separations from the raw data is based on the assumption that the intensity distribution in the images of the components of a double is identical and that this identity is preserved in our scanning process. Our problem is to obtain an acceptable agreement between the observed intensity profile (i. e. the accumulated scan) and one calculated on the assumption that the profile for a double star consists of the sum of a constant background and two overlapping peaks of identical shape but with different maximum heights and positions of maxima (see Figure 2). The ratio between the maximum heights is identical to the ratio between the total intensities of the two components and therefore leads to the magnitude difference between the components. The distance between the positions of maxima of the fitted peaks leads to the separation between the components.

Franz (Franz, Millis and White 1971, Franz 1973) found that fitting two Gaussians plus a constant background did not work very well. Instead Franz obtained (Franz, Millis and White 1971, Franz 1973) a formula for the profile of a single star which has more free parameters and succeeds in matching observed profiles very closely. For a single star the function is

$$I = \frac{H}{1 + \left\{ \frac{\text{abs}(x - A)}{B} \right\}^P} \quad \text{where } P = P_0 \left\{ 1 + \frac{\text{abs}(x - A)}{C} \right\} \dots [6.1]$$

In this expression I is the intensity at x, H is the maximum intensity.

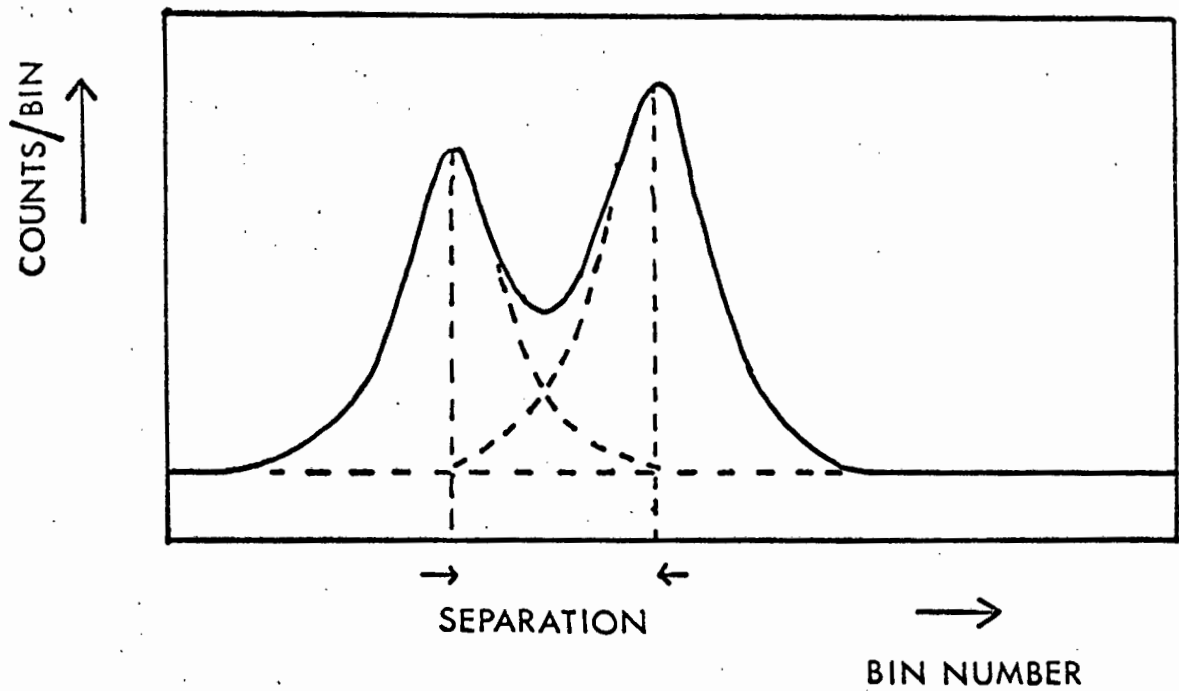


Figure 2. Profiles obtained from the scanner are assumed to be composed of two identically shaped peaks of different heights plus a flat background.

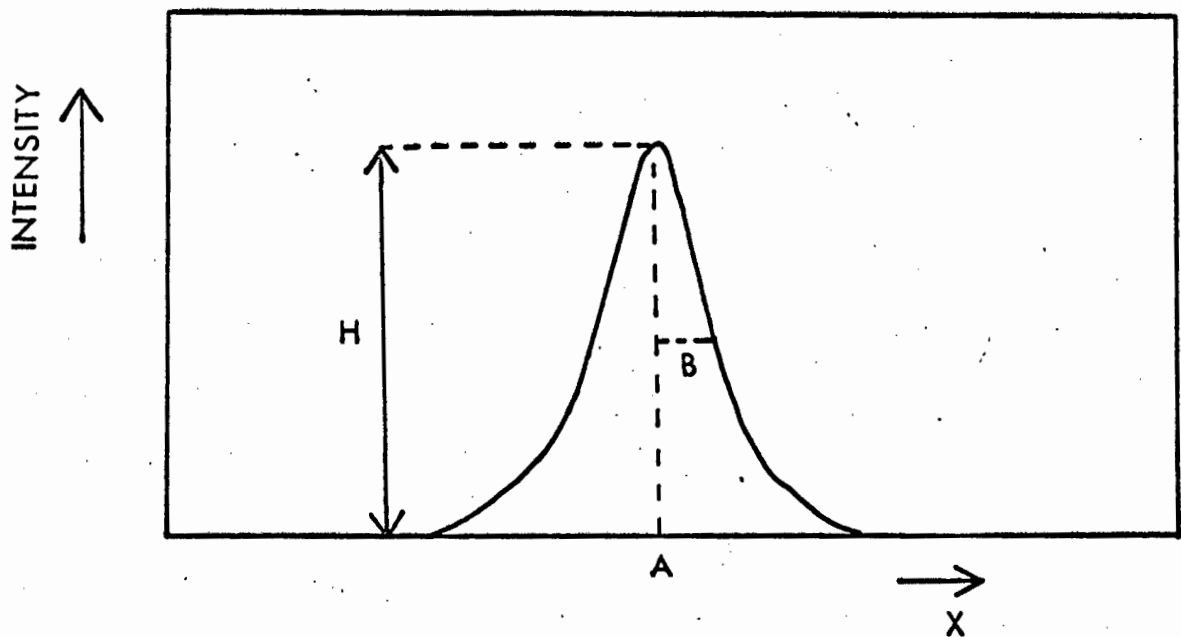


Figure 3. The basic parameters for a peak are: H - height, A - position of maximum and B - half-width at half-height.

A is the x coordinate of the centre of the profile, B is the half-power width (half-width at half-height), P_0 and C are constants determining the rate at which exponent P varies with x (see Figure 3). The shape parameters B, P_0 and C are the same for the peaks (profiles) of both components so there are eight parameters to be fitted, namely, two positions of maxima, two heights, three shape parameters and the constant background. Unfortunately the peaks we obtained were very frequently appreciably asymmetrical. Each shape parameter was therefore allowed to take on two values, one on each side of the maximum of a peak. We thus had eleven parameters to be fitted. The asymmetry is discussed further in Section 6.8.1.

6.2 The non-linearity of the scans

The amount by which the image of a star is shifted sideways by the passage of the converging light beam through the wobble plate depends on the angle of incidence on the wobble plate in a non-linear way.

Let i be the angle of incidence and r the angle of refraction in the normal sense, n be the refractive index of the wobble plate, d the thickness of the plate and s the sideways displacement of the light beam (see Figure 4).

$$\text{We have } n = \frac{\sin i}{\sin r}, \quad AC = d \tan i, \quad AB = d \tan r, \quad \text{and } \cos i = \frac{s}{BC}$$

$$\begin{aligned} \text{Therefore } s &= BC \cos i \\ &= (AC - AB) \cos i \\ &= d (\tan i - \tan r) \cos i \\ &= d \left(\sin i - \frac{\sin r \cos i}{\cos r} \right) \\ &= d \left(\sin i - \frac{\sin i \cos i}{n \cos r} \right) \end{aligned}$$

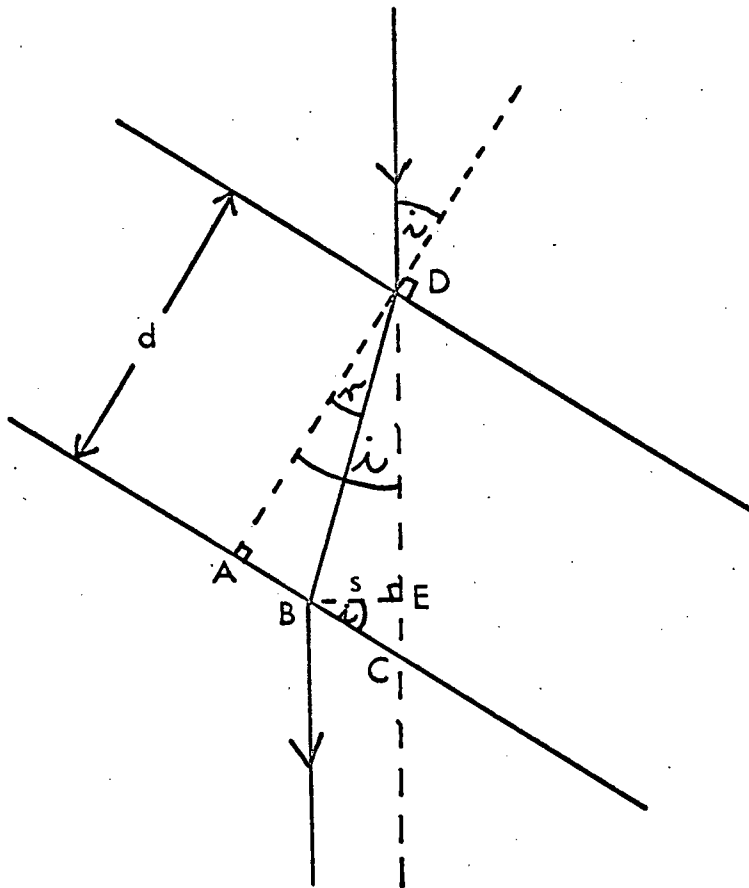


Figure 4. The displacement of the convergent light beam by the wobble plate.

$$\begin{aligned}
&= d \sin i \left(1 - \frac{1}{n} \frac{\cos i}{\cos r} \right) \\
&= d \sin i \left(1 - \frac{1}{n} \sqrt{\frac{1 - \sin^2 i}{1 - \sin^2 r}} \right) \\
&= d \sin i \left(1 - \frac{1}{n} \sqrt{\frac{1 - \sin^2 i}{1 - \frac{\sin^2 i}{n^2}}} \right) \dots\dots\dots [6.2]
\end{aligned}$$

The bins on our scans are separated by a single step of the stepping motor and thus by a fixed change in the angle of incidence of the light beam on the wobble plate. The formula is not linear for a changing angle i . In fact the shift per step gets bigger as i increases. It is essential to allow for this as both the separations and the magnitude differences obtained would be seriously in error otherwise.

It is easily seen that moving a point image from a fixed point a certain distance r to the right (for example) by rotating the wobble plate means that another point image which was exactly that distance r to the left of the fixed point will now fall at the fixed point. Thus moving the images a distance r to the right by wobbling the plate is equivalent to moving the slit a distance r to the left. We can therefore think of our bins as being positioned along the image of the field in the focal plane. We have chosen to see things from this point of view.

We assumed that zero degrees angle of incidence fell between bins 60 and 61 i.e. that bins 60 and 61 were spaced at equal distances on either side of the straight through position. Bins 60 to 1 and 61 to 120 were therefore situated symmetrically about this central position at positions which were determined for each bin by inserting the appropriate angle i in the formula. In order to avoid having negative coordinates for

bins on one side of the centre the constant which made the bin coordinates run upwards from zero at bin 1 was added. For convenience the value of d (the thickness of the plate) was not inserted in the formula and all coordinates were multiplied by a factor of 1000. Instead of the coordinates being in millimetres or metres they were thus in more convenient units which we refer to as our "arbitrary units".

The positions of the bins depend on the refractive index n . They are therefore different for different wavelengths and for different wobble plate materials. In the actual fitting program different bin positions were used for scans in U, B and V. The separations fitted to profiles in the three colours were thus in the same (arbitrary) units (see Sections 6.8.3 and 5.2). However the same values were used for all the various wobble plate and gearing combinations used (see Section 5.1). This was permissible because the bin spacings for each of the other wobble plate and gearing combinations were, to a good approximation (error less than 1%) merely a constant factor different from those for the original 3 mm plate with 4:1 gearing whose bin positions we used. In extreme cases this procedure could lead to errors of the order of 1% in the magnitude difference and even less in the separations.

Different sets of bin positions should really be used for each wobble plate/gearing combination. That one set of positions was used mainly as a result of the inconvenience in altering the fitting program and the reduction methods in general to allow the "correct" positions to be used. The necessary modifications would enlarge the fitting program and make the preparation of the data for the program (see Section 6.5.2) more laborious still.

6.3 Normalization of residuals

One might expect the noise in the counts per bin to be proportional to the square root of the counts. In the fitting program the residuals (observed counts minus fitted counts) were therefore normalized by dividing by the square root of the fitted counts. Unnormalized residuals and residuals normalized by dividing by the fitted count were also tried (see Section 6.8.2).

6.4 The fitting procedure

We wish to obtain the best fit, in a least squares sense, of our calculated profile (see Section 6.1) to the observed profile using normalized residuals. We use a differential correction technique.

In general if we have a function $f(x_i; p_1, p_2, \dots, p_m)$ where x_i are the x values and y_i the y values of the n data points and p_1, p_2, \dots, p_m are the parameters to be fitted then we want to minimise

$$\chi^2 = \sum_{i=1}^n w_i \{y_i - f(x_i; p_1, p_2, \dots, p_m)\}^2$$

where the w_i are the weights of the squared residuals i.e. we want the p_j for which

$$\frac{\partial \chi^2}{\partial p_j} = 0 \quad j = 1, \dots, m$$

Let $f_i^{0 \min} = f(x_i; p_1^{\min}, p_2^{\min}, \dots, p_m^{\min})$ be the value of f at x_i when χ^2

is minimised and let $f_{i,j}^{1 \min} = \frac{\partial f_i^{0 \min}}{\partial p_j}$.

$$\frac{\partial \chi^2}{\partial p_j} = 0 \quad j = 1, \dots, m$$

gives us

$$\sum_{i=1}^n \{ w_i \cdot 2 \cdot (y_i - f_i^0 \min) \cdot (-1) \cdot f_{i,j}^{1, \min} \} = 0 \quad j = 1, \dots, m$$

leading to the normal equations

$$\sum_{i=1}^n \{ w_i f_{i,j}^{1 \min} (y_i - f_i^0 \min) \} = 0 \quad j = 1, \dots, m \quad \dots [6.3]$$

We estimate the values of $p_1 \dots p_m$ at the minimum and use a Taylor expansion truncating after the first derivatives obtaining

$$f_i^0 \min = f_i^0 \text{ estim} + \sum_{j=1}^m (f_{i,j}^{1 \text{ estim}} \cdot q_j)$$

$$\text{where } q_j = p_j^{\min} - p_j^{\text{estim}}$$

[6.3] becomes

$$\sum_{i=1}^n w_i \cdot f_{i,j}^{1 \text{ estim}} \cdot (y_i - f_i^0 \text{ estim} - \sum_{k=1}^m [f_{i,k}^{1 \text{ estim}} \cdot q_k]) = 0 \quad j = 1, \dots, m$$

Interchanging the order of the summations we get

$$\sum_{i=1}^n w_i (y_i - f_i^0 \text{ estim}) f_{i,j}^{1 \text{ estim}} - \sum_{k=1}^m (\sum_{i=1}^n w_i f_{i,j}^{1 \text{ estim}} \cdot f_{i,k}^{1 \text{ estim}}) q_k = 0$$

$j = 1, \dots, m$

$$\text{Writing } A_j = \sum_{i=1}^n w_i (y_i - f_i^0 \text{ estim}) f_{i,j}^{1 \text{ estim}}$$

$$\text{and } C_{j,k} = \sum_{i=1}^n w_i f_{i,j}^{1 \text{ estim}} \cdot f_{i,k}^{1 \text{ estim}}$$

$$\text{we get } A_j - \sum_{k=1}^m C_{j,k} q_k = 0 \quad j = 1, \dots, m$$

$$\text{or } \sum_{k=1}^m C_{j,k} q_k = A_j \quad j = 1, \dots, m$$

The equations are now linear and we can solve for the corrections q_k . We can then iterate until some goodness-of-fit criterion is satisfied.

Initially a program was written to fit symmetric peaks by this method. However the shape parameter C in formula [6.1] gave trouble and

it became necessary to place restrictions on the alterations in this parameter. Fortunately a program by Lang and Müller (1971) was found which employs a sophisticated method to do this. The original program was therefore abandoned and two subroutines from Lang and Müller's program were adapted for inclusion in a new program which fits asymmetric peaks.

Lang and Müller's method involves selecting boundaries beyond which the Taylor expansion is assumed to be invalid. These boundaries are transformed into the principal axis system of the matrix $C_{k,j}$. The alterations along the principal axes are calculated and if any of these goes outside the transformed boundaries they are reduced to the corresponding boundary values. The alterations are then transformed back and the iterations continue with the initial estimated values of the parameters plus calculated alterations as the new estimated parameters.

6.5 Preparation of the data for reduction

6.5.1 Reading the paper tapes

The paper tapes are read by the paper tape reader attached to the UNIVAC 1106 at UCT. A program TPREAD was written to do this. This program reads a tape using the software provided by the UNIVAC and writes it in octal onto a scratch file. The tape reader is then released and the data on the scratch file are translated. The translation routine contains a translation table array. The various characters are stored in elements of this array such that the octal code of a character corresponds to the number of the array element containing the character. Translation is thus reduced to a look-up procedure. After translation of a tape is completed the data are stored as an element in a program file on disc. Each tape is numbered

and the file element is named .TAPE x where x is the tape number.

6.5.2 Editing the file elements

The file elements are twice edited. In the first edit any unwanted data are deleted, punching errors are corrected and any data accidentally missing from the tape are inserted. The typewriter printout is consulted where necessary. In the second edit the block of data corresponding to each accumulated scan is given an identification number. This number consists of the observing log sequence number of the observation and a filter code. This coding procedure is laborious because it cannot be fully automated. Furthermore there is a possibility that errors may occur in identifying the data. It would be possible to add a section to the ASHCAN program so as to detect which filter is being used and to print and punch the sequence number and the filter code with the other data. However we believe that this would not be worthwhile. Neither do we think it would be worthwhile entering the star name via the teletype keyboard before (or after) each observation. In general we would like to avoid having to enter information via the teletype except at the start of observing. Also we would not like to have a fixed ordering of the observing procedure nor would we like to complicate the equipment further.

6.5.3 Examining graphs of the data

A graph is plotted for each accumulated scan. The graphs are plotted on the line printer using the program GRPRNT which calls the subroutine GRAPH (see Section 6.6). These graphs are then cursorily examined chiefly to detect those cases where it is necessary to enter initial

values of the parameters to be fitted (see Section 6.6). However errors in the data are sometimes detected at this stage.

6.6 The fitting program

The program which fits a curve to the observational data is then run. This program consists of a main program (CONTRL) and 6 subroutines (INPAR, FIT, FRANZ, JACORD, GRAPH and GREER). The way in which the program works is explained briefly here and a listing is given as an appendix.

The main program, CONTRL, is informed, via data cards, which observations are to be processed and is also given the values of various parameters required by it. The program file element in which the observational data are to be found must be added into the runstream. After finding the data for the first accumulated scan to be processed, CONTRL sets the initial values of the parameters to be fitted. The 6 shape parameters can be set specifically for any individual accumulated scan via an input data card, they can be set at the values found for the previous profile fitted or they can be set to fixed, pre-set, values. The positions of the maxima, the maximum heights and the background are normally estimated by the subroutine INPAR but if the profile is extremely noisy or if the secondary star is too faint to give a clear peak on the profile some or all of these start values may have to be entered on a data card. It is seldom necessary to enter anything more than estimates of the positions of the maxima and these estimates may be very rough. CONTRL also stores, for each filter, the x coordinates of the bins and selects the set of coordinates appropriate to the filter with which the profile currently being processed was obtained.

The subroutine FIT is then called. This subroutine, adapted from Lang and Müller (1971), uses the procedure outlined in Section 6.4 to fit, by least squares, the best curve to the data. No corrections are made for coincidence losses. The bins to be used in the fit are passed from CONTRL. These can be chosen specifically for any profile. Otherwise pre-set bins are used. x Coordinates of the bins are passed from CONTRL. During execution of FIT the values of $F_i^{0 \text{ estim}}$ and $F_{i,j}^{1 \text{ estim}}$ are calculated using the analytic expressions for the function and its derivatives in the subroutine FRANZ. This subroutine sets the weights w_i as $1/F_i^{0 \text{ estim}}$, equivalent to normalising the residuals by dividing by the square root of the fitted counts. FRANZ also sets the parameter alteration boundaries required by FIT. In practice the boundaries are not critical except for the shape parameters, especially C. FIT narrows the boundaries if chi-squared increases. The subroutine JACORD is called by FIT to calculate the eigenvalues and eigenvectors of the correction matrix.

It was found necessary to include four criteria for deciding when to stop the iterations. The first criterion stops the iterations when the square sum of the parameter alterations divided by their errors is less than some constant. The second criterion stops the iterations when chi-squared per degree of freedom no longer decreases significantly. The third criterion is similar to the second. It stops the iterations if chi-squared per degree of freedom will not decrease significantly despite narrowing the boundaries set on the parameter alterations. The last criterion stops the iterations when the parameter alterations are no longer significantly affecting the fitted magnitude difference. The constants in these criteria are set so that, in practice, the first, second and fourth criteria stop the iterations

with about equal frequency and the third criterion very rarely. Which criterion stops the iterations depends on the nature of the particular profile being fitted.

The program also allows for various abnormal terminations. In the event of an abnormal termination control is returned to the main program. One of these abnormal terminations occurs when the number of iterations reaches a pre-set maximum.

At a normal stop FIT provides errors in the fitted parameters. FIT also calculates an estimate of the total intensity of the double star and converts this to a magnitude which we call the relative magnitude.

The amount of printout from FIT is controlled by various options. Usually only the number of iterations, initial values of parameters, fitted values of parameters and their errors, magnitude difference, separation and relative magnitude are printed. Some of these values are also punched on a card.

Control then returns to CONTRL. An option allows the calculation of a rough estimate of the percentage error in the fit of each peak by comparing the total number of counts under the fitted curve for each peak with the total observed number of counts in the corresponding bins. These percentage errors are smaller than the errors in the fitted maximum heights as calculated in FIT. This option was seldom used.

The subroutine GRAPH is then called. This plots, on the line printer, a graph of the observed and fitted points. The bin number, x coordinate, observed and fitted counts per bin are printed underneath the axis. If the secondary peak is less than one fifth the height of the primary peak a separate graph is plotted, at a larger scale, of the 25 bins centred

on the secondary peak.

Lastly the subroutine GREER is called. This plots graphs of the residuals and the normalised residuals.

The main program then finds the data for the next profile to be processed.

6.7 Operating performance of the fitting program

The program uses about 15K words of storage. The time taken for each fit depends to a large extent on the number of iterations required as each iteration takes of the order of 0.5 secs of CPU time on the UNIVAC 1106. Typically a fit takes 10-15 seconds. The profiles are fitted in conveniently sized batches, usually of 10-30 profiles each. Thus one night's work, say 40 observations each with 3 filters, requires several runs of the program and a total CPU time of perhaps 30 minutes.

The time taken could be reduced by making the stopping criteria less stringent. However it was felt that the saving in computer time did not warrant possible increases in the errors in the fitted parameters. A set of criteria was used which stopped the iterations at a stage where further iterations would not significantly alter the magnitude difference fitted. The number of iterations was normally between 5 and 45. The maximum number of iterations (see Section 6.6) was usually set at 60.

The number of iterations could also be reduced by more accurate initial estimates of the parameters. This was felt not to be worthwhile in view of the greatly increased number of data cards required and consequent increase in preparation time. In practice the positions of the maxima of the peaks are specifically estimated only when it is felt that

the automatic estimated by the program might fail. The other parameters were very seldom specifically estimated.

The guiding idea behind the way we used the program was to obtain fits of an acceptable accuracy in a reasonable amount of computer time with as little preparation and as few failures as possible.

It very seldom happened that the program could not obtain a fit or obtained an incorrect fit. In a handful of cases the observational data was extremely poor and was discarded after it was found that a fit could not be obtained. More often the failures were due to extremely bad initial estimates of the positions of the maxima of the peaks.

As a test of the program some profiles were fitted several times over using different sets of specifically estimated initial values of the parameters. It was found that the number of iterations and the stopping criterion which stopped the iterations both varied but the magnitude differences and separations fitted were not significantly altered.

6.8 Variations of the fitting program

Several variations of the fitting program were tested, sometimes on fairly large quantities of data, in order to ensure that the program finally adopted for use was the best one in the circumstances.

6.8.1 Symmetry versus asymmetry

The program was modified to fit symmetric peaks instead of asymmetric ones i.e. the number of parameters fitted was reduced to 8. The observations on 10 stars of various separations and magnitude differences were fitted using this modified program. As expected the

number of iterations performed by the program and the CPU time taken were decreased. The fits obtained were not as good as those obtained using asymmetric peaks.

The magnitude differences found were analysed using the methods described in Section 7.5 and the results compared with those found using asymmetric peaks. It was found that for most of the stars in the sample the errors in the mean magnitude differences in V, B and U respectively were slightly greater using symmetric peaks but that the differences between the mean magnitude differences obtained using symmetric peaks and those obtained using asymmetric peaks were not significant. However for close stars ($\lesssim 3''$) with V magnitude difference $\geq 1.0^m$ the symmetric peaks gave very much larger errors in the mean magnitude differences than the asymmetric peaks. The mean magnitude differences also differed significantly from those obtained using asymmetric fits and led to very unlikely colours for the secondaries.

There is an obvious danger in fitting asymmetric peaks in the case of very close stars of fairly large magnitude difference whose peaks overlap considerably. This is especially so if the peaks of the primary and secondary are in fact not identically shaped. The program can make considerable alterations in the number of counts in the primary peak falling under the peak of the secondary by making small alterations in the shape parameters on that side of the peak. Thus it may happen that the best fit is obtained by depressing/raising the contribution of the primary in the region of the secondary peak from its correct level and decreasing/increasing the maximum height of the secondary accordingly. This probably does happen in practice but causes an error comparable with or less than the

error calculated by the program for the height of the secondary peak.

Using symmetric peaks the situation is actually worse. Here the shape of the fitted peaks is to a considerable extent determined by the shape of the observed primary peak on the side opposite to the secondary. It may happen that this results in a marked depressal/raising of the contribution of the primary in the region of the secondary peak. This can be extremely serious. In one case, for instance, it was found that the best fit would have been obtained with a negative contribution from the secondary!

For each star the mean separation obtained using symmetric fitted peaks was compared with the mean separation obtained using asymmetric peaks. No significant differences were found.

It was therefore decided to use asymmetric fitted peaks throughout.

6.8.2 Which normalization?

The obvious way to normalize the residuals is to divide by the square root of the fitted value of the counts per bin. However tests were made using unnormalized residuals and using residuals normalized by dividing by the fitted value of the counts per bin i.e. essentially fractional residuals.

In the tests fits were made to batches of profiles using, in turn, each of the three normalizations of the residuals. Not surprisingly the magnitude differences obtained using normalization by dividing by the square root of the counts were usually between the values obtained using the other normalizations. Where the profiles of components were severely overlapped and the magnitude differences fairly large it sometimes occurred that the magnitude differences obtained using the three normalizations differed by

several tenths of a magnitude. In these cases the unnormalized residuals fits tended to give smaller, and the fractional residuals fits larger, magnitude differences than the square root of counts normalization fits. The differences between the magnitude differences obtained using each of the other two normalizations and those obtained using the square root normalization seldom exceeded two or three times the fitted error of the secondary in the fit with square root normalization. The systematic differences between the magnitude differences obtained using the three normalizations were small, of the order 0.01^m and barely significant.

The best fits for nearly equal components tended to be the ones made using unnormalized residuals. For very unequal components unnormalized residuals gave the worst fits, the background frequently being fitted obviously too high or too low and the profiles of faint secondaries tending to be poorly fitted. Fits made using fractional residuals tended to be poor.

The normalized residuals were of the order 1 for the square root normalization whereas they were very much less or very much more than 1 respectively for the other two methods. Thus chi-squared per degree of freedom was mostly between 1 and 10 for the square root normalization and very small or very large respectively for the other two methods. The normalized residuals also seemed to be more uniform across the scan for the square root normalization.

The square root normalization thus appears to be the best one to use and it was used for all our fits as described in Sections 6.6 and 6.7.

6.8.3 Linear x axis versus non-linear x axis

Although the non-linearity of the scans must be allowed for if

accurate magnitude differences and separations are to be obtained the program was tried using a linear x axis to see what effect this had on the fitted magnitude differences. It was found that the differences between the magnitude differences thus obtained and those obtained using the normal program were small, seldom exceeding 0.02^m . This close agreement occurs because for most stars the peaks in the profiles are in the nearly linear part of the scan within 30 bins of the centre and, usually, the two peaks are approximately equally far from the central bin. The separations obtained using a linear axis with identical coordinates for U, B and V showed the expected effect, namely that the components appeared further apart in V than in U (see Section 6.2). See Section 7.4 for further discussion of the effect of using incorrect x axis coordinates.

6.8.4 Relative magnitudes by two methods

The relative magnitudes (see Section 6.6) were found by summing the fitted counts per bin over all 120 bins, dividing by 120, subtracting the contribution of the background, dividing by the total number of scans included in the profile, taking the logarithm (base 10) and multiplying by 2.5. These magnitudes thus became more positive for brighter stars. How they were used is explained in Section 7.2. This is not the proper method of estimating total intensity as more photons are counted from very close stars scanned with both components near the centre of the scan than from wider stars of equal combined light magnitude where the components are scanned at, for example, bins 30 and 90. This occurs because of the non-linearity of the scan mentioned before (see Section 6.2). The difference in relative magnitude between two equal stars might be up to approximately

10% because of this effect.

The correct method of estimating total intensity is to sample the fitted curve at points a fixed distance apart (of the order of the bin spacing) on the correct x axis and across the whole profile. Relative magnitudes obtained by the two methods were compared for a sample of observations. It was found (using analysis as described in Sections 7.2 and 7.3) that the relative magnitudes were not significantly improved by using the correct method. It appears that in practice the errors in using the incorrect method were less than about 0.02^m and are smaller than errors from other sources (see Section 7.3).

6.9 Examination of the fits

All the fits obtained were carefully examined. Where necessary profiles were fitted again. Most of these refits were done in order to use some of bins 1-16 and 105-120 which were not used in the initial fits. This was only done if it was fairly certain that the extra bins used had not suffered a loss in counts due to shifting before adding of the scans (see Section 3.4.2) and if it was expected that the fit would be improved by using more bins in that the background and/or one of the peaks (usually the secondary) would be defined by more points. Sometimes a profile was fitted a third or even a fourth time and what seemed to be the best fit chosen. Occasionally a profile was rejected when it was found that the magnitude difference fitted was highly sensitive to changes in the bins used.

6.10 Goodness of fit

The profiles were extremely varied in their appearance. They

could not always be well fitted by the fitting program despite the large numbers of parameters used. The minimized values of chi-squared per degree of freedom were usually in the range 1 to 10 but occasionally values much larger than this were obtained. On rare occasions these exceeded 100. Chi-squared tended to be larger for bright stars indicating that there were systematic differences between the observed points and the fitted curve. Examination of the error-of-fit graphs showed that in many cases errors were entirely random but that in some cases bad systematic effects were present.

Extremely bad fits were usually due to a breakdown of the basic assumption that the peaks due to the two components are of the same shape. The half-widths were in fact not identical in these cases. This was noticed only in profiles in which the peaks did not overlap much. As the effect occurred even when the scans were made horizontally (in the sense previously described) it could not be due to the slits having non-parallel sides. Usually but not always the primary peak was sharper than the secondary peak. This led to the assumption that the effect was due to the correlation before accumulation in the ASHCAN program. One would expect the primary to dominate the correlation. Since the number of bins between the two peaks would vary slightly because of image motion occurring in the interval between the two images being scanned the secondary peak in the accumulated scan would be broadened slightly. This spreading would be greater for greater separations. The centre of the secondary peak should not be displaced so no error in separation would result. The peak fitted to the primary peak would be too rounded and the peak fitted to the secondary too sharp but the peaks would be sufficiently far apart for the program to

obtain the best fit for each peak essentially independently of the other. The magnitude differences would therefore not be in error.

However this explanation did not explain those cases where the secondary had the sharper peak. It was also noticed that the sharper peaks tended to be on one side of the scan for whole nights at a time. It was also found that the fitted separations of individual standard stars varied by several per cent from night to night (see Section 7.4). This led to another explanation for the bad fits (see Section 7.4). According to this explanation the bad fits occur in observations for which the oscillations of the wobble plate are not centred on the "flat" position of the plate.

These two causes of bad fits would compete with one another confusing things and making it nearly impossible to apply corrections.

There were various causes of asymmetric peaks. One cause was the wrong centring mentioned above. Another cause was the images formed by the telescopes. Early in the observing program the images formed by the 100 cm were found to be astigmatic. This was later corrected by the SAAO staff. The images of the 75 cm had a flare on one side. This was due to the method of supporting the primary mirror. When a dome was used as an aperture stop this sometimes resulted in asymmetry. Small asymmetries could also be introduced by the correlation procedure in ASHCAN. Badly asymmetric peaks could not always be well fitted. It must be noted that even for an ideally symmetric scan the noise in the data and numerical inexactness in the fitting program would cause very small differences between the values of the fitted shape parameters on either side of the peaks.

Some very strangely shaped peaks occurred. It was found that some of these were due to vibration of the 50 cm telescope at the frequency of the oscillations of the stepping motor (or some harmonic of this frequency). This occurred when the wobble plate shaft was aligned nearly east-west and was probably due to backlash in the declination worm gear. The vibrations could be avoided by skilful hanging of weights on the telescope tube or by avoiding scanning with the wobble plate shaft aligned in directions close to east-west.

The fits obtained in U usually had highest chi-squared. The half-widths of the fitted peaks showed a not unexpected increase from V through B to U. The fitted errors in the peak heights tended to be largest for U probably mainly because of the greater noise and half-widths mentioned. Frequently also the primaries were bluer than the secondaries resulting in larger magnitude differences in U than in V and B and thus exaggerating the difficulties in obtaining reliable estimates of magnitude differences in U.

6.11 Examples of fits obtained

Some plots of observed and fitted profiles are given to illustrate the performance of the scanner and of the fitting program. In all the plots photon (pulse) counts per bin are plotted versus bin number. The observed points are represented by plus signs and the fitted profile by a continuous curve. Sudden slope changes in the continuous curve are artefacts of the plotting routines used. Most of the profiles were obtained using 1 scan per integration. (Scans per integration is the number of scans added together without shifting before being correlated with the accumulated scan and added to it with shifting (see Section 3.4.2)). Unless relevant the

number of scans per integration is not included in the figure caption. The values given for the fitted magnitude differences are in the instrumental system and may be a few hundredths of a magnitude off the UBV system. The stars were all scanned in the horizontal position unless indicated to the contrary. In most cases the mean separation from Table I is given rather than the separation fitted for the particular profile. Unless otherwise stated the 3mm wobble plate was used.

Figure 5 shows a profile obtained in seeing so poor (3-4 arcsecs) that observations of close stars or those with large magnitude differences would not have been possible. A slight systematic misfit occurs on the secondary peak. However the fitted ΔV agrees well with the mean in Table I. The observation was made using the 50 cm telescope.

Figures 6, 7 and 8 show the U, B and V profiles of an observation of Antares. These profiles were obtained within a few minutes of each other using the 75 cm telescope in exceptionally good seeing. The dome was used as an aperture stop for the scans in B and V to avoid coincidence losses in the amplifier. The hump clearly visible on the side of the secondary peak in the enlargement in Figure 8 is due to an internal reflection image (see Section 5.6) of Antares A and is about 8 magnitudes fainter than Antares A and about 3 magnitudes fainter than Antares B. The small peak at about bin 100 is probably due to a pinhole in the aluminized slit set used.

Figure 9 shows a profile obtained on the 75 cm telescope. A slight systematic misfit occurs at identical positions on the primary and secondary peaks. This misfit was caused by the poor shape of the images. An image flare was clearly visible through the viewing eyepiece and the

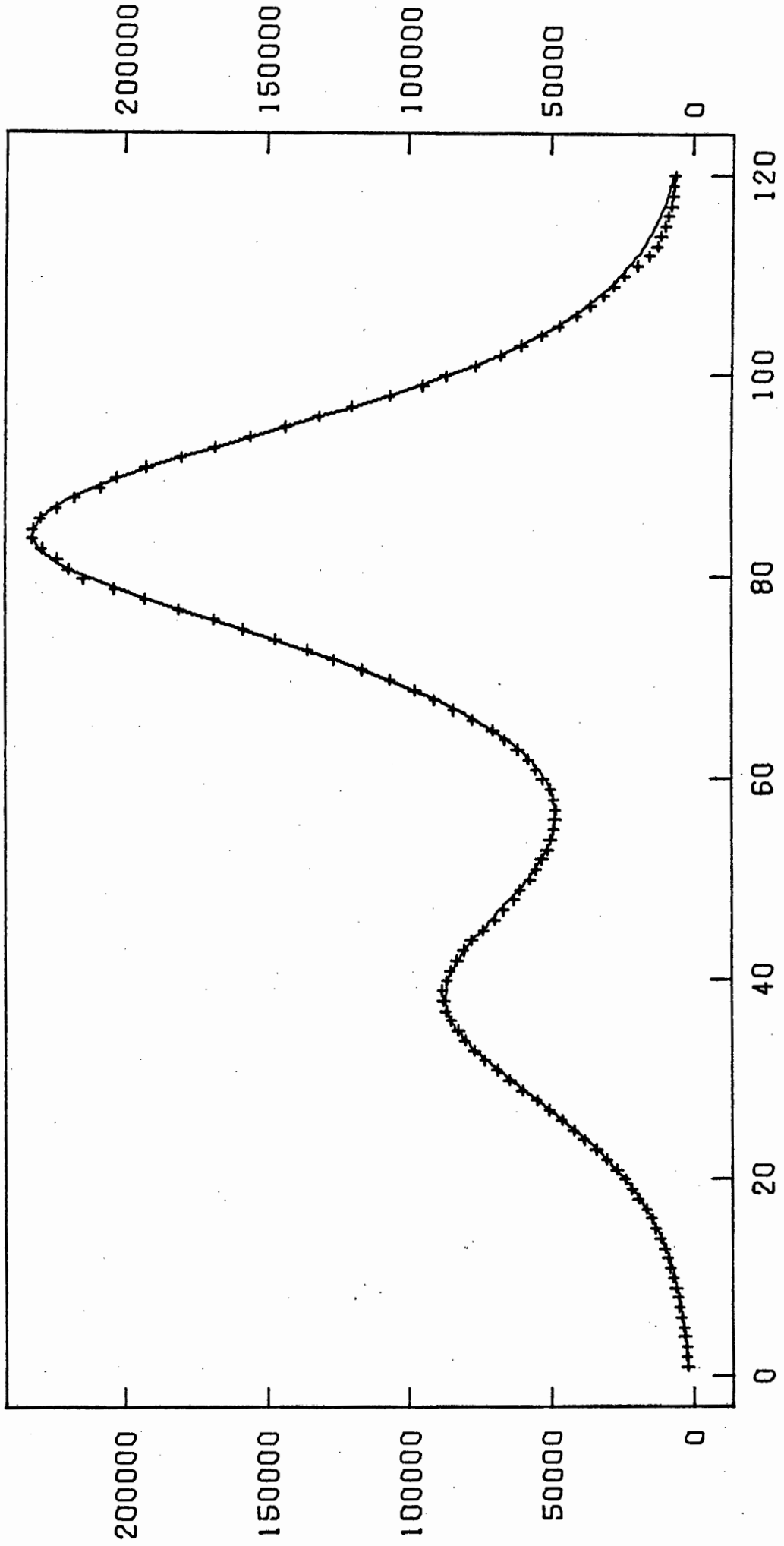


Figure 5. HR897/8. 416 scans in V. Fitted $\Delta V: 1.10 \pm 0.01$. Separation (Table I): 8.23.

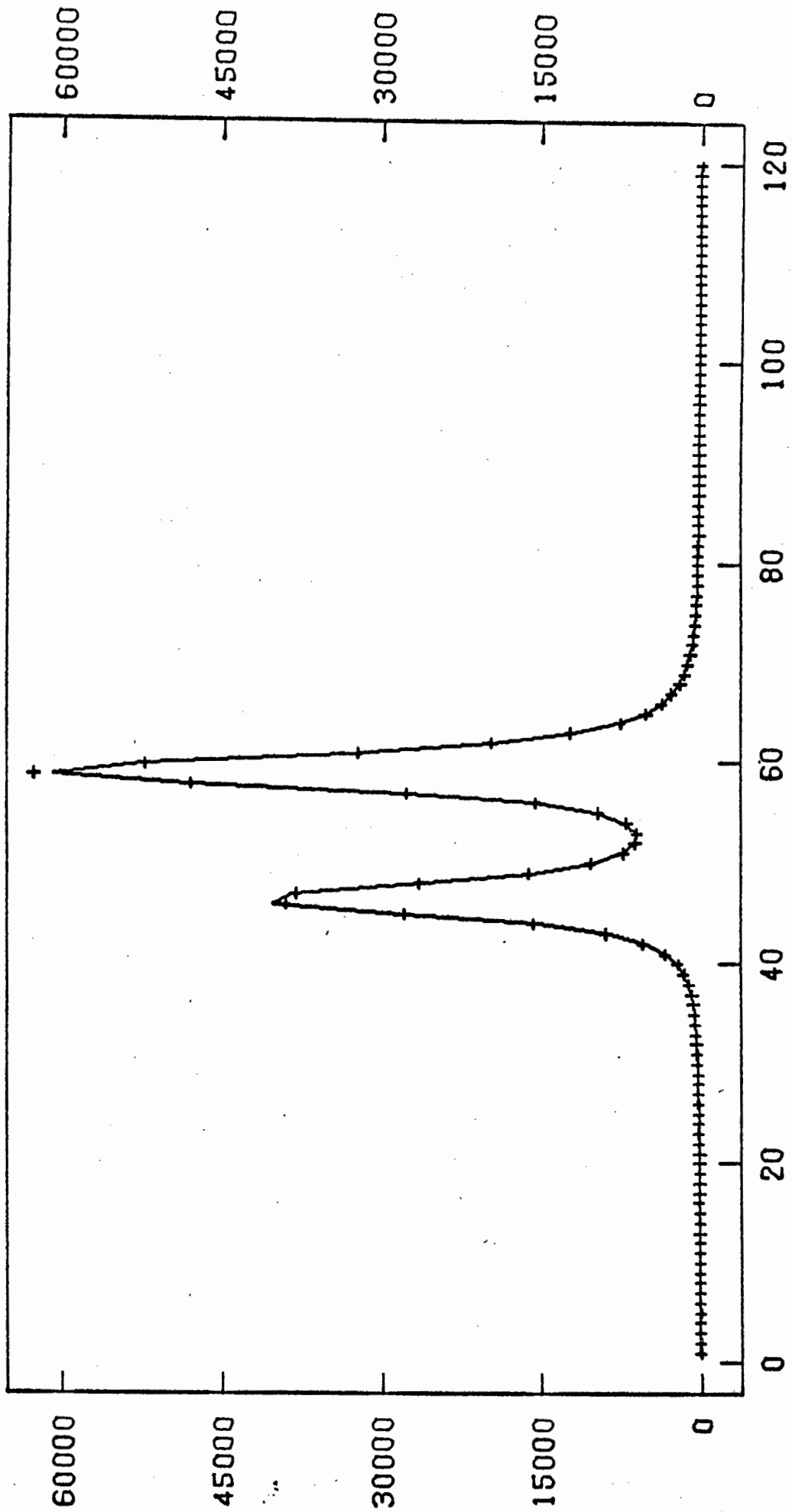


Figure 6. HR 6134. Antares. 374 scans in U. Fitted ΔU : $-0^m.43 \pm 0^m.01$ i.e. B is brighter. Fitted separation: $2''.88$. 5 mm wobble plate.

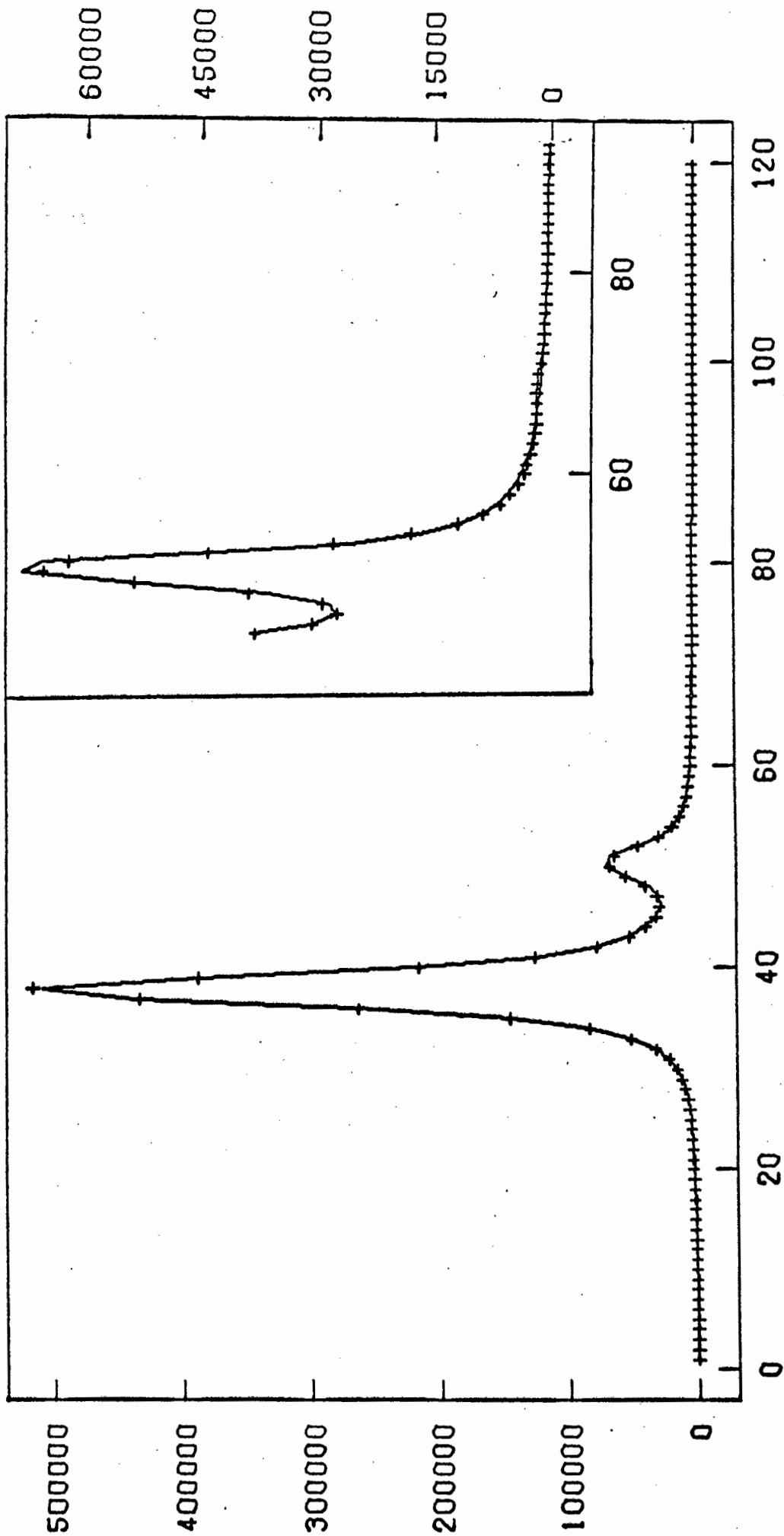


Figure 7. HR 6134. Antares. 326 scans in B. Fitted $\Delta B: 2^m.27 \pm 0^m.02$. Fitted separation: $2^m.85$. 5 mm wobble plate.

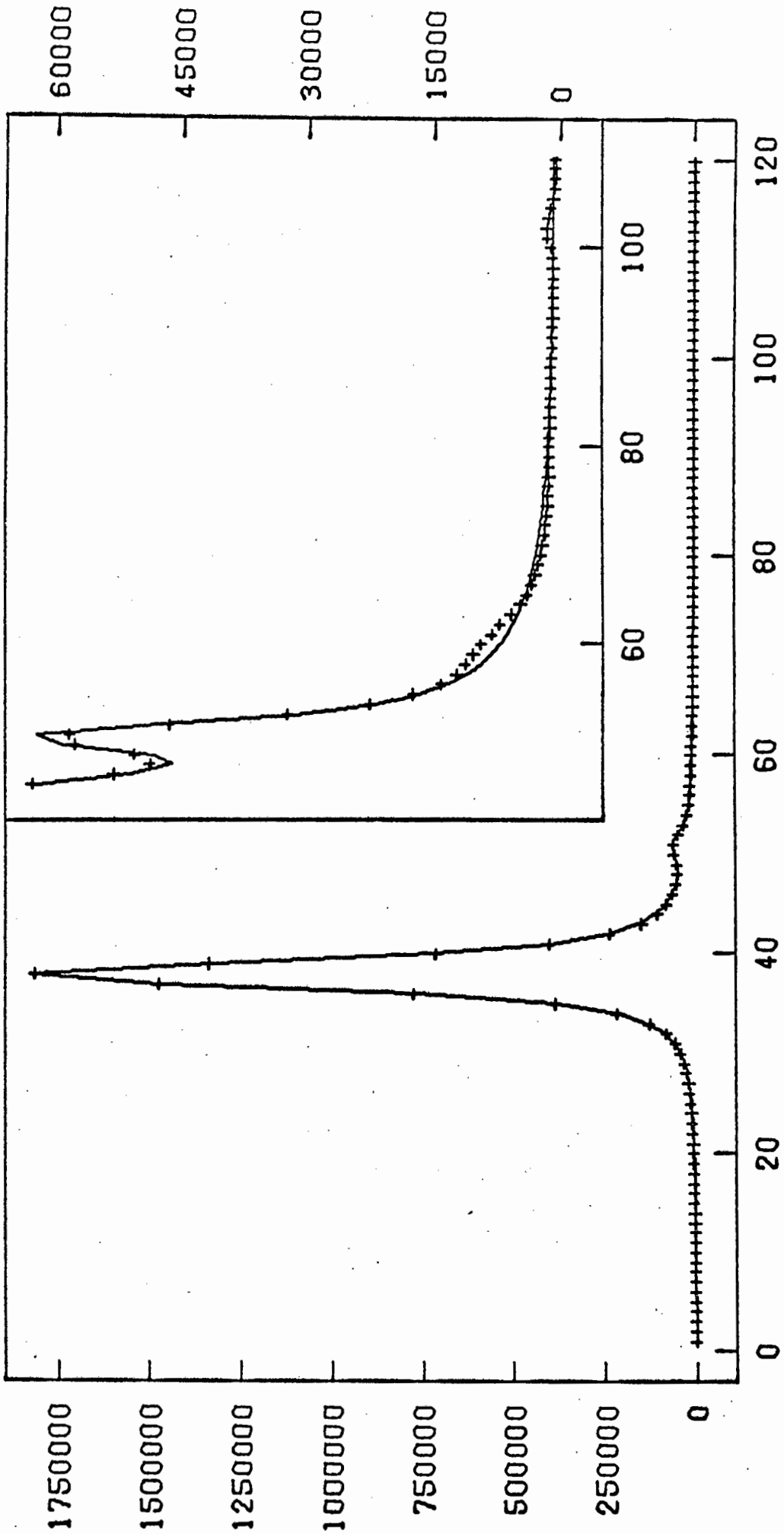


Figure 8. HR 6134. Antares. 334 scans in V. Fitted ΔV : 4.08 ± 0.05 m. Fitted separation: 2.92 ± 0.05 mm wobble plate.

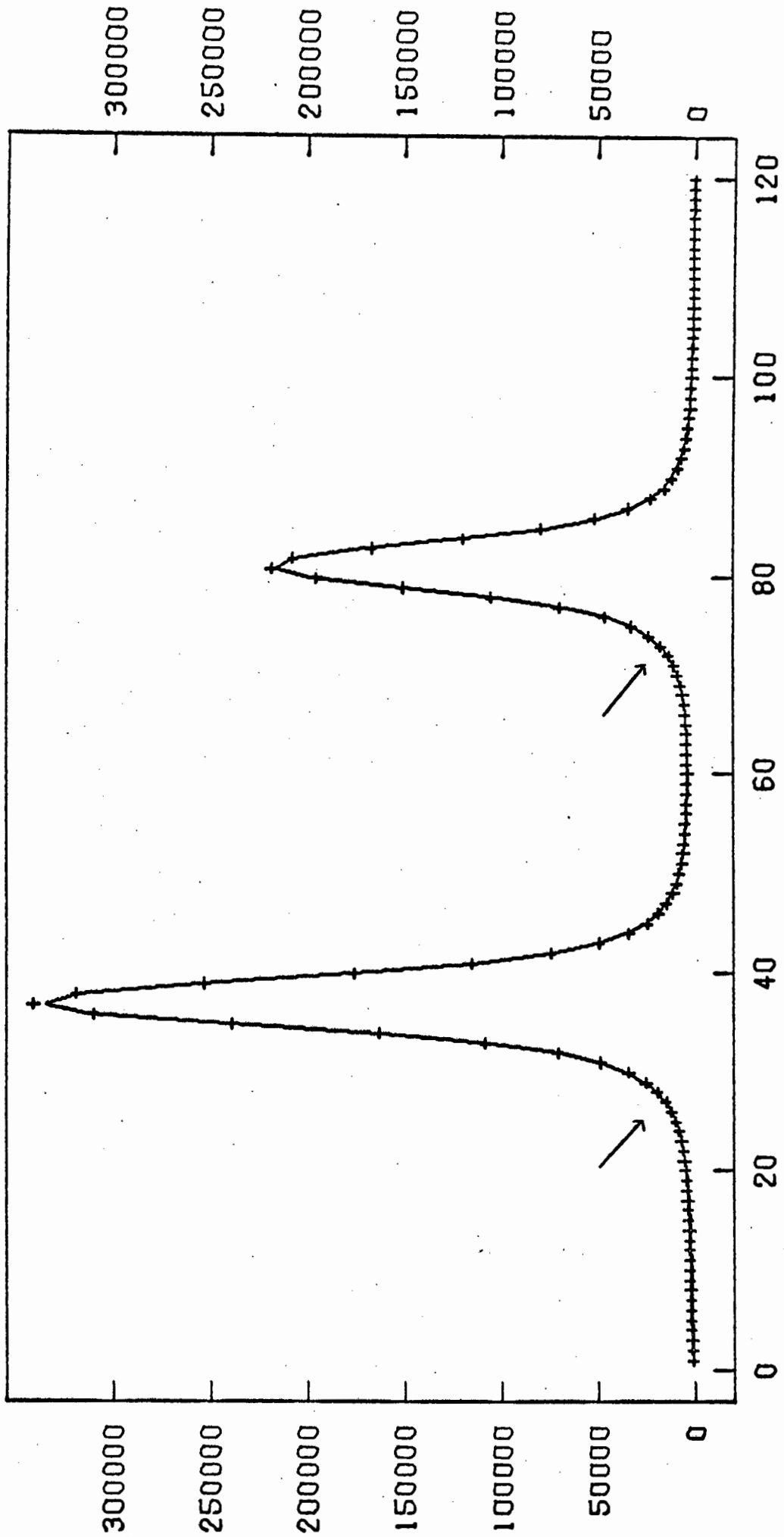


Figure 9. HR 4135/6. 334 scans in B. Fitted ΔB : 0.48 ± 0.01 m. Effective separation: 9"9. True separation: 13"5. 5 mm wobble plate.

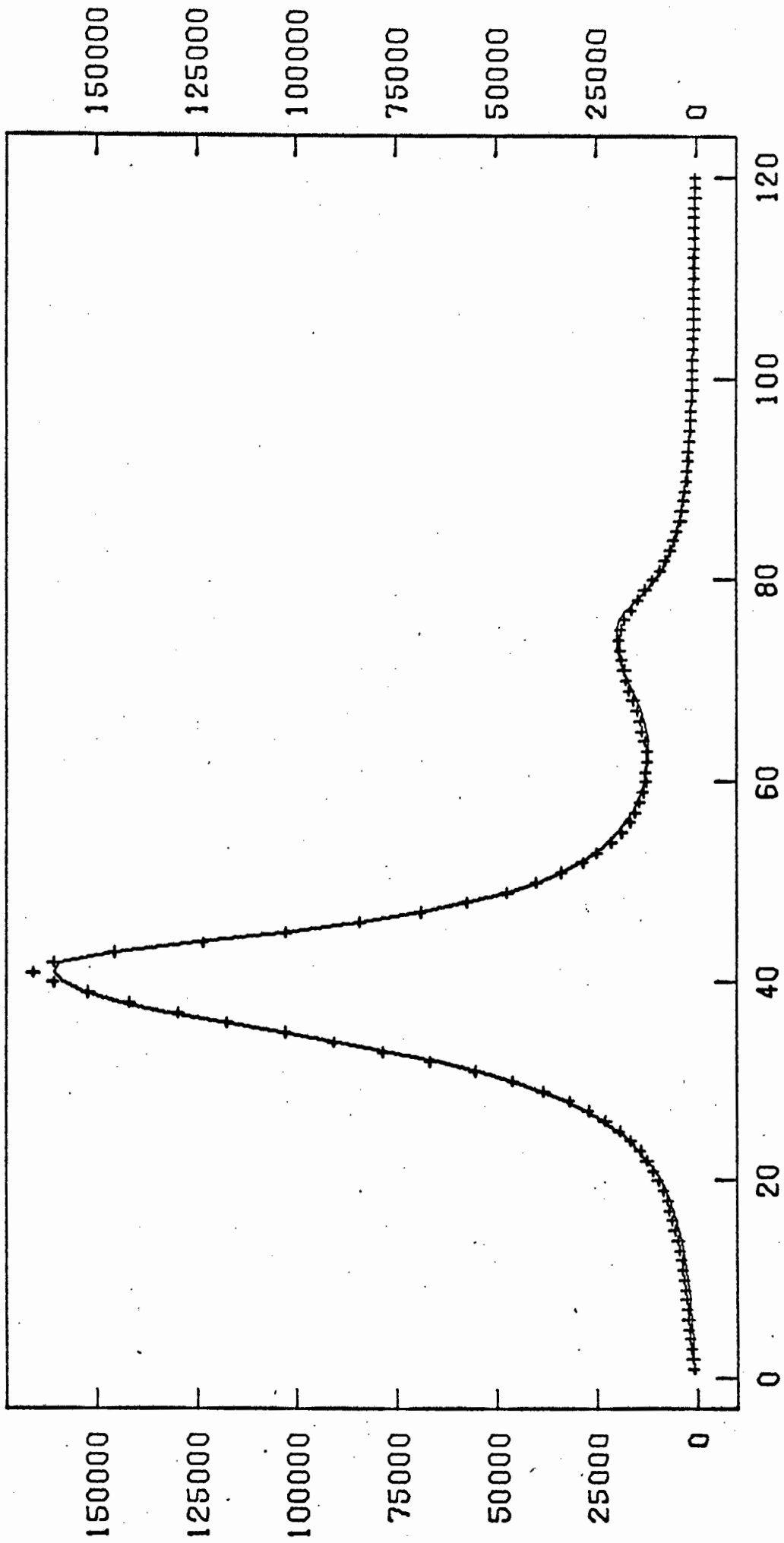


Figure 10. HR 5362. 640 scans in V. Fitted $\Delta V = 2.42 \pm 0.03$ m. Separation (Table I): 3''64.

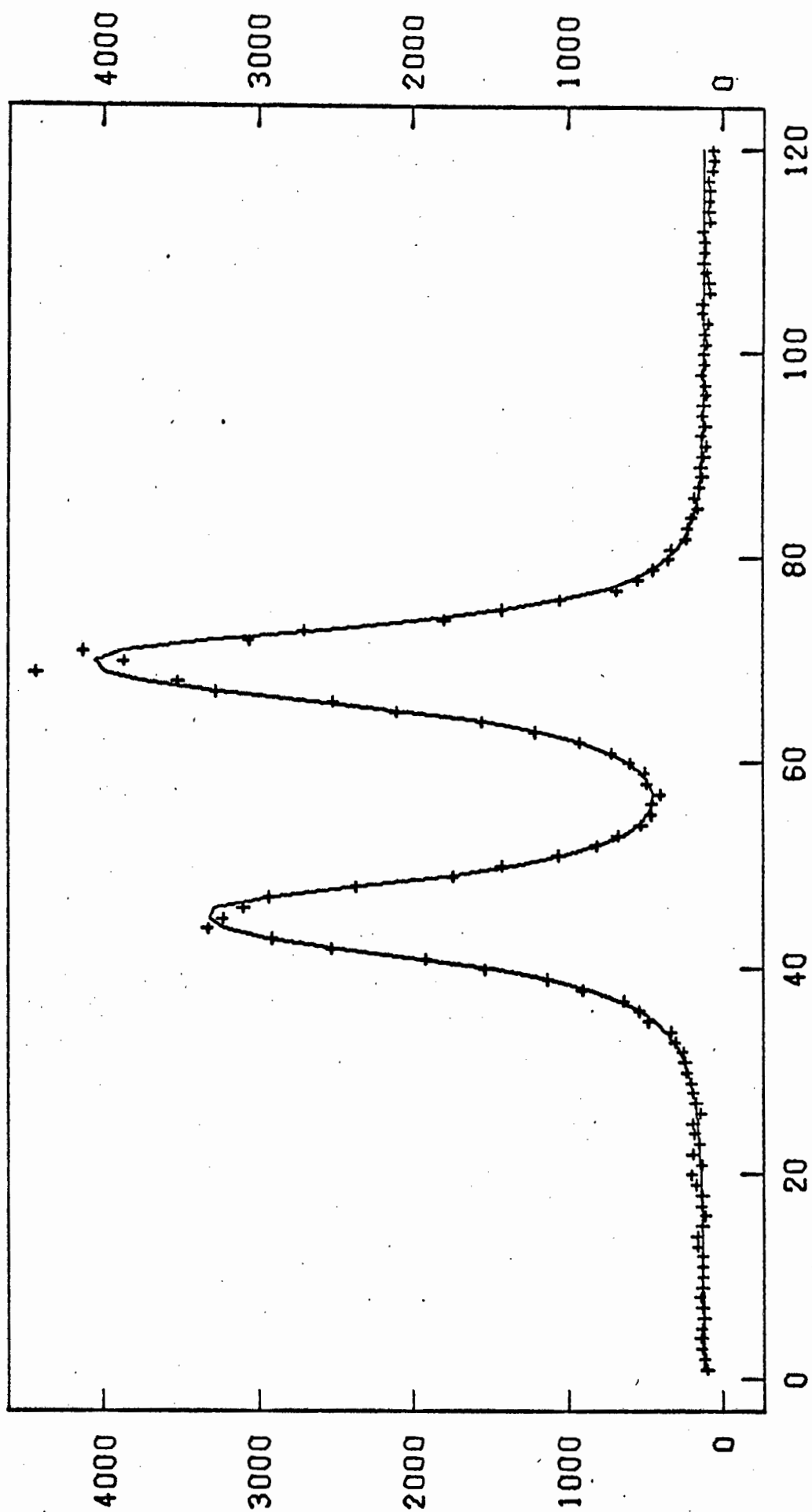


Figure 11. HD 81695. 1520 scans in U. 4 scans per integration. Fitted $\Delta U: 0.23 \pm 0.03$. Separation: 5"59. Separation standard not included in Tables I or II. 5 mm wobble plate.

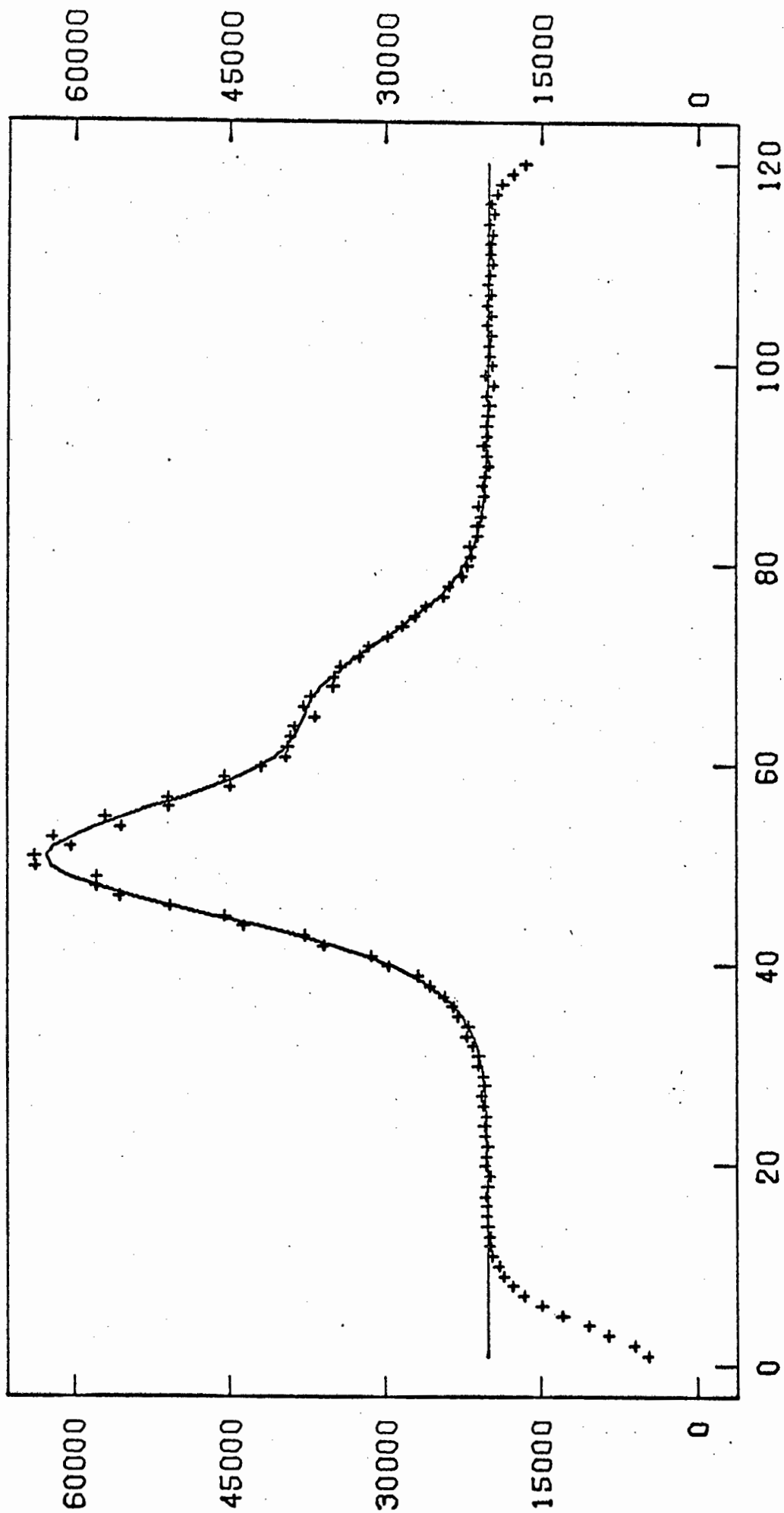


Figure 12. HR 7989. 1526 scans in U. 1 scan per integration. Fitted $\Delta U: 1.18^m \pm 0.05^m$. Separation (Table I): 1'85.

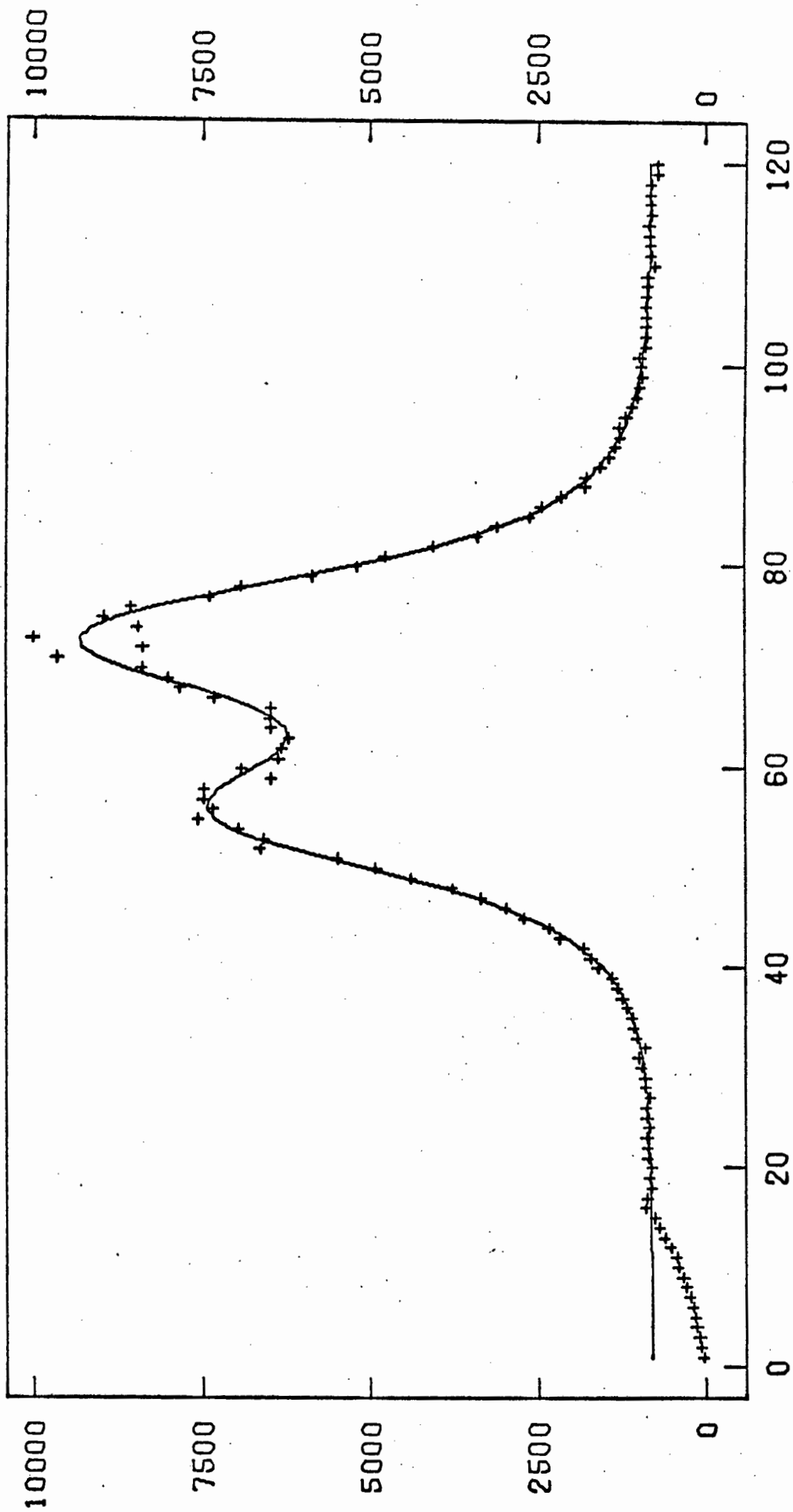


Figure 13: HR 3399. 2060 scans in U. 4 scans per integration. Fitted $\Delta U: 0^m32 \pm 0^m03$. Separation (Table I): 1^m92.

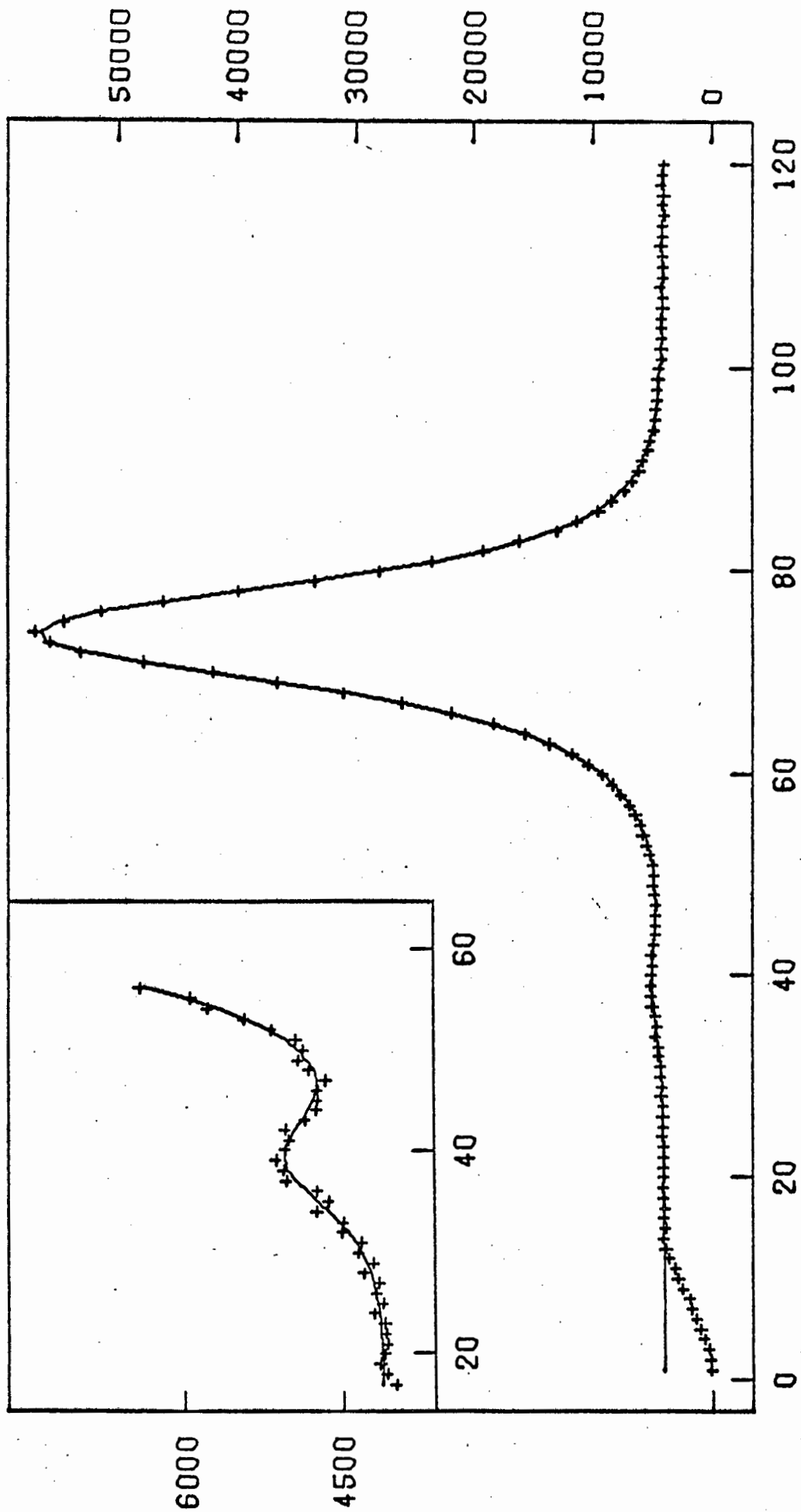


Figure 14. HR 1058. 476 scans in U. 1 scan per integration. Fitted $\Delta U: 4^m.44 \pm 0^m.05$. Separation (Table I): $6^s.22$. 5 mm wobble plate.

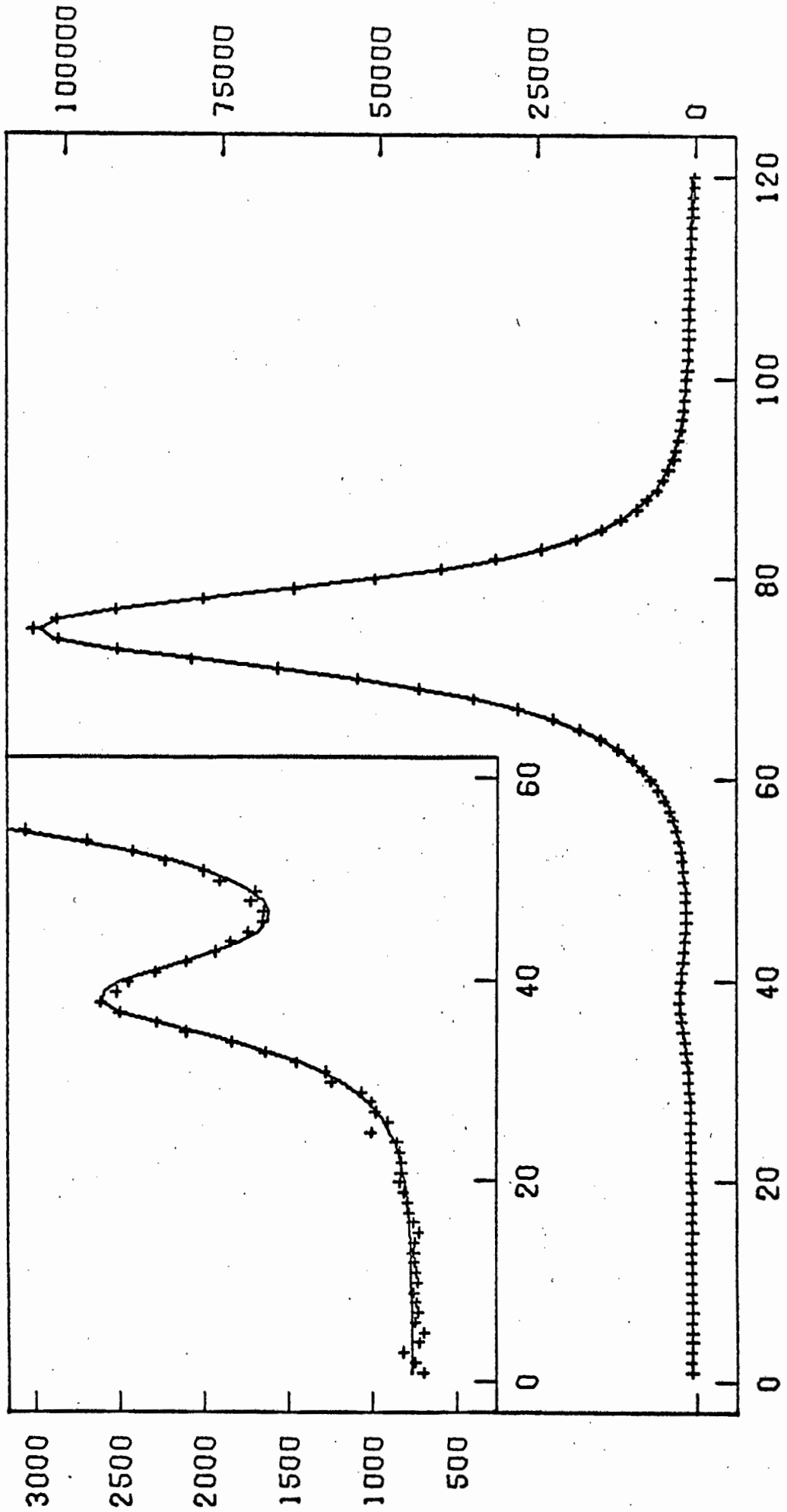


Figure 15. HR 1058. 897 scans in U. 1 scan per integration. Fitted $\Delta U: 4.44^m \pm 0.03^m$. Separation (Table I): $6.22. \quad 5 \text{ mm wobble plate.}$

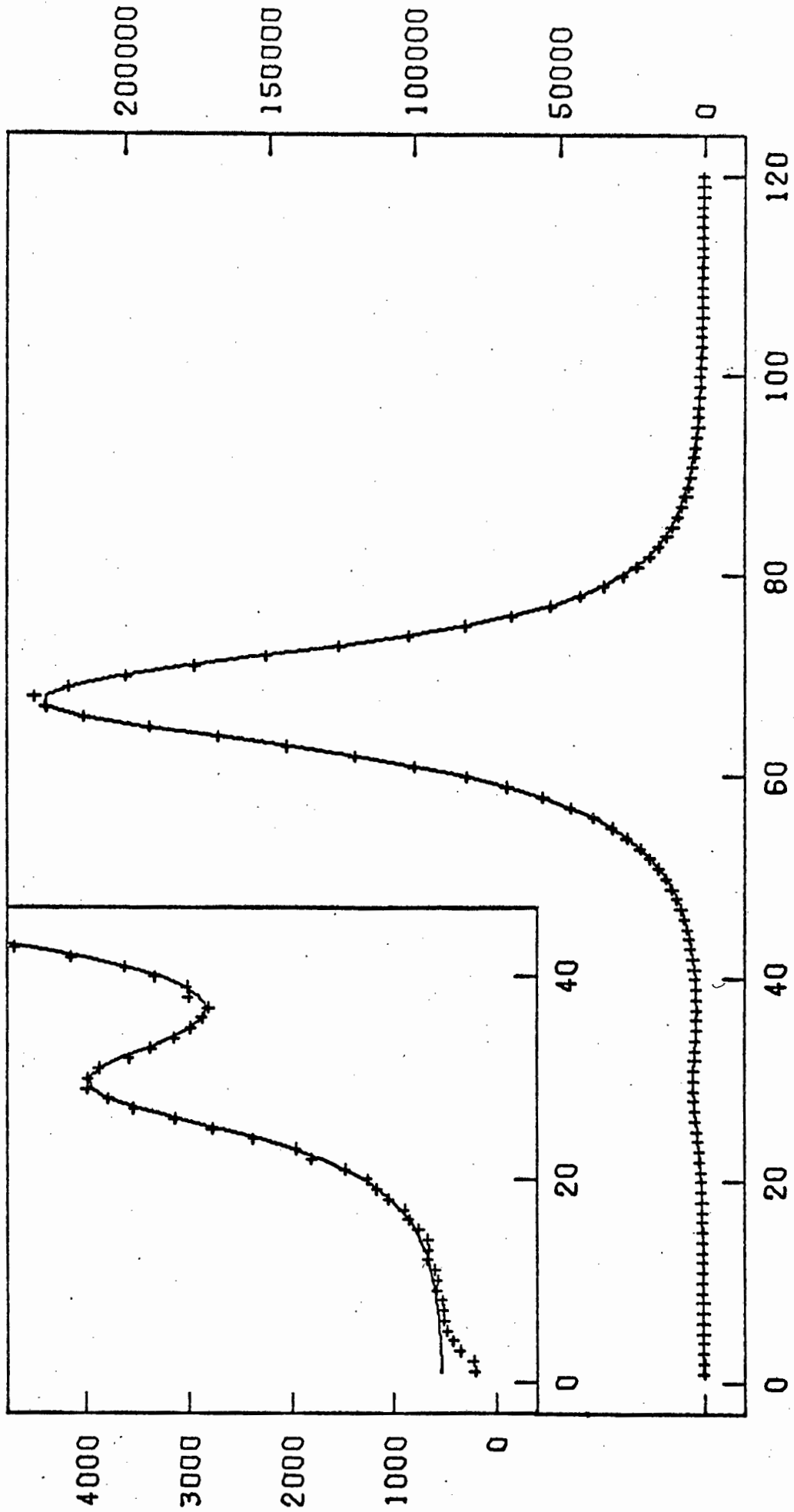


Figure 16. HR 3432. 768 scans in V. 1 scan per integration. Fitted $\Delta V: 4.67 \pm 0.02$. Separation (Table D): 6"50. 5 mm wobble plate.

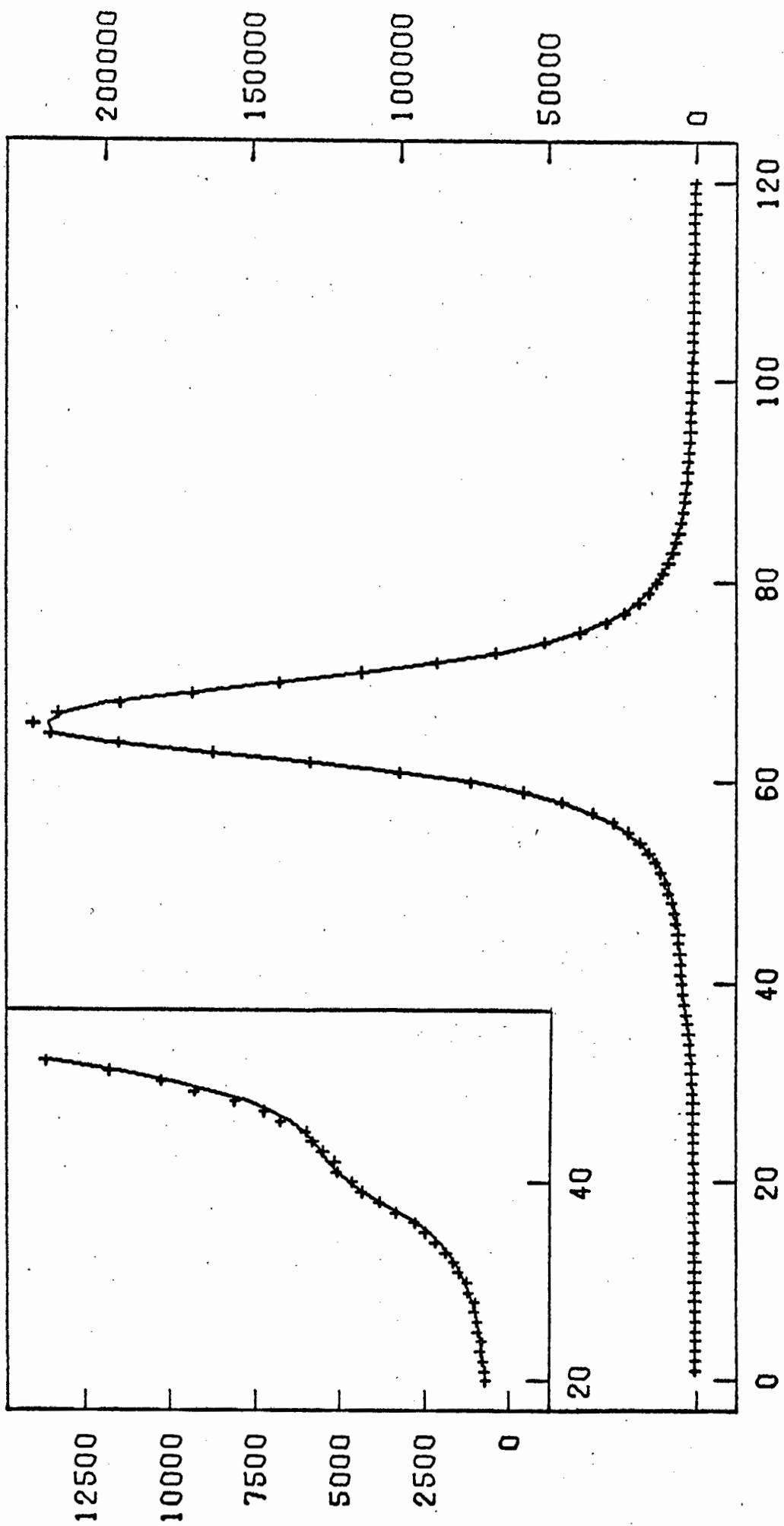


Figure 17. HR 436. 534 scans in V. 1 scan per integration. Fitted $\Delta V = 5.07 \pm 0.06$ m. Separation (Table I): 2''93.

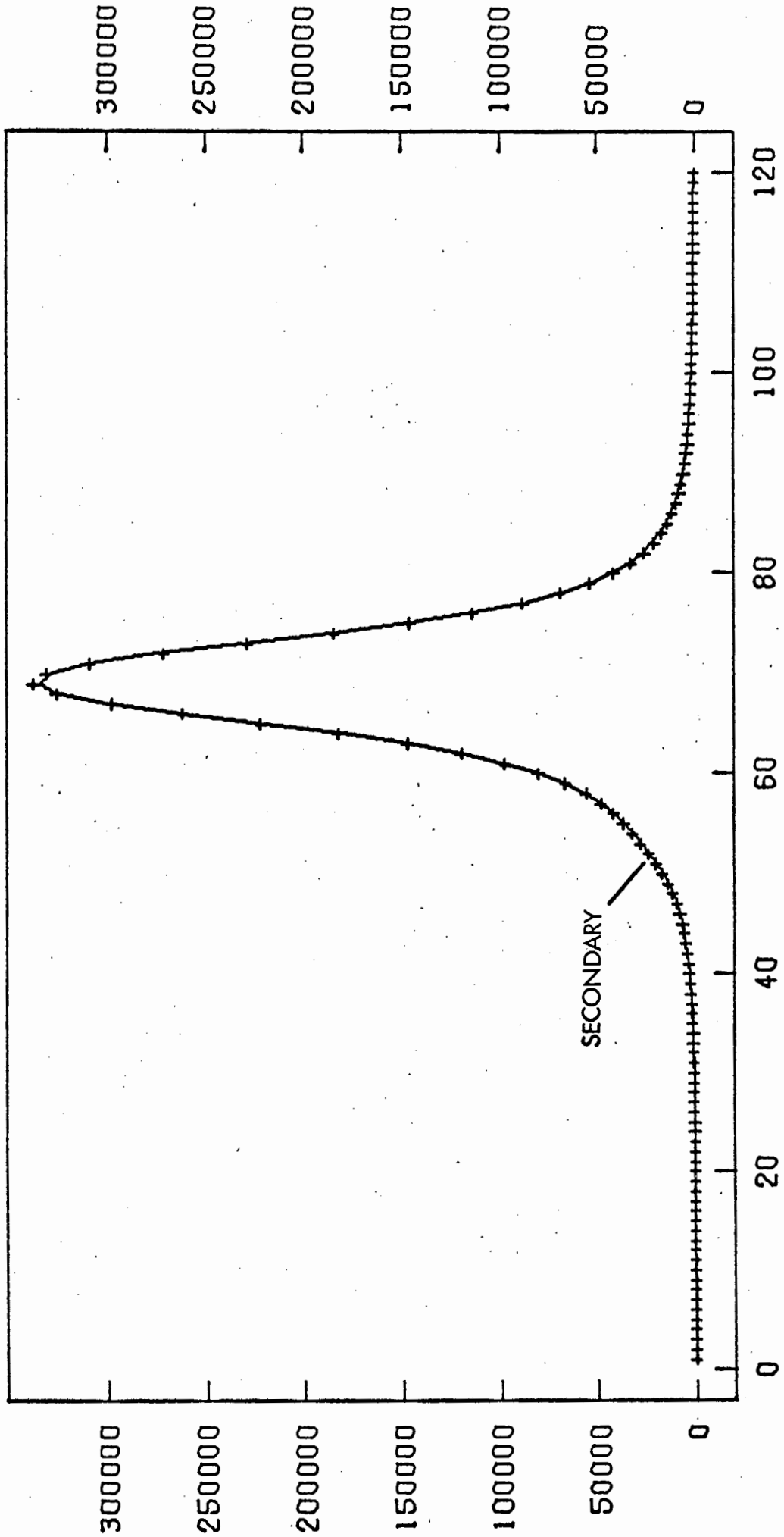


Figure 18. HR 2412. 332 scans in B. 1 scan per integration. Fitted $\Delta B: 3^m.92 + 0^m.06$. Separation (Table D): $2^m.42$. 5 mm wobble plate.

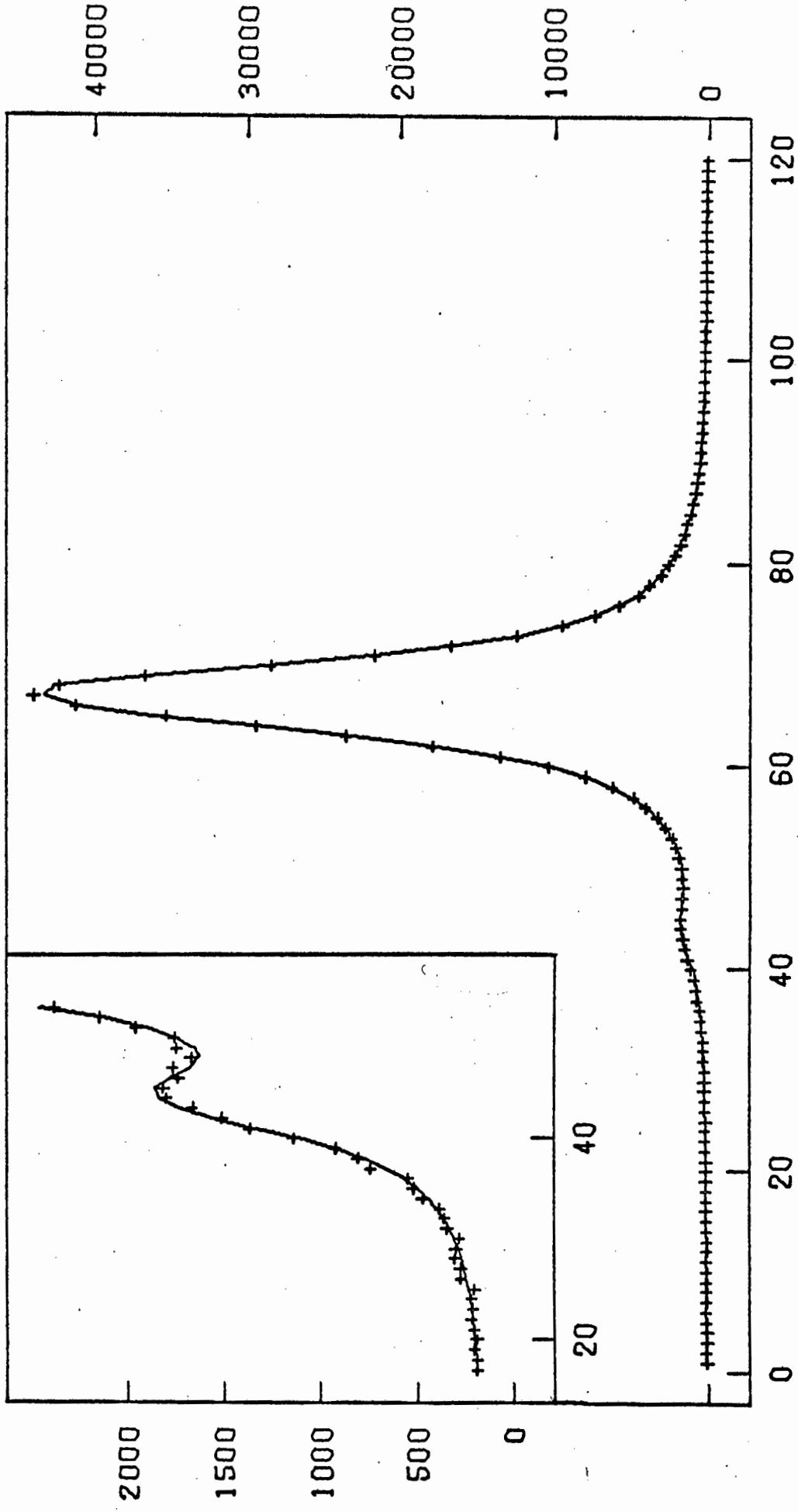


Figure 19. HR 4636. 1119 scans in V. 1 scan per integration. Fitted $\Delta V: 3.94 \pm 0.04$. Separation (Table I): 2.62.

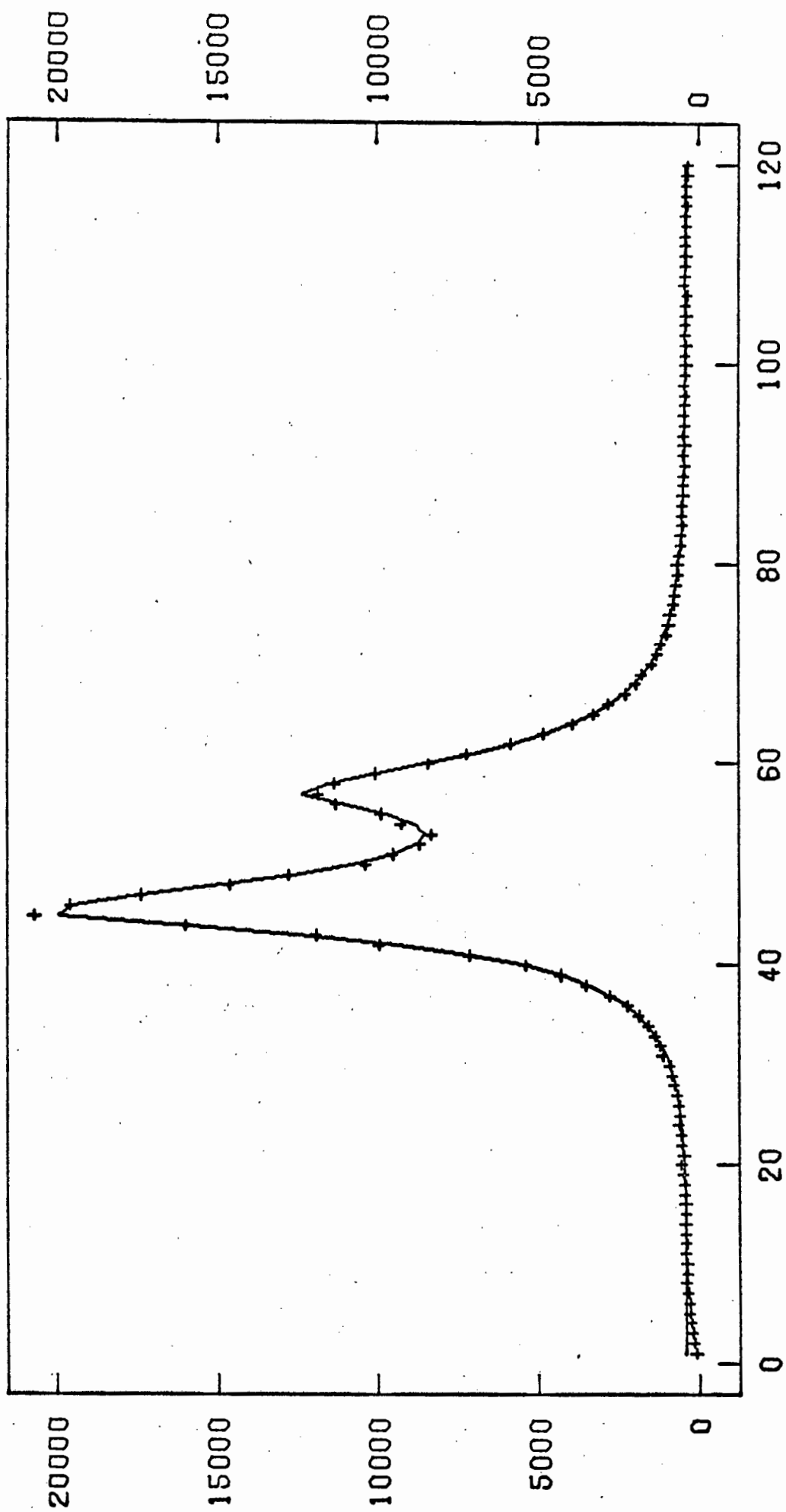


Figure 20. HR 4262. 1564 scans in V. 1 scan per integration. Fitted $\Delta V: \delta^m_{.72} \pm \delta^m_{.02}$. Separation (Table I): 1".42.

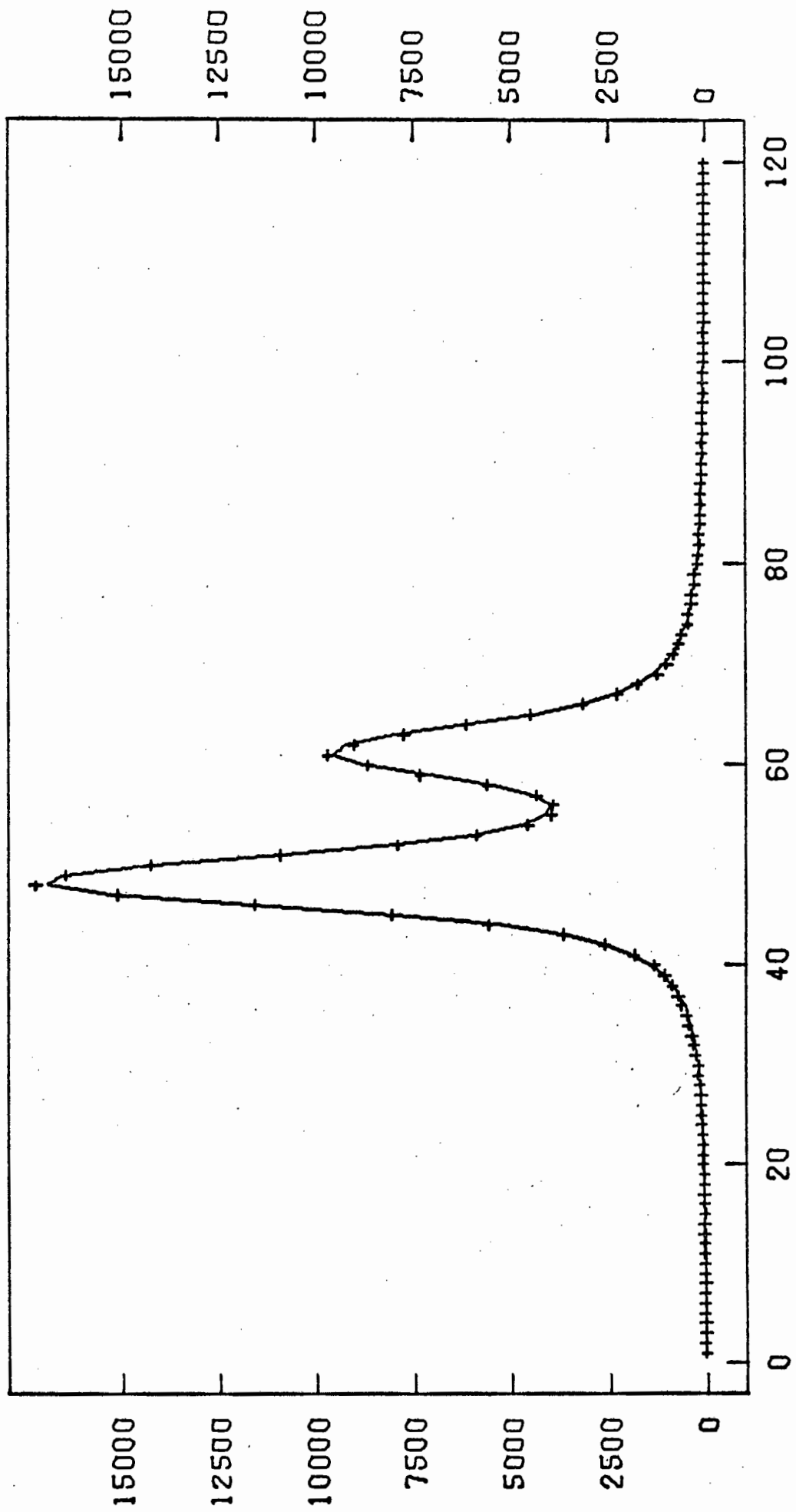


Figure 21. HR 4262. 284 scans in V. 1 scan per integration. Fitted $\Delta V: 0.68 \pm 0.02$. Separation (Table I): 1.42.

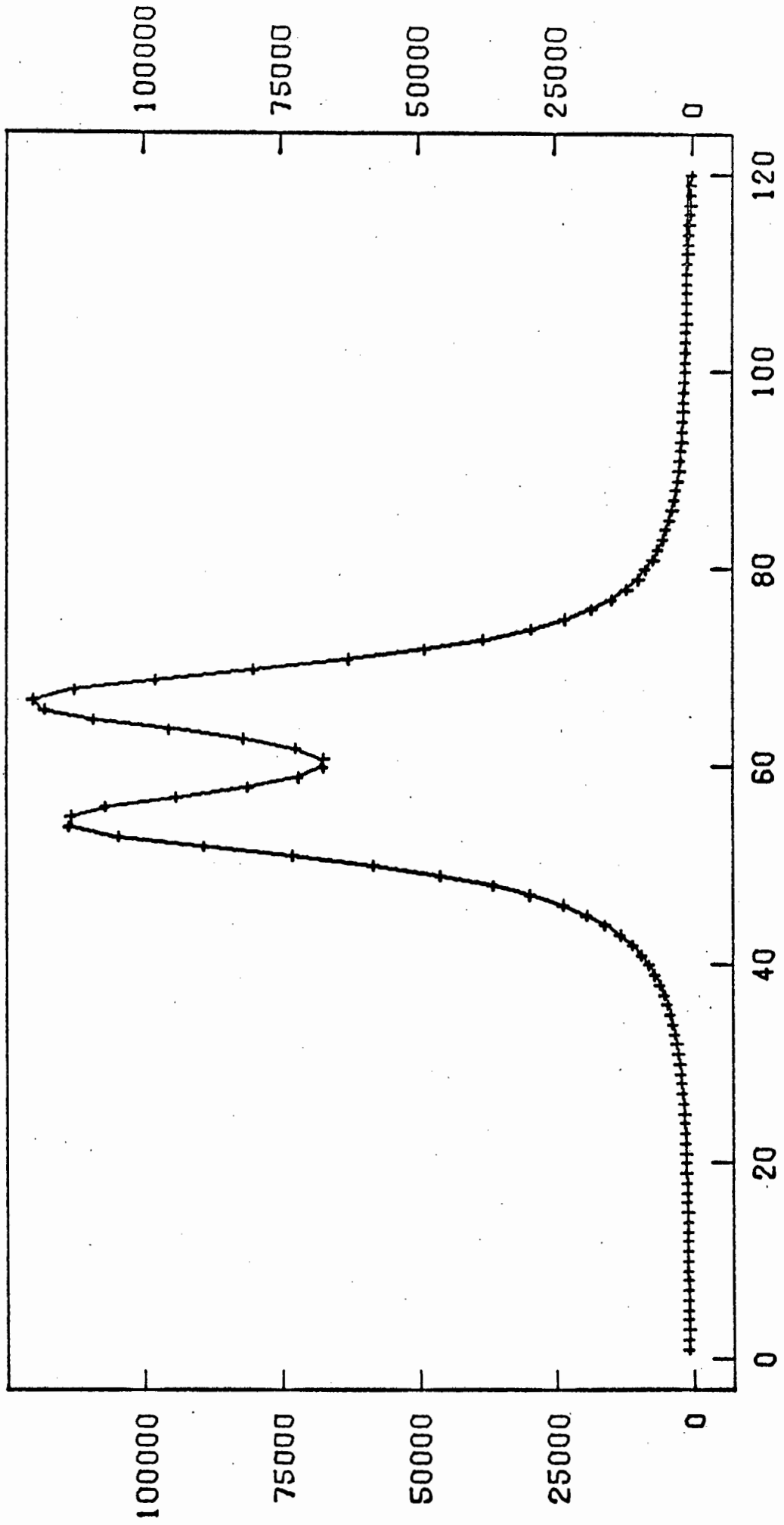


Figure 22. HR 24. 271 scans in V. 1 scan per integration. Fitted $\Delta V: 0.087^m \pm 0.004^m$. Fitted separation: 1.40 ± 0.03 . Separation (Table I): 1.40 ± 0.03 .

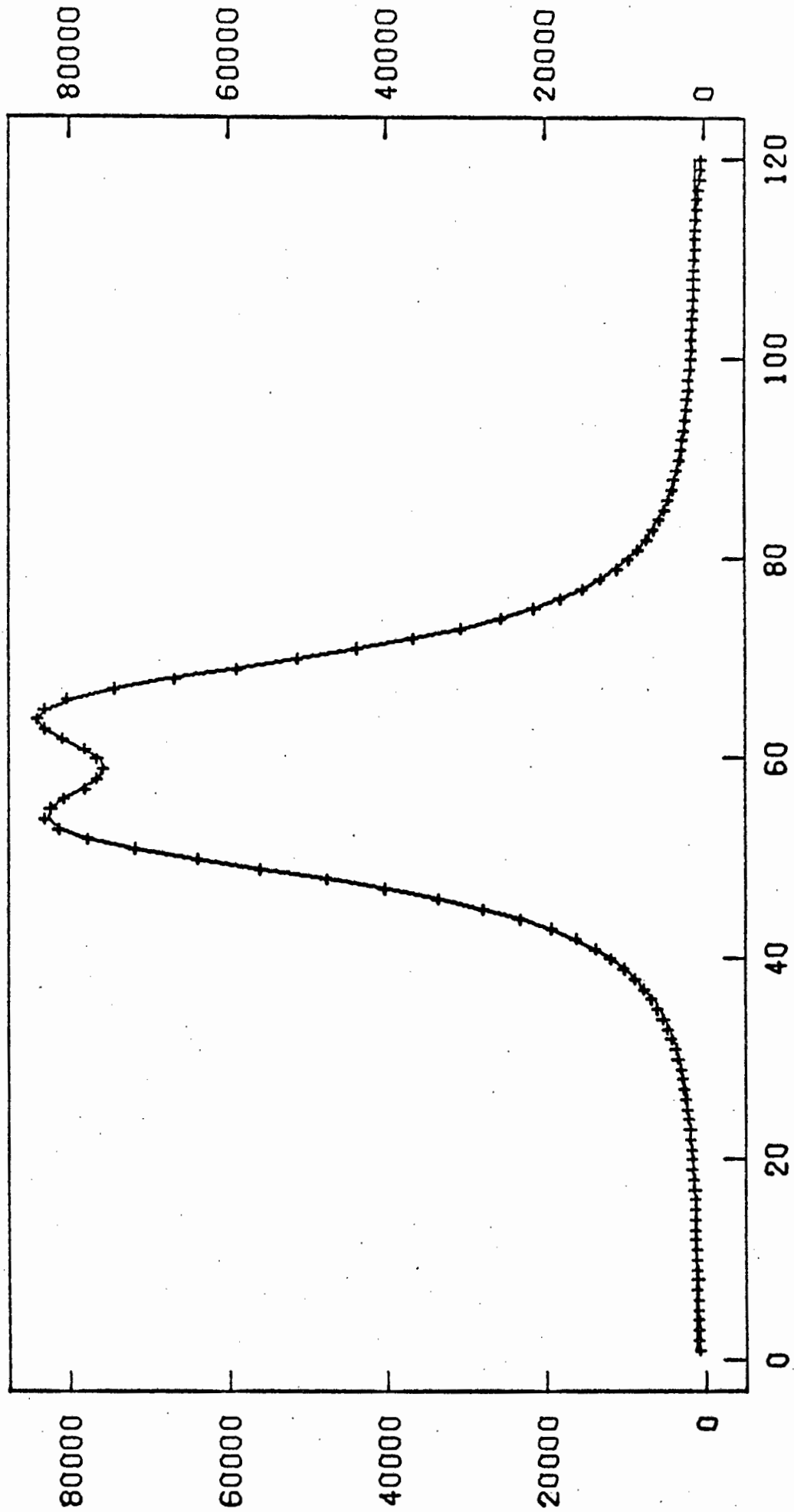


Figure 23. HR 24. 290 scans in V. 1 scan per integration. Fitted $\Delta V: 0^m.013 \pm 0^m.005$. Fitted separation: $1^m.39$. Separation (Table I): $1^m.40 \pm 0.03$.

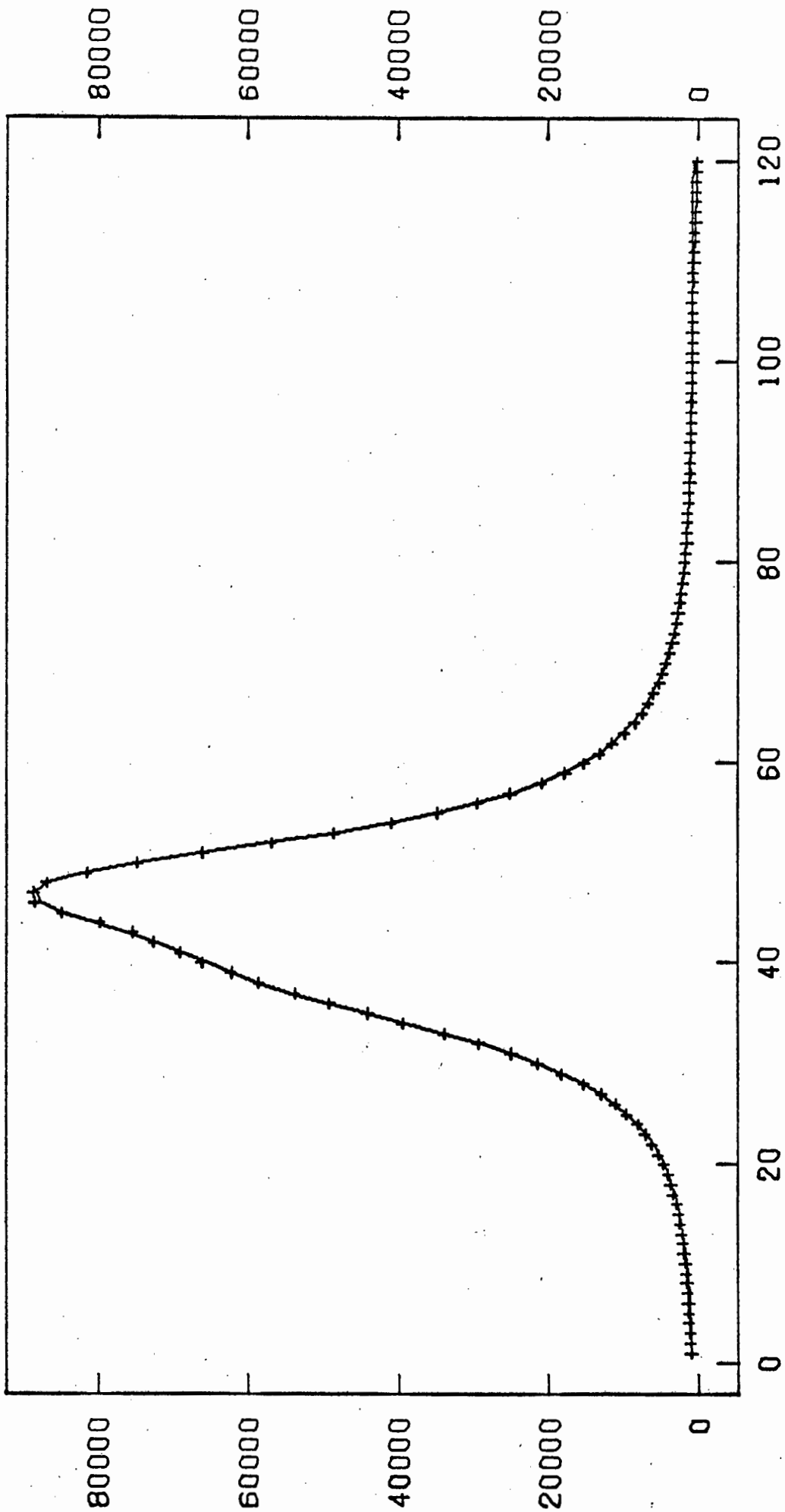


Figure 24. HR 6426. 468 scans in V. 1 scan per integration. Fitted $\Delta V: 0.972 \pm 0.014$. Fitted separation: 1.06.

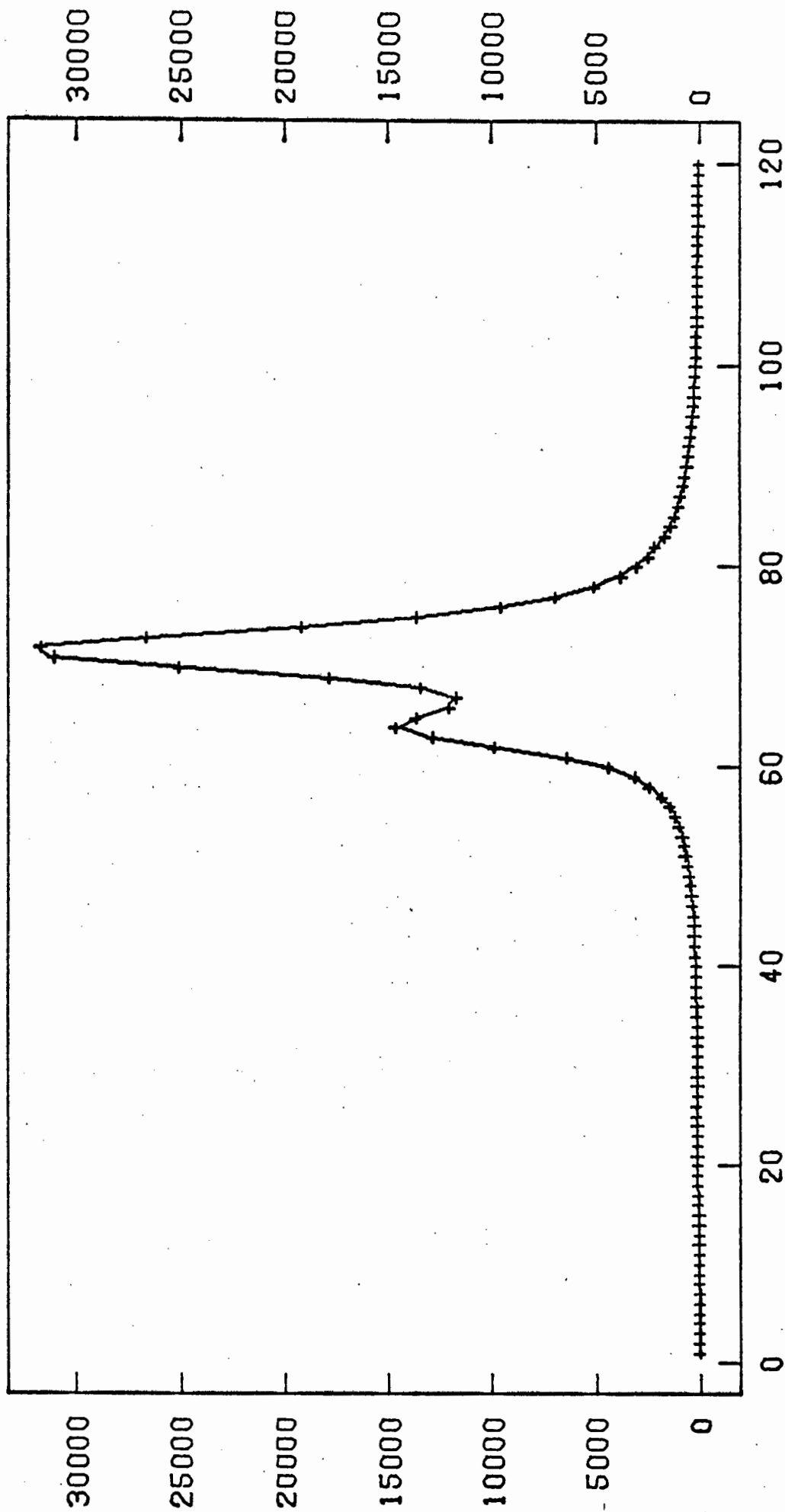


Figure 25. HR 6426. 406 scans in V. 1 scan per integration. Fitted ΔV : 1.035 ± 0.014 . Fitted separation: 0.85 .

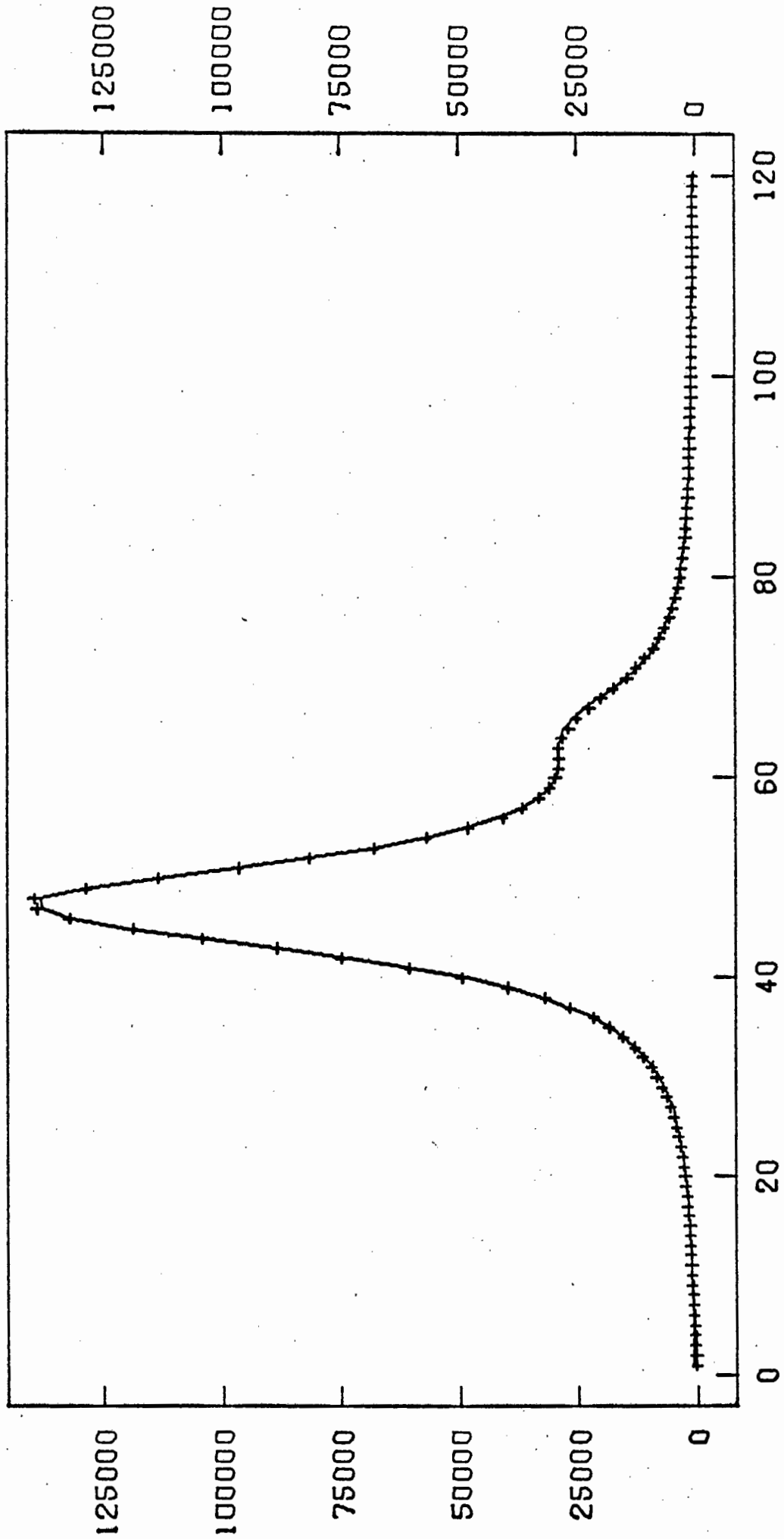


Figure 26. HR 7989. 1209 scans in V. 1 scan per integration. Fitted $\Delta V: 2.16 \pm 0.02$. Separation (Table I): 1"85.

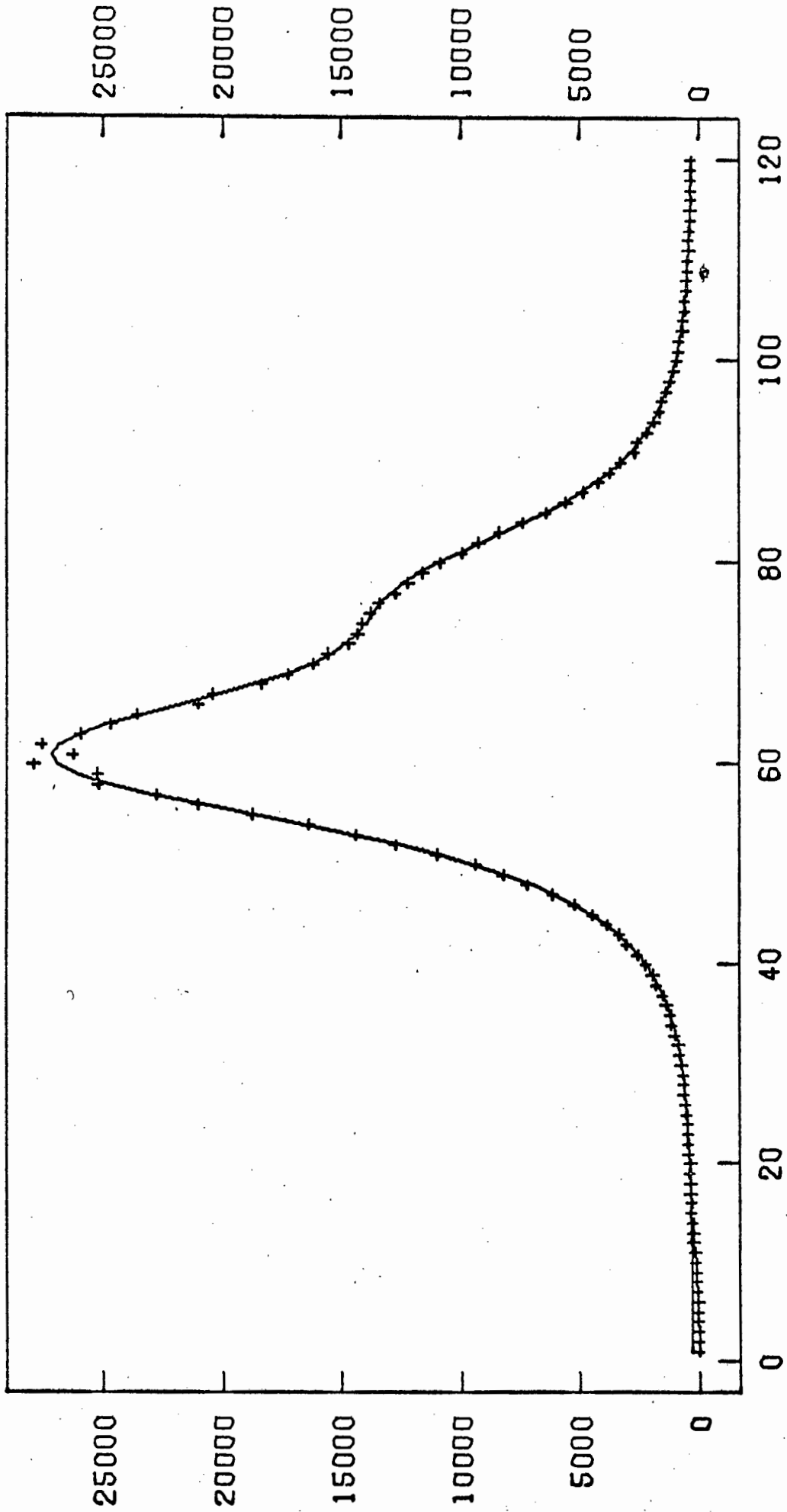


Figure 27. HR 7989. 1190 scans in U. 2 scans per integration. Fitted $\Delta U: 1.18 \pm 0.02$. Separation (Table I): 1.85.

offset guider eyepiece. This observation was made with the slit tilted to give an effective separation less than the true separation of the star.

Figure 10 shows a badly asymmetric profile obtained on the 1 metre telescope. The observed profile is probably asymmetric due to wrong centreing of the scans (see Sections 7.4 and 7.6) and the fitting program has not been able to obtain a good fit, especially for the secondary. However the magnitude difference (transformed to the UBV system) differs from the mean for the star by little more than the 0.02^m fitted error.

Figure 11 shows a profile obtained on a faint star. Due to the low count rate there is considerable noise. The noise at the top of the primary peak is however very much larger than it should be. This effect occurred quite frequently and it is believed to be caused by the correlation process (see Section 3.4.2). This observation was made on the 75 cm telescope and the effect of the image flare is just visible.

Figure 12 shows a profile obtained on a faint star using the 1 metre telescope. There is considerable noise and an unexplained "twinning" of points similar to that obtained on the 50 cm telescope and explained as being due to telescope wobble (see Section 6.10). The twinning in this profile may be due to the same cause despite the fact that the 1 metre telescope was used. This profile and the V and B profiles obtained immediately afterwards were not used in obtaining the means for the photometry of HR 7989 in Table I. ΔU in Table I is 1.19^m so the fitted value for ΔU is in good agreement with the mean. Figure 12 also illustrates the losses in the bins on either end of the scan which occur because of the shifting of the scans in the correlation process (see Section 3.4.2).

It is normal for more bins to be affected on one end of the scan than on the other because the shifting is mostly necessary because of backlash and tracking problems (see Section 3.4.2) rather than image motion.

Figure 13 shows another profile obtained on a faint star. Once more the top of the observed primary peak is noisier than it should be. The losses at the left of the scan are again obvious, 15 bins being affected in this case (the maximum allowable shift being 16 bins).

Figures 14 and 15 show two profiles obtained on the same star using the same telescope and the same slit and with the equipment in all other respects identical. The profiles were obtained 5 weeks apart with rather different seeing and background light level. In Figure 14 the fitted background light level is about 4.7 times greater than the contribution from the secondary at the top of the secondary peak. In both Figures 14 and 15 there is also some light from the primary falling into the bins under the secondary peak. These figures are also discussed in Section 7.6.

Figure 16 shows a good fit obtained for the secondary peak on a profile of a wide star with large magnitude difference obtained in good, but not exceptional, seeing.

Figure 17 shows a profile obtained in exceptionally good seeing. A slight systematic misfit occurs at the secondary "bump". With the present scanner observations of stars like HR 436 are inaccurate and possibly give systematically wrong magnitude differences.

Figure 18 shows a profile obtained in seeing slightly worse than that of Figure 17. Note that a different wobble plate was used (on the same telescope). The fact that HR 2412 is 0!5 closer than HR 436 (and the seeing slightly worse) more than offsets the 1.2^m smaller magnitude difference

and the secondary bump is almost invisible on the profile. An error in the fitted magnitude difference much larger than the fitted error seems very probable.

Figure 19 shows an exceptionally good profile obtained on another difficult star. The number of counts from the secondary is low due to its faintness.

Figures 20 and 21 show profiles of a very close star with small magnitude difference. These profiles were obtained on the 1 metre telescope 10 weeks apart using different slits and different photomultiplier tubes.

Figures 22 and 23 show profiles of a very close star with very small magnitude difference. These profiles were obtained 4 weeks apart on the 1 metre telescope. The separation between the highest points of the peaks in Figure 23 appears to be very much less than that between the highest points of the peaks in Figure 22. This is due to the heavy overlap of the peaks in Figure 23 - the light curve from one peak is decreasing steeply at the bin corresponding to the rather flat topped maximum of the other peak and hence the maximum of the "summed" curves is displaced. The separations fitted by the fitting program are unaffected and are in acceptable agreement. The overlap of the star images in the focal plane would have been much less than shown in the figures - the slit width is an appreciable fraction of the separation. The magnitude difference fitted for the profile in Figure 23 is discordant and differs from the mean (Table I) by 13 times its fitted error. The reason for this discrepancy is not known. Such unexplained discordancies of magnitude differences were rare.

Figures 24 and 25 show profiles of HR 6426, the closest star

we observed. Figure 24 shows a profile obtained in April 1973, Figure 25 one obtained in June 1974. The state of the equipment was very different for the two observations which were both made on the 1 metre telescope. However the main cause of the different appearances of the profiles is the difference in seeing. The change in separations is real.

Figures 26 and 27 show profiles of the same star obtained a few minutes apart using V and U filters respectively. Due mainly to worse seeing in U the primary peak is much broader in U than in V so that, despite a much smaller magnitude difference in U, the secondary forms a very much less pronounced bump on the side of the primary peak in the U profile than it does in the V profile.

Two further illustrations of fits are given in Figures 28 and 29 in Section 7.4.

using all observed constant stars for which combined light magnitudes and colours are already available as standards. Each star has therefore to be identified and information supplied about it. V, B and U zero points are separately calculated by making the sum of residuals zero for the stars used as standards. Corrections are made to bring the magnitudes onto the UBV system. The sidereal time, hour angle or sec Z of each observation can be used by the program to be correct for extinction. Stars for which no combined light photometry is available and stars specifically designated as variable (they may, for example, be constant stars observed through cloud) are not used in obtaining the zero points. Provision is made for the effects of using the two wobble plates. However if different slits are used on the same night (a rare occurrence) then stars not observed with the most commonly used slit must be declared variable.

The program calculates the root mean square of the residuals in V, B and U for the stars used as standards. These can then be used to estimate the errors in the calculated V, B, U magnitudes of the other stars. The zero points and root mean square of the residuals are printed followed by the results for each star in turn. The name, known combined light photometry (if any), calculated V, B, U and residuals (if known) are printed for each star. In order to keep the program simple and versatile colours are not calculated. A plot of residuals versus known (B-V) is printed for each of V, B and U.

The fitted separations (in our arbitrary units) are averaged for each observation of a standard star. Separations obtained with different filters can be averaged - see Sections 5.1, 5.2 and 6.2. The known separation of the standard is divided by this average to obtain the scale factor

in arcsecs per arbitrary unit. An error reflecting the disagreement between the fitted separations with the different filters is calculated for each scale factor. These errors are later used to judge the quality of the scale factors so that unreliable ones can be rejected. A list of the standards observed, the resulting scale factors and their errors is printed by the program. The scale factors thus obtained for each telescope and wobble plate combination are averaged by hand to get mean factors (see Section 7.4) for use in determining separations of the program stars in arcsecs (see Section 7.5).

7.3 The MAGCHK program: Photometry results

The root mean square of residuals in V, in B and in U was about 0.03^m on the best nights. If residuals for B-V and U-B had been calculated these would have been smaller. However many nights gave much higher residuals. Some of these nights were recorded as cloudy, others probably were non-photometric but this was not noticed. Those nights on which the wobble plate problem described in Section 7.4 was most severe tended, not surprisingly, to have high residuals. It is possible, but unlikely, that the relative magnitudes would be significantly affected by the preferential rejection of scans (see Section 3.4.2) for which scintillation decreases the total counts below the mean. Such rejections were in fact extremely rare. Use of the more correct method of calculating the relative magnitudes did not decrease the root mean square residuals significantly (see Section 6.8.4).

While the combined light magnitude and colours obtained were used as evidence to deny variability in some stars we did not have sufficient

confidence in these results to use them to support claims of variability. We also found that using the magnitudes and colours as combined light photometry for known variables did not give good results when calculating magnitudes and colours of the components.

7.4 The MAGCHK program: Scale factors

The scale factors obtained for any one telescope, wobble plate and gearing were found to have a range of about 6%. This range was far greater than expected and seemed to indicate some underlying error. The fact that the scale factors obtained for the same star on different nights in the same observing run or in a different run showed a considerable range was particularly worrying. The fault therefore had to lie in the equipment or in the reduction. The scale factors for the original 4:1 gearing and 3 mm wobble plate did not seem to vary systematically from observing run to observing run and gave mean scale factors with acceptably small standard errors so the fault was not considered serious.

However a 5% difference between the mean scale factors obtained on one, apparently very good, observing run and the two immediately preceding runs on the same telescope using the same 4.032:1 gearing and both wobble plates prompted a more thorough investigation. It was found that changes in scale factor of the correct magnitude could be expected by using in the fitting program bin positions shifted by about 30 bins. This implied that the oscillations of the wobble plate were centred on a position 30 steps (i.e. about 15°) away from the horizontal. It is possible that the oscillations of the wobble plate could have been centred 15° wrong on occasion. The wobble plate makes about 4 scans per second, two in each direction,

and there are no scales for reading the angle of rotation of the shaft. An error of 15° in the centring would in fact be difficult to detect directly by watching the oscillating shaft. In practice the motor and shaft were seldom watched while moving. However a 15° error in centring would be easily seen while the shaft is stationary. It is believed that a fault in the observing technique was responsible for the incorrect centring of the oscillations. The backlash in the gears and the way this is allowed for (see Section 3.4.1) require that the shaft be initially set with the wobble plate horizontal and the gears aligned so that there is no backlash to be taken up when the motor takes its first step. Should the gears be slack or aligned in anticipation of the motor taking its first step in the opposite direction to that in which it initially moves then an error of less than or equal to the number of steps in the backlash will result.

In order to test this explanation the fitting program was rerun on some observations of separation standard stars using bin positions shifted by 30 bins. The observations chosen were amongst those for which bad fits has been obtained (see Section 6.10). The resulting scale factors were different from those originally obtained by the amount required to remove the difference which led to the investigation of this problem. Furthermore the fits were now good and the fitted peaks more symmetric.

The improvement in the fit can be explained as follows. The image of one component was, in the actual observation, scanned across the slit when the plate was nearly horizontal thus crossing the slit slowly while the image of the other component was scanned across the slit when the plate was highly tilted and hence crossed the slit fast. There were thus more counts in the wings of the "slow" peak than in those of the "fast" peak

causing a difference in peak shapes. The normal bin positions did not allow correctly for this (the peaks being nearly equidistant from bin 60) resulting in a bad fit and an incorrect magnitude difference whereas using bin positions shifted by the appropriate amount gave a good fit and, hopefully, a good estimate of magnitude difference.

Figures 28 and 29 show the fits of an observation of HR2870/1, an 8!89 separation standard. The fit using the normal bin positions was probably the worst fit ever obtained in the sense that it had the largest systematic deviations between the observed points and the fitted curve. The fit using bin positions shifted by 30 bins is very good. The change in fitted magnitude difference is about 0.18^m so that 0.2^m should be the upper limit on errors in magnitude difference caused by this effect. This is discussed further in Section 7.6.

Small shifts would in fact have occurred as a matter of course. This is because of the difficulty in correctly estimating the backlash constant (see Sections 3.4.1 and 4.2). Errors of up to 7 or 8 bins in the backlash constant could go undetected as the method used to determine it is rather crude (see Section 4.2). Thus data recording on the forward scan might start up to 8 steps too early or too late depending on whether the backlash constant is too small or too large. The centring could therefore be wrong by up to 8 bins for the forward scans. The return scans would be correctly centred but unfortunately these would be shifted by the correlation so as to match the forward scans. The errors in separation and magnitude difference for an 8 bin shift would be less than one quarter of those expected from a 30 bin shift.

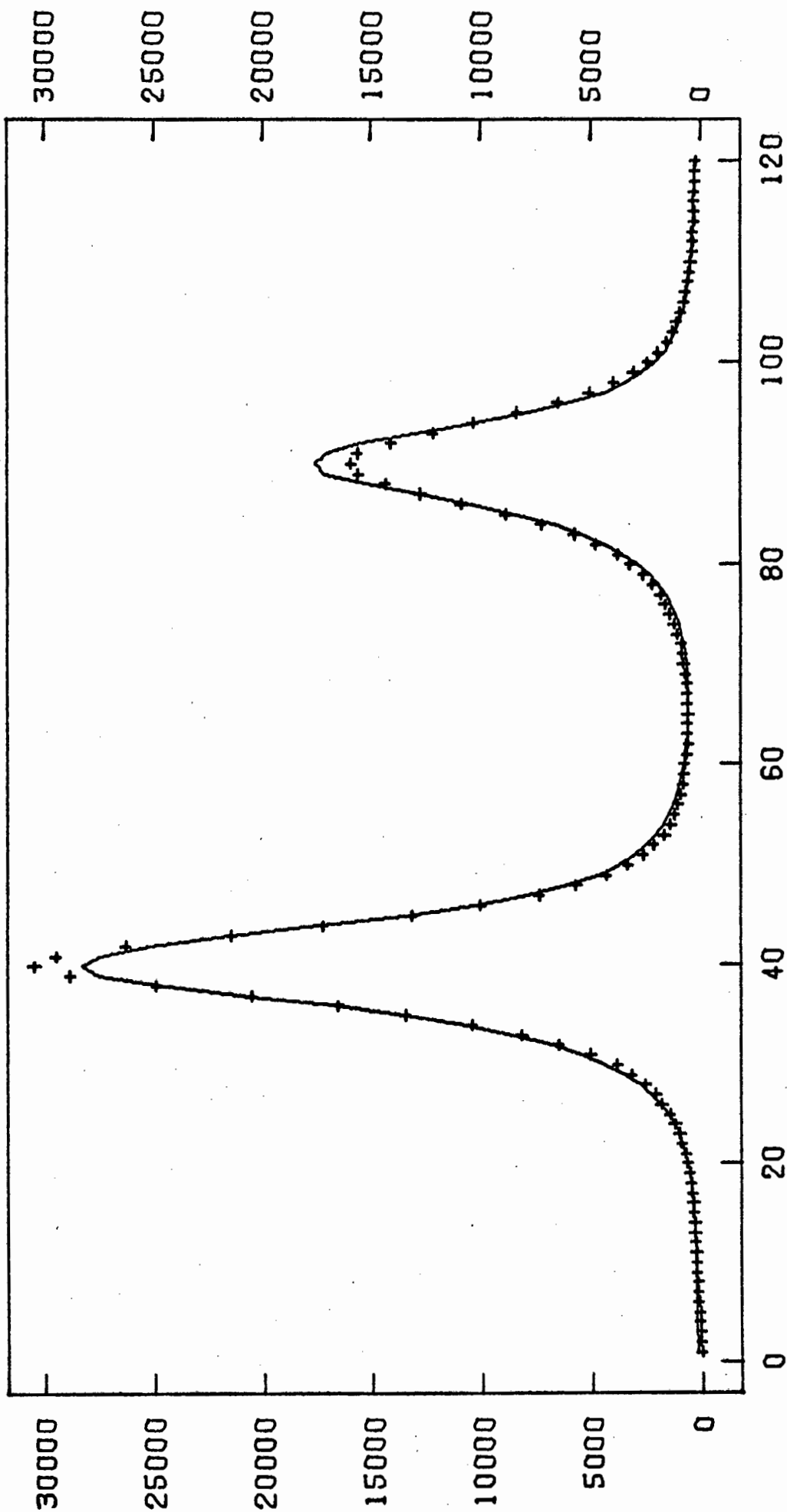


Figure 28. HR 2870/L. 196 scans in V. 1 scan per integration. Normal bin positions used in fit. Fitted ΔV : 0.52 ± 0.03 . Separation: 8.9. 5 mm wobble plate.

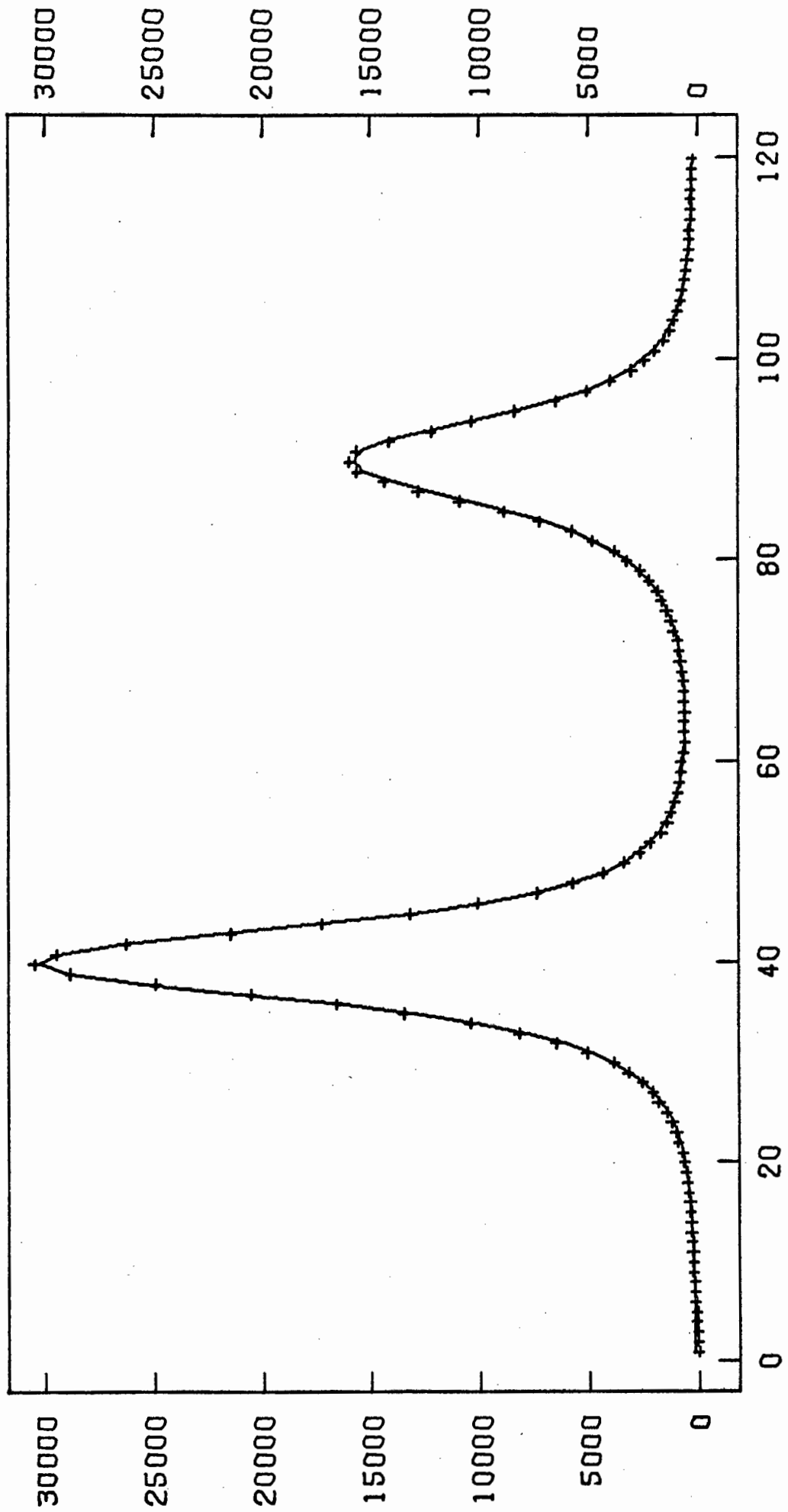


Figure 29. HR 2870/1. 196 scans in V. Bin positions shifted by 30 bins (see text, Section 7.4) used for fit.
 Fitted ΔV : 0.70 ± 0.01 . Separation: 8.9 . 5 mm wobble plate.

Since the extent of the shift occurring was variable it would not be a simple matter to correct for it in the reduction of all the observations. We could write a fitting program which tries shifting the bin positions if it cannot obtain a good fit with the normal bin positions. This has not been done because the program would be rather complicated and it would be very slow. Furthermore we feel that this would have been a dangerous procedure as there are undoubtedly other reasons for differences in shape between the peaks. Lastly we feel that the human effort and computing expenses involved would not have been justified by the improvement in the accuracy of the separations and magnitudes which might have been obtained. We therefore decided to do as best we could using the separations and magnitude differences obtained using the normal bin positions. The consequences of this decision will be discussed in Section 7.6.

The scale factors actually used in calculating the separations of the stars in seconds of arc from the separations in our arbitrary units are given in an Appendix. It should be noted that most of the observations were made using the 50 cm and 100 cm telescopes, the 3 mm plate and the original 4:1 gearing and that really bad fits were rare for these observations. The scale factors obtained and used for these two cases were 0.06565 and 0.03893 arcsecs per unit respectively for the 50 cm and 100 cm telescopes. The standard errors of the means for these scale factors were 0.00024 and 0.00019 arcsecs per unit respectively. It should also be noted that special scale factors were used for the observations made during the two observing runs most affected by the shift problem.

Because of the non-linearity of the scan it is not possible to give accurate scales in arcsec/bin (i. e. arcsec/step). However the following very rough values give an idea of the scales used. The 5 mm wobble plate scales are given in brackets after the 3 mm plate scales.

50 cm Telescope	0.20 (0.33) arcsecs/bin
75 cm Telescope	0.14 (0.24) arcsecs/bin
100 cm Telescope	0.11 (0.18) arcsecs/bin

7.5 The UBVCN Program: Principles

This program calculates magnitudes and colours of the components of double stars from the differences in magnitude in V, B and U and the separations between the components in seconds of arc from the fitted values in arbitrary units. The photometric and astrometric calculations are essentially separate so an option is included in the program which allows the photometric calculations only, the astrometric calculations only, or both sets of calculations to be performed.

The data cards produced by the fitting program must be sorted by hand. The cards containing the data for all observations on a star are arranged behind a "heading" card containing information on that star. These heading cards are actually the same as the ones used by the MAG-CHK program. For variable stars combined light magnitudes and colours for each observation can be supplied. Otherwise the combined light values given on the heading card are used in the calculations. Other cards can be inserted amongst the data cards for various purposes. Provision is made for excluding individual magnitude differences from the means. The scale factors to be used and look-up tables enabling the date, telescope,

filters and tube used and wobble plate and gearing used to be ascertained for any observation are supplied on cards. These are read before the data cards pertaining to the individual stars.

The main program UBVCON reads and prints various preliminary data and the look-up tables. The data for one star is then read. Various rearrangements of the data are done by the subroutine PRELIM before the subroutines in which the photometric and astrometric calculations are done are called.

The subroutine UBVCLC calculates the magnitudes and colours for the components of a star. The fitted differences in magnitude in U, B and V are first corrected (using subroutine CORREC) to bring them onto the UBV system. The magnitudes and colours of the components are then calculated by one of two methods. Either the V, B and U magnitude differences are weighted and averaged separately and the mean differences used to calculate the magnitudes and colours of the components (using subroutine MAGCOL) or the magnitudes and colours of the components are calculated for each observation (using MAGCOL) and the weighted means of these calculated. Variable stars for which combined light photometry is supplied for each observation are always treated in the latter way. For the first method the weights used are proportional to the inverse of the sum of the squares of the fitted percentage errors in the peak heights of the components (see Section 6.6). For the second method obtaining weights is rather more tedious but the basic idea is the same. In neither case are there limits on the permitted weights.

The residuals with respect to the weighted means, the weighted residuals and the standard deviations of the single readings and of the

means are then calculated. For each mean the result which has the highest weighted residual is rejected if the probability of obtaining this residual is less than $1/(2 \times \text{number of results in mean})$. If any results are rejected the appropriate means are recalculated. This procedure is repeated until no more results are rejected. In the case of the method using averaged magnitude differences the magnitudes and colours are calculated once the last of any rejections of results have taken place. The errors in these magnitudes and colours are then estimated. Suitable printing is done and the final magnitudes and colours are punched.

The subroutine SEPS calculates the separation in arcsecs for the components of a star. For each observation the appropriate scale factor is selected (see Section 5.2) and the separations in arbitrary units as fitted by the fitting program to the profiles obtained using the various filters are converted into seconds of arc and averaged. The (unweighted) standard error of this mean is calculated - usually there are only 3 separations measured per observation. The separations obtained from the various observations are then averaged, with weighting as the inverse of $(100 \times \text{std. error of mean sep. for observation} / \text{mean sep. for observation})^2$ i.e. essentially as $1/(\text{percentage error})^2$. A maximum weight of 4 is arbitrarily imposed. This corresponds to a standard error of the separations from one observation of $\frac{1}{2}\%$ of the mean separation. No minimum weight is set. The mean separations (and their standard errors) for observations made using each different telescope/wobble plate/gearing are calculated as well as the mean separation for all the observations together with its standard error and (weighted) epoch. Provision is made for excluding observations from the mean. All the calculated separations,

means, errors and so forth are printed and the final mean, its error, its epoch, and the number of observations in the mean are punched on a card.

7.6 Obtaining the final magnitudes and colours

The stars were grouped into batches and the UBVCN program was run on the data for these batches. Each batch was analysed by both of the methods outlined in Section 7.5 above to obtain magnitudes and colours. Several runs of the program were usually necessary as minor alterations had to be made to the data.

There were very few stars for which the colours obtained for the components using the two methods of analysis were significantly different. These were mostly stars for which the colours had large errors by either method. However it was found that the errors in the colours were frequently much greater using the method of analysis which averages the magnitude differences for each filter and then calculates magnitudes and colours of the components. This indicated that systematic effects were present, the magnitude differences for the colours tending to move together. The alternative method was thus preferred and the results it gave were used for the final colours and errors. Using this method the (weighted) standard errors of the single readings showed up the same effect. In fairly many cases high standard error of a single reading for V magnitude of a component showed that the scatter in V values was higher than the fitting errors used in the weighting would suggest. However for the colours of the components the standard errors of the single readings were usually as expected.

There were probably many causes for this tendency of the fitted magnitude differences for the different filters to move together. One cause probably was a systematic (seeing-dependent?) incorrect fitting of the secondaries in scans with badly overlapping profiles. These scans would be those of very close stars with fairly large magnitude differences observed when the seeing was not so good. We do not believe that this is a serious effect but investigation of its severity is difficult. The tests with different normalizations (see Section 6.8.2) suggest that systematic errors of up to a few tenths of a magnitude (several times the fitted error) might occur in some cases. On the other hand agreement between observations made on some very close stars under a wide variety of conditions suggests that serious systematic errors do not occur. For some close stars a relation between fitted magnitude difference and seeing was looked for but not found.

It would be possible to observe a wide star repeatedly on one night at various scan angles so as to make the profiles of the components overlap by different amounts. Systematic fitting errors should then be easily seen. It might even be possible to draw up a table of systematic corrections to be used on magnitude differences of close stars. However our experience suggests that essentially random errors are a more serious problem for close doubles of medium or large magnitude difference and that obtaining sufficient observations, in adequate seeing, to give a reasonably accurate result may take a long time.

Another possible cause is use of slits with possibly non-parallel sides. This does not seem to have been a significant factor however. In any case most stars were scanned horizontally (see Section 4.3). As mentioned in Section 5.6 internal reflection images can cause errors in

the magnitude differences in the case of stars with large magnitude differences. These errors would be largest (with magnitude differences too small) when the first internal reflection image of the primary falls directly on the secondary's image. As a consequence of our habit of positioning the stars at roughly equal distances from the centre of the scan this coincidence of images is unlikely. This is especially so in the case of stars with large magnitude differences as these were mostly wide. It seems that the first internal reflection image may cause a scatter in the observed magnitude differences on some stars but it is very unlikely that any significant systematic depression of the magnitude differences occurred.

The major cause of the systematic effect was certainly the incorrect centring of the wobble plate oscillations discussed in Section 7.4. Considerable time was devoted to a thorough investigation of the effects of wrong centring on the magnitudes and colours obtained. It would be expected that wrong centring would affect the magnitude differences for all filters by the same amount, this amount depending on the separation of the star and the number of bins by which the centring was out. For close stars and small errors in the centring, the displacement of the magnitude differences from their true values would be extremely small. As explained in Section 7.4 tests showed that the maximum error in the magnitude differences would be about 0.2^m . These tests showed that the magnitude differences on a given star were out by roughly the same amount for the various filters. The calculated colours of the components should therefore be unaffected by this source of error. However the V magnitudes could be seriously affected. A thorough check of the fits showed that the wobble

plate must have been wrongly centred by small amounts for a large number of observations but that it was wrongly centred by very large amounts on a few occasions and in particular during two of the last observing runs. It was found possible to estimate roughly the size of the error in the V magnitude difference. A star by star check was therefore made. Very few stars were found whose final results were liable to be significantly affected by the error. This was partly because the affected observations usually had high fitted errors and were therefore given low weights, partly because so many observations were usually made on each star and partly because the effect was small for very close stars and hence hard to detect especially for stars with large magnitude difference. Badly affected observations on these few stars were refitted using bin positions shifted by 30 channels (see Section 7.4). The data for seven stars were then re-analysed using UBVCN. The new magnitudes and colours are quoted in the table of results in Chapter 9. The most seriously affected star was HR 2870/1, an 8".89 double on which only 3 observations were made, all during the same observing run, all badly affected by the bad centring, and all made in the "horizontal" position (see Section 4.3). The new V magnitude difference was 0.18^m higher whereas the colours of the components were changed by less than 0.01^m . One other star, also one on which only 3 observations were made had its V magnitude difference increased by 0.10^m . The other stars reanalysed showed rather smaller changes. Usually the standard errors of the means are quoted in the table of results in Chapter 9. However for 5 stars whose results are suspected of being affected by wrong wobble plate centring, but whose data were not reanalysed, errors 0.02^m or 0.03^m larger are quoted. We believe that there

are no V magnitudes quoted in the table for which the error due to this effect significantly exceeds the quoted error. However there may well be a number of stars, especially amongst those wider doubles for which separations are given in parentheses, for which the V magnitude difference is in error by up to about 0.05^m due to this cause. There should not be any systematic over- or under-estimating of magnitude differences because of these errors.

The program occasionally rejected discordant results. Others had to be rejected by hand. It was found that the observations on a few nights gave results which differed from the means for the stars concerned by much more than their errors indicated. This was connected with the wobble plate centreing problem already mentioned. It was also found that sometimes observations made on wide stars in very bad seeing gave unrealistically small fitted errors. Since there is no maximum weight in this part of the UBVCN program the magnitude differences for such an observation, although significantly wrong, could dominate the result on a star leading to a large actual error. A search was made to see whether this had happened in practice. Fortunately it had not occurred.

For most stars the corrections to the magnitude differences to bring them onto the UB system were small. However for some stars the corrections were significant (up to about 0.10^m) so that more careful monitoring of the colour equations would be worthwhile.

It is not possible to detect the effects on the magnitude differences of the rejection of scans during the scanning process (see Section 3.4.2). It is likely that the effect would be a small overestimate of the magnitude differences. However rejection of scans rarely occurred so errors due to this cause can be neglected.

The results indicate that it is possible to obtain reliable magnitude differences in cases where the peak height of the secondary is comparable with the background or even considerably less than it. This is only possible though when the seeing is such that the profiles of the components do not overlap significantly. Bright moonlight is therefore not a serious limitation on the use of the area scanner. Figures 14 and 15 (see Section 6.11) show two observations of the 6!2 double HR 1058 with the U filter. The observations were made five weeks apart and give magnitude differences of 4.440 ± 0.046 and 4.435 ± 0.021 respectively. In figure 14 the background is about 4.7 times the peak height of the secondary. This is an extreme case. Very few observations were actually made with background substantially greater than the peak height of the secondary. The agreement between the magnitude differences for the two observations illustrated is exceptional and not typical.

We were not able to confirm variability of any of the constant or suspected variable stars in our program. The nature of our program and the paucity, irregularity and inhomogeneity of our observations made it unlikely that variations of less than about 0.2^m would have been detected. Discordant magnitude differences could usually be explained in terms of one of the sources of error.

7.7 Obtaining the final separations

The separations were obtained using the UBVCN program. Several runs were necessary on each batch of stars. It was found that all observations on two nights gave separations which were of too poor quality to be used. Observations made with the stars not in the horizontal position

were of course excluded from the means. Some discordant separations were also excluded. A few of these were probably discordant because the observations had been erroneously recorded as horizontal. The error caused by setting the turntable a few degrees off the true horizontal position is small and should not be responsible for any noticeably discordant results. The observations of the separation standards are also liable to this error so no systematic underestimating of separations should occur because of it. For some discordant separations the profiles and/or the fits made to them by the fitting program were extremely poor.

The results for each star were carefully examined. In particular if the mean separation for a star depended only or mainly on one observation the mean was rejected. Most means which depended only or mainly on several observations made during the same observing run were also rejected. This was because of the possibility of the separations obtained on any one observing run being systematically incorrect because of wrong centring of the wobble plate. With one exception all means with standard errors greater than $0''.07$ were rejected. There were also some stars for which no horizontal observations were made. The separations obtained for separation standards are not included in the table of results in Chapter 9.

No refraction corrections to the separations were made. Even for the largest zenith angles we used the refraction correction to the separations of the widest stars would not exceed $0''.01$ or about 0.1% which is much less than our scaling errors and also much less than our random observational errors.

Systematic errors in the fitted separations may occur for very close stars with large magnitude difference. This possibility was not experimentally

excluded. It would be possible to observe a wide star of large magnitude difference at various scan angles and to compare the fitted separations in the non-horizontal scan positions with values calculated from the horizontal (i.e. maximum) separation and the appropriate angles. It is believed however that the main causes of error in our separations were the wobble plate centreing problem already mentioned which caused errors of several percent and the more or less random fitting errors.

CHAPTER 8COMBINED LIGHT UBV PHOTOMETRY8.1 Motivation

In order to calculate magnitudes and colours of the components of double stars from magnitude difference measurements it is necessary to know the combined light magnitudes and colours for the stars at the time of observation. Since most of the stars in our program were constant it was sufficient to use combined light photometry from the literature for these stars. A search of the literature was made but for many stars no photometry could be found. For many others no (U-B) or only a (U-B) on the Cape refractor system could be found. For a few stars the photometry in the literature was discordant. It was therefore necessary to do combined light UBV photometry observations on a substantial number of stars.

8.2 Method

The observations were mostly made during time which would otherwise have been wasted. This occurred in a variety of ways. Very occasionally the seeing was too bad for area scanning although the night was photometric. On other nights equipment faults prevented area scanning but either the phototube and amplifier were still working or a conventional photometer was available which could be quickly mounted on the telescope. On one occasion sudden illness of another observer made available several nights of observing at less than 12 hours notice. In consequence the observations were made with three different photometers - our own photometer using a Monsanto pulse counter and hand recording of the counts, the

South African Astronomical Observatory (SAAO) 'tin can' photometer (DC system with Brown recorder) and the SAAO People's Photometer (DC system with integrator and Brown recorder).

Since great accuracy was not required no attempt was made to use sophisticated observing procedures. Mean extinction coefficients of 0.12^m , 0.23^m , 0.48^m per air mass were used for V, B, U respectively. In the event the accuracy obtained was extremely satisfactory.

8.3 The results

The results were given in a published paper (Hurly 1975) which is reproduced below. Some of the stars for which results are quoted in this paper are not included in the table of area scanning results in Chapter 9. In most cases this is because they are in fact difficult or impossible to observe successfully with the scanner.

Observations

COMBINED-LIGHT UBV PHOTOMETRY OF 103 BRIGHT SOUTHERN VISUAL DOUBLES*

P.R. Hurly

Combined-light UBV photometry of 103 bright southern close visual doubles is presented. Most of the pairs have separations between 1 and 10 seconds of arc. The UBV photometry of these stars was required in connection with a programme to obtain magnitudes and colours of the components. Values of V and B-V for many of the stars were already available but these stars were observed in all colours so as to obtain measures of U-B and to check on the V, B-V photometry. In addition, a few stars for which UBV photometry was available were reobserved because the values published by various authors were not in complete agreement.

All the observations were made during 1974 using the 50 cm and 100 cm reflectors at Sutherland. Three different photometers were used, two of them incorporating conventional d.c. systems with chart recorder, the third using pulse counting. Although the observations made with the pulse-counting photometer were found to be somewhat less accurate, all the observations have been used without weighting as this was adequate for the present purpose. E Region stars (Cousins 1973) were used as standards. Mean extinction coefficients were used to reduce observations to the zenith. The filters and photomultiplier tubes used gave results very close to the standard UBV system and only small corrections were required.

For most stars 2 or more observations were made. In the few cases where only 1 observation was made U-B alone is quoted, values of V and B-V of much higher weight being already available from Cape photometry. The number of observations is given in the column headed "n" in the table. An "N" in the column headed Notes refers to a note at the end of the table.

For 71 stars not suspected of variability a comparison between this paper and published Cape photometry was made. The arithmetic mean of the differences in V was 0.000 and in B-V was 0.002. The root mean square of the differences was 0.015 in V and 0.012 in B-V.

*Received 17 January, 1975; accepted 27 January 1975

HR	HD	α (1900) δ		V	B-V	U-B	n	Notes
24	493	00 ^h 04.2	-28 ^o 33'	5.41	+0.42	+0.06	2	
199	4294	00 40.2	-63 03	6.08	+0.44	+0.11	2	
251	5156	00 48.3	-25 19	6.45	+0.44	+0.01	2	
	6334	00 59.2	-60 38	6.82	+0.47	+0.03	2	
436	9228	01 25.7	-26 43			+1.46	1	
479	10241	01 34.9	-53 57	6.83	+0.44	+0.09	2	
514	10830	01 41.0	-25 33	5.29	+0.39	+0.00	2	
	15994	02 29.1	-06 04	7.14	+1.08	+0.93	2	
848	17793	02 46.2	-36 15	5.91	+0.90	+0.61	2	
1058	21635	03 24.3	-36 12			+0.08	1	
1157	23508	03 40.6	-40 58			+0.95	1	
1168	23697	03 42.0	-54 35			+0.89	1	
1359	27490	04 15.3	-34 09	6.36	+0.13	+0.10	2	
1372	27657	04 16.5	-63 30			-0.26	1	N
1771	35162	05 17.7	-24 52			+0.39	1	
2412	46860	06 30.5	-58 41	5.69	-0.06	-0.17	2	
2433	47247	06 32.5	-22 32			-0.53	1	
2468	48189	06 36.9	-61 27	6.19	+0.62	+0.10	2	
2482	48543	06 38.9	-38 18	6.28	+0.34	+0.10	2	
2501	49131	06 41.7	-30 51	5.81	-0.19	-0.86	2	
2674	53921	07 01.7	-59 02	5.51	-0.13	-0.46	3	
2677	53952	07 01.9	-34 37	6.15	+0.35	+0.00	2	
2726	55718	07 08.9	-36 23	5.93	-0.14	-0.63	2	N
2813/4	57852/3	07 17.9	-52 08	5.52	+0.48	+0.01	2	
2482/3	58634/5	07 21.2	-37 06	6.15	+0.25	+0.15	2	
2870/1	59499/500	07 25.0	-31 39	5.94	-0.16	-0.67	2	
2948/9	61555/6	07 34.7	-26 34	3.83	-0.16	-0.57	4	N
3035	63465	07 43.9	-38 16	5.07	-0.11	-0.65	2	
3062	64067	07 47.0	-56 09	5.58	+1.13	+0.83	3	
3079	64379	07 48.5	-34 27	5.01	+0.45	-0.05	2	
3205	68242	08 06.4	-42 21	6.25	-0.04	-0.32	3	N
3251	69445	08 11.9	-30 37	6.20	+0.78	+0.34	3	
3260	69863	08 13.7	-62 36	5.17	+0.11	+0.09	3	N
3267	70003	08 14.5	-37 04	6.70	+0.25	-0.03	2	
3358	72108	08 25.9	-47 36	5.34	-0.15	-0.78	2	N
3359	72127	08 26.1	-44 23			-0.80	1	
3371	72350	08 27.3	-44 24			-0.49	1	
3373	72436	08 27.7	-38 44	6.30	-0.14	-0.56	2	N
3432	73887	08 35.5	-62 30	5.45	+1.04	+0.83	2	
3439	74067	08 36.6	-39 55			-0.08	1	
3489	75086	08 42.7	-58 22	6.20	-0.08	-0.47	2	N
3542	76230	08 49.6	-51 45			-0.13	1	
3715	80773	09 16.5	-31 20	6.80	+0.01	-0.04	2	
	81695	09 22.1	-29 00	8.68	+0.36	+0.01	3	
3752	81830	09 23.0	-61 31			+0.12	1	
3780/1	82383/4	09 26.5	-31 27	5.76	+0.05	+0.05	2	

HR	HD	α (1900)	δ	V	B-V	U-B	n	Notes
3817	82984	09 30.1	-48 34	5.11	-0.12	-0.59	2	
3831	83368	09 32.8	-48 18	6.17	+0.27	+0.12	2	
	85100	09 44.5	-34 33	7.32	+0.26	+0.12	3	
3925	85980	09 50.3	-44 49	5.71	-0.12	-0.56	2	
4118	90972	10 25.0	-30 06	5.55	-0.04	-0.18	2	N
4135/6	91355/6	10 27.7	-44 33			-0.62	2	
4266	94683	10 50.6	-61 18	5.93	+1.76	+2.00	2	N
4290	95324	10 55.2	-60 47	6.17	-0.06	-0.30	2	
4411	99333	11 20.7	-37 12	5.88	+1.54	+1.71	2	
4443/4	100286/7	11 27.3	-28 43	4.99	+0.53	+0.02	3	
4469	100893	11 31.6	-33 01	5.73	+1.02	+0.83	2	
4577	103974	11 53.3	-40 23	6.79	+0.96	+0.70	3	
4628	105686	12 04.9	-34 09	6.16	+0.03	-0.02	3	
4718	107998	12 19.4	-40 50	6.24	+1.17	+1.06	2	
4835	110532	12 37.7	-58 21	6.45	+1.12	+1.00	3	N
4952	113904	13 01.7	-64 46	5.52	-0.02	-0.87	3	N
5120	118349	13 31.2	-25 59	5.39	+0.23	+0.17	2	
5122	118384	13 31.6	-57 54	6.43	+1.12	+0.93	3	
5141	118991	13 35.3	-54 03	5.00	-0.05	-0.22	3	
5234	121336	13 49.8	-53 38	6.16	+0.07	+0.04	2	N
	121579	13 51.2	-27 10			+0.06	1	
5362	125383	14 13.9	-42 36	5.55	+0.92	+0.60	2	
5375	125721	14 16.1	-47 52	6.09	-0.13	-0.90	3	N
5428	127624	14 27.2	-30 16	6.08	+1.03	+0.84	3	
5497	129926	14 40.2	-25 01	4.94	+0.35	+0.08	2	
	134799	15 06.7	-36 52	7.32	+0.23	+0.11	3	
5663	135235	15 08.9	-47 42	5.94	+0.21	+0.09	2	
5683	135734	15 11.6	-47 30	4.29	-0.03	-0.41	2	N
5697	136347	15 15.0	-37 51	6.47	-0.06	-0.29	3	
5738	137465	15 21.1	-51 15	6.09	+1.09	+0.76	3	N
5756	138268	15 26.0	-19 49	6.20	+0.23	+0.12	3	
5900	142049	15 47.1	-59 53	5.77	+0.36	+0.11	4	N
6006	144927	16 03.2	-32 23	6.18	+0.79	+0.45	4	
6080	146954	16 13.8	-39 11	6.11	-0.07	-0.21	3	
6097	147553	16 17.5	-32 58	6.46	+0.01	-0.02	3	
6105/6	147722/3	16 18.4	-29 28	5.41	+0.59	+0.12	4	
6236	151556	16 43.0	-49 52	6.45	+0.33	+0.07	4	
6244	151771	16 44.3	-37 20	6.10	+0.12	-0.15	3	
6344	154310	16 59.6	-37 05	5.97	+0.07	+0.09	2	N
6438	156768	17 14.3	-57 55	5.86	+1.08	+0.86	2	
6645	162220	17 44.8	-30 32	6.46	+0.04	-0.04	2	
6693/4	163755/6	17 52.7	-30 15	4.98	+1.63	+1.52	3	N
6759	165493	18 01.1	-45 47	6.13	-0.08	-0.48	2	
6780	166023	18 03.6	-30 45	5.52	+0.98	+0.70	3	
7959/60	198160/1	20 43.3	-62 48	5.67	+0.16	+0.07	3	
7989	198732	20 47.1	-24 09	6.32	+0.88	+0.55	3	

HR	HD	α (1900)	δ	V	B-V	U-B	n	Notes
8202	204018	21 20.6	-42 59	5.50	+0.39	+0.15	3	
8386	209014	21 55.1	-28 56	5.43	-0.08	-0.34	3	N
8501	211415	22 11.7	-54 07	5.38	+0.60	+0.06	2	
8540	212581	22 20.2	-65 28	4.50	-0.01	-0.07	3	N
8602	214150	22 31.1	-41 06	5.86	+0.06	+0.05	2	
8760	217642	22 57.0	-36 57	6.46	+0.94	+0.71	2	
8793	218268/9	23 01.5	-51 14	5.82	+0.48	+0.01	3	
8956	222004	23 31.8	-32 25	6.51	+1.26	+1.21	2	
8966	222287	23 34.1	-47 12	6.08	+0.24	+0.09	3	
8999	222872	23 39.3	-26 48	6.18	+0.48	+0.08	2	
9026	223466	23 44.6	-25 53	6.43	+0.13	+0.11	2	

Notes

HR	Notes	HR	Notes
1372	Suspected variable GCVS 100382. Present observation agrees with Corben (1971) in V, B-V within errors. Suspected as variable by Gould (1879).	4835	Component C, $9^m.8$, $30''$ away was excluded.
2726	Suspected variable GCVS 102551. V differs from Cape result, as corrected, in Johnson et al. (1966) by $-0^m.04$. Listed as possible variable by Baize (1962) on basis of widely varying visual estimates of Δm .	4952	Disagreement with Hogg (1958) result as quoted in Washington Photoelectric Catalogue is not real. Hogg's result is for A only and is in quotes.
2948/9	V, B-V agree with Cousins (1971) and differ from Catalina result in Johnson et al. (1966) by $+^m.03$, $+^m.03$ respectively. U-B is closer to the Catalina value.	5234	Component C, $28''$ away, was excluded.
3205	V differs by $-0^m.03$ from Corben (1966).	5375	A range of $0^m.06$ was measured in V but this is probably not real. V, B-V agree with Cape result in Johnson et al. (1966).
3260	B-V differs by $+^m.03$ from Cape result, as corrected, in Johnson et al. (1966).	5683	Component C, $7^m.2$, $24''$ away, was excluded.
3358	Component C, $18''$ away, was excluded.	5738	B-V differs by $0^m.03$ from Corben (1966).
3373	Component C, $30''$ away, was excluded.	5900	Suspected variable GCVS 101532. V, B-V agree with Cape result in Johnson et al. (1966). Suspected as variable by Gould (1879).
3489	Components C, $50''$ away, and D, $60''$ away, were excluded.	6344	V differs by -0.03 from Corben and Stoy (1968).
4118	Suspected variable GCVS 101131. V, B-V agree with Cape result in Johnson et al. (1966). Suspected as variable by A. Stanley Williams (1887).	6693/4	Suspected variable GCVS 7736. V, B-V agree with Cape result in Johnson et al. (1966).
4288	The companion was not seen.	8386	U-B differs by $+0^m.08$ from Crawford (1963) where the result was based on only 1 observation.
		8640	V differs from results in Johnson et al. (1966), Stoy (1968) and Cousins (1971). The star may vary by $0^m.04$, the different results being due to bad sampling.

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CHAPTER 9THE RESULTS9.1 The observed stars

The results of observations on 145 stars are given in Table I. All the stars are in the Catalogue of Bright Stars (Hoffleit 1964) and they are all southern, most being south of -25° . The separations vary between the limits 0.8 and 14 arcsecs. Most of the stars in the Catalogue of Bright Stars with declination south of -25° , separations between 2 and 10 arcsecs and V magnitude differences less than 4.0^m are included. The results of observations on 8 other stars are given in Table Ib. These stars are all included in the Henry Draper Catalogue and are also all southern. All but three of them were observed primarily as separation standards.

9.2 The tables of results

In Tables I and Ib the columns contain the following information for each star:-

- Col. 1 : The number of the star in the Catalogue of Bright Stars (Table I) or in the Henry Draper Catalogue (Table Ib).
- Col. 2-4: The combined light UBV photometry used in calculating UBV for the components.
- Col. 5 : A code number indicating the source of the combined light photometry. The sources are identified at the end of Table Ib.

- Col. 6 : The V magnitude difference between the components.
- Col. 7 : The error (s.e. of [weighted] mean) in the magnitude difference (in hundredths of a magnitude).
- Cols. 8-13 : The magnitudes and colours of the components and their respective errors (s.e. of [weighted] means). The errors are in hundredths of a magnitude. The results for the brighter component appear above those for the fainter component.
- Col. 14 : The number of observations used in obtaining the results in columns 6-13.
- Col. 15 : The separation between the components in arcsecs. Values in parentheses are not original results (see Section 9.3). Separation standards are indicated by an asterisk.
- Col. 16 : The error (s.e. of [weighted] mean) in the separation in hundredths of an arcsec.
- Col. 17 : The number of observations used in obtaining the results in columns 15-16.
- Col. 18 : Remarks and references to notes. Unacknowledged remarks are mostly from the Index Catalogue of Visual Double Stars (IDS) (Jeffers et al. 1963) or the Catalogue of Bright Stars (Hoffleit 1964) or are original. GCVS is the General Catalogue of Variable Stars and its supplements.

TABLE I

UBV Photometry and Separations

(1) HR	(2) V	(3) B-V	(4) U-B	(5) S	(6) ΔV	(7) ϵ	(8) V	(9) ϵ	(10) B-V	(11) ϵ	(12) U-B	(13) ϵ	(14) N	(15) d	(16) ϵ	(17) n	(18) Remarks
24	5.41	+0.42	+0.06	3	0.09	01	6.12	01	+0.44	01	+0.06	01	5	1.40	03	5	
199	6.08	+0.44	+0.11	3	1.78	03	6.21	01	+0.40	01	+0.06	01	5	2.35	07	5	
251	6.45	+0.44	+0.01	3	2.52	02	6.27	01	+0.44	01	+0.12	01	6	5.44	05	5	
377	4.855	+0.475	+0.02	2	2.63	01	8.05	03	+0.45	01	+0.06	01	4	5.22	02	4	κ Tuc. See note.
380	6.24	+0.05	-0.02	1	1.84	04	6.55	01	+0.43	01	+0.01	01	4	2.40	02	4	
436	5.94	+1.32	+1.46	3, 6	4.91	11	9.07	01	+0.61	01	+0.07	01	3	2.93	03	3	
479	6.83	+0.44	+0.09	3	1.44	04	4.95	01	+0.45	01	-0.00	01	5	(10.4)			
486/7	5.06	+0.88	+0.56	17	0.11	01	7.58	01	+0.85	02	+0.53	03	6	(11.0)			p Eri HR487. See note. HR486
514	5.29	+0.39	+0.00	3	3.32	03	6.42	01	+0.00	01	-0.01	01	5	4.87	04	4	ϵ Scl. See note.
749	4.90	-0.05	-0.12	2	2.98	02	8.26	03	+0.37	02	-0.07	01	6	(10.8)*			ω For
848	5.91	+0.90	+0.61	3	4.50	03	5.95	01	+1.33	01	+1.51	01	4	5.04	11	4	
897/8	2.91	+0.125	+0.13	2	1.11	01	10.86	11	+0.62	06	+0.10	11	4	8.23	05	2	θ^1 Eri HR896
963	3.86	+0.52	+0.02	2	3.14	03	7.09	01	+0.42	01	+0.09	01	7	3.17	03	7	α For. See note.
1058	6.50	+0.13	+0.08	1, 3	3.83	04	8.52	04	+0.53	01	+0.11	01	3	6.22	06	3	χ^3 For
1157	6.45	+1.06	+0.95	1, 3	3.03	03	5.76	01	+0.87	01	+0.53	01	3	(5.1)*			
1168	6.30	+1.04	+0.89	1, 3	3.09	05	5.87	01	+0.90	01	+0.59	01	3	(5.1)*			

HR	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	n	Remarks
1189/90	4.265	-0.015	-0.04	2	0.67	03	4.73	01	-0.03	01	-0.07	01	7	7.82	03	6	HR1190 HR1189
1271	6.41	-0.01	-0.10	1	1.55	02	5.40	02	+0.01	01	+0.01	01	4	1.87	04	4	
1359	6.36	+0.13	+0.10	3	2.18	02	6.64	01	-0.05	01	-0.13	01	4	5.99	07	4	
1372	5.87	-0.07	-0.26	3,9	1.72	01	8.19	02	+0.16	03	+0.05	06	4	4.08	05	4	
1405	6.28	+0.66	+0.17	14	0.42	02	6.50	01	+0.09	01	+0.11	01	4	5.70	07	4	See note
1504	6.53	+0.68	+0.22	17	0.17	02	8.67	02	+0.45	02	+0.02	01	4	2.69	02	3	See note
1505/6	6.00	+0.635	+0.33	2	0.18	05	6.07	01	-0.10	01	-0.31	01	4	(9.2)*			55 Eri HR1506 HR1505
1652	4.555	+1.19	+1.20	2	3.86	02	7.79	01	+0.10	02	+0.10	01	4	3.05	06	4	γ Cae
1771	5.06	+0.67	+0.39	3,5	1.37	02	6.67	03	+0.94	01	+0.59	01	4	3.28	04	4	C is 60", 9.2 ^m , K0, optical.
2158	5.93	+0.49	-0.01	1,4	3.13	02	6.84	03	+0.37	02	+0.18	01	4	5.03	06	4	C is HR2157, 200", common proper motion. See note.
2162	6.63	+0.74	+0.26	11	0.43	03	4.59	01	+1.21	01	+1.29	01	5	2.40	02	5	See note
2412	5.69	-0.06	-0.17	3	3.55	05	8.45	02	+0.64	01	+0.16	02	3	2.42	04	3	μ Pic
2468	6.19	+0.62	+0.10	3	2.35	04	5.33	01	+0.90	01	+0.59	01	3	1.62	04	3	See note
2482	6.28	+0.34	+0.10	3	1.38	04	6.70	02	+0.11	01	+0.12	01	4	(8.0)*			
2497	6.53	-0.10	-0.48	15	3.63	03	5.99	01	+0.46	01	-0.03	01	3	4.39	03	3	
2501	5.81	-0.19	-0.86	3	2.53	05	9.12	02	+1.15	02	+0.96	08	5	4.89	05	6	
2546	6.540	+1.514	+1.818	18	4.63	02	7.19	02	+0.73	01	+0.21	01	2	6.18	04	2	
2674	5.51	-0.13	-0.46	3	1.00	04	7.62	02	+0.76	01	+0.34	01	3	1.55	03	4	
							5.73	01	-0.07	01	-0.17	01	3	5.87	01	3	
							9.28	05	+0.31	06	-0.16	05	3	6.87	03	4	
							6.31	01	+0.58	01	+0.06	01	3				
							8.66	03	+0.99	02	+0.86	01	3				
							6.55	01	+0.32	01	+0.13	01	4				
							7.93	03	+0.40	02	-0.00	01	3				
							6.57	01	-0.11	01	-0.49	01	3				
							10.20	03	+0.28	03	-0.02	12	5				
							5.91	01	-0.19	01	-0.89	01	5				
							8.44	04	-0.20	02	-0.49	01	2				
							6.56	01	+1.53	01	+1.89	01	2				
							11.19	02	+0.85	01	+0.52	01	3				
							5.87	01	-0.14	02	-0.53	01	3				
							6.87	03	-0.12	04	-0.26	01	3				

HR	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	n	Remarks
2677	6.15	+0.35	+0.00	3	1.32	02	6.43	01	+0.31	01	+0.01	01	4	3.10	03	4	C is 10 ^m .0, 38", common proper motion D is 39", 10 ^m .8, E is 18", 13 ^m .5
2726	5.93	-0.14	-0.63	3	2.38	04	7.76	01	+0.49	01	-0.05	02					
2735/6	3.61	+0.92	+0.61	2	1.91	05	6.05	01	-0.16	01	-0.68	01	4	2.65	04	4	
2813/4	5.52	+0.48	+0.01	3	0.65	03	8.42	04	-0.00	06	-0.02	06		(13.6)			γ^2 Vol HR2736
2842/3	6.15	+0.25	+0.15	3	0.13	04	3.78	01	+1.04	01	+0.88	01	2	(9.2)			γ^1 Vol HR2735
2870/1	5.94	-0.16	-0.67	3	0.74	02	5.69	05	+0.40	02	+0.04	02	6	(7.0)			HR2813
3079	5.01	+0.45	-0.05	3	3.23	04	6.00	01	+0.42	01	-0.02	01	5	(8.9)*			HR2814
3205	6.25	-0.04	-0.32	3	1.15	03	6.64	02	+0.60	01	+0.07	01	3	(3.3)			HR2843
3223	4.35	-0.11	-0.46	1	2.98	02	6.84	01	+0.27	01	+0.15	01	4	(5.6)			HR2842
3251	6.20	+0.78	+0.34	3	1.81	03	6.97	04	+0.22	01	+0.15	01	3	(8.9)*			HR2870
3260	5.17	+0.11	+0.09	3	2.51	04	6.38	01	-0.17	01	-0.70	01	5	(3.3)			HR2871
3267	6.70	+0.25	-0.03	3	0.76	01	7.13	01	-0.15	01	-0.60	01	3	(6.1)			ϵ Vol
3327/8	6.08	-0.03	-0.24	4	0.71	02	8.29	04	+1.01	04	+0.97	08	3	(2.0)			C is 19", 14 ^m
3358	5.34	-0.15	-0.78	3	1.82	02	6.57	01	-0.06	01	-0.39	01	4	(3.9)			A. NO Pup. HR3327. Out-of-eclipse photometry. See note.
3359	5.02	-0.18	-0.80	3,8	1.89	03	7.72	02	+0.02	02	-0.07	02	3	(2.0)			BC. HR3328.
3373	6.30	-0.14	-0.56	3	1.81	01	4.42	01	-0.12	01	-0.48	01	5	(8.0)			AP. See note. B
							7.39	02	-0.01	01	+0.02	01	5	(4.6)*			C is 30", 8 ^m .3, B3 (not included in photometry)
							6.39	01	+0.87	01	+0.46	01	5	(4.4)*			
							8.20	02	+0.41	01	+0.02	02	5	(4.4)*			
							5.27	01	+0.08	01	+0.09	01	5	(4.4)*			
							7.78	04	+0.41	03	+0.04	05	5	(4.4)*			
							7.14	01	+0.44	01	+0.08	01	5	(4.4)*			
							7.90	01	-0.06	01	-0.15	01	5	(4.4)*			
							6.53	01	-0.09	01	-0.36	01	5	(4.4)*			
							7.25	02	+0.08	01	+0.06	01	5	(4.4)*			
							5.53	01	-0.15	01	-0.82	01	5	(4.4)*			
							7.34	02	-0.12	04	-0.58	01	5	(4.4)*			
							5.20	01	-0.18	01	-0.83	01	5	(4.4)*			
							7.09	02	-0.18	02	-0.61	01	5	(4.4)*			
							6.49	01	-0.15	01	-0.59	01	5	(4.4)*			
							8.30	01	-0.12	01	-0.40	02	5	(4.4)*			

HR	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	n	Remarks
3399	6.27	+1.55	+1.62	4,7	2.41	05	6.38	01	+1.65	01	+2.01	01	5	1.92	03	5	See note.
3432	5.45	+1.04	+0.83	3	4.74	06	8.79	04	+0.92	02	+0.66	03	3	6.50	03	2	
3439	5.20	-0.01	-0.08	1,3	3.71	05	10.20	06	+0.62	04	+0.09	02	4	(4.3)			
3455	6.34	+0.20	+0.14	1	1.86	02	8.94	04	+0.54	05	+0.02	02	4	(3.8)			
3489	6.20	-0.08	-0.47	3	0.06	02	6.52	01	-0.09	01	-0.52	01	4	(4.1)			C is 50", 11 ^m . D is 61", 10 ^m .8.
3542	6.39	+0.00	-0.13	1,3	1.52	01	8.38	02	+0.68	02	+0.22	02	3	(2.9)			
3574	4.69	-0.125	-0.47	2	3.11	02	6.92	01	-0.09	01	-0.41	01	4	2.36	03	3	See note.
3661	5.566	-0.112	-0.481	18	0.79	04	6.98	02	-0.08	01	-0.16	01	4	(2.7)			AB 0:1 $\Delta m = 0.5$. Not resolved.
3715	6.80	+0.01	-0.04	3	0.61	01	8.15	01	+0.26	03	+0.07	01	2	(3.0)			C
3780/1	5.76	+0.05	+0.05	3	0.82	02	7.86	02	+0.20	06	+0.10	10	3	(8.0)*			ζ^1 Ant HR3781 HR3780
3817	5.11	-0.12	-0.59	3	0.68	01	5.99	01	-0.14	01	-0.56	01	6	1.99	04	5	See note.
3831	6.17	+0.27	+0.12	3	2.85	05	6.78	03	-0.06	01	-0.28	01	4	3.29	05	4	See note.
3890/1	2.96	+0.27	+0.12	2	3.24	03	7.90	01	+0.05	01	+0.02	02	5	5.06	04	2	ν Car HR3890 HR3891
3925	5.71	-0.12	-0.56	3	2.44	04	6.26	01	-0.13	01	-0.57	01	4	5.42	03	2	
4065	5.67	+0.05	+0.05	1	0.15	01	6.25	01	+0.25	01	+0.12	01	6	2.31	05	5	See note.
4074	4.505	-0.13	-0.57	2	3.90	03	9.09	05	+0.64	02	+0.15	01	4	(7.2)			C is 37", 9 ^m .5.
4118	5.55	-0.04	-0.18	3	3.99	03	3.01	01	+0.28	01	+0.18	01	3	(11.0)			δ Ant
4135/6	5.16	-0.15	-0.62	1,3	0.38	04	6.26	02	+0.08	02	-0.54	02	5	(13.5)			HR4135 HR4136
							5.82	01	-0.14	01	-0.59	01					
							8.26	03	+0.06	01	-0.09	01					
							6.35	01	+0.05	01	+0.05	01					
							6.50	01	+0.06	01	+0.05	01					
							4.53	01	-0.13	01	-0.58	01					
							8.44	03	+0.01	02	-0.24	03					
							5.58	01	-0.05	01	-0.18	01					
							9.57	03	+0.71	04	+0.09	04					
							5.74	02	-0.18	01	-0.71	01					
							6.12	02	-0.11	01	-0.47	01					

HR	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	n	Remarks
4262	5.99	-0.02	-0.46	1	0.68	01	6.45	01	-0.03	01	-0.51	01	4	1.42	03	4	
4370	6.31	+0.40	-0.03	1,13	0.34	02	7.14	01	-0.00	01	-0.36	01	5	2.53	02	4	See note.
4401	5.11	-0.08	-0.45	15	1.23	02	7.25	01	+0.41	01	-0.03	01	4	2.41	04	4	
4443/4	4.99	+0.53	+0.02	3	0.13	02	5.68	01	+0.53	01	+0.03	01	4	(9.5)*			HR4444
4469	5.73	+1.02	+0.83	3	1.93	02	5.81	01	+0.53	01	+0.02	01	4	3.42	05	4	HR4443 C is 48", 13.5. ^m
4577	6.79	+0.96	+0.70	3	2.71	03	7.83	02	+0.85	01	+0.55	03	5	3.09	04	5	
4615	5.93	+0.60	+0.32	1	2.04	02	6.08	01	+0.64	01	+0.40	01	6	(8.7)			AB 0:1 $\Delta m = 0.0$. Not resolved. C
4628	6.16	+0.03	-0.02	3	1.77	01	8.13	02	+0.36	01	+0.00	01	5	3.56	05	5	
4636	6.604	+1.074	+0.780	18	3.97	05	6.35	01	-0.00	01	-0.04	01	5	2.62	04	6	
4652	5.306	+1.430	+1.581	18	1.19	03	10.60	05	+0.62	04	-0.03	01	5	(2.8)*			
4718	6.24	+1.17	+1.06	3	2.68	01	5.62	01	+1.52	01	+1.82	01	5	(10.0)			
4730/1	0.76	-0.25	-1.00	2	0.40	02	6.81	02	+1.21	01	+1.19	01	4	4.29	04	4	α^1 Cru HR4730. C is 90", 5.1. ^m , B5 See note.
4804	6.49	+0.08	-0.24	1	2.59	07	9.01	01	+0.54	01	+0.09	01	7	2.00	04	4	α^2 Cru HR4731.
4819	2.16	-0.015	-0.01	2	0.09	01	1.73	01	-0.26	01	-0.95	01	4	1.45	02	3	γ Cen. C is 40", 14.4. ^m See note.
4844	3.055	-0.19	-0.74	2	0.52	03	2.96	01	+0.01	01	-0.02	02	5	1.21	01	3	β Mus. See note.
4952	5.52	-0.02	-0.87	3	1.98	03	3.58	01	-0.20	02	-0.77	01	5	(5.3)*			θ Mus.
5120	5.39	+0.23	+0.17	3	0.95	03	4.10	02	-0.18	02	-0.69	01	8	(10.1)*			C is 198", 11.3. ^m D is 218", 10.0. ^m
							5.68	01	-0.02	01	-0.87	01	5				
							7.66	03	-0.02	02	-0.90	01	8				
							5.77	01	+0.22	01	+0.18	01	8				
							6.71	02	+0.24	01	+0.14	01	8				

HR	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	n	Remarks
5122	6.43	+1.12	+0.93	3	3.51	02	6.47	01	+1.15	01	+1.03	01	4	2.45	03	4	
5141	5.00	-0.05	-0.22	3	1.35	05	5.28	01	-0.08	01	-0.28	01	5	(5.4)*			
5189	6.54	+0.565	+0.04	10	3.58	04	6.58	01	+0.55	01	+0.03	01	5	(11.6)			Only 2 observations of ΔU .
5210/1	4.32	-0.135	-0.60	2	1.52	02	4.56	01	-0.15	01	-0.68	01	5	(7.9)			3 Cen HR5210.
5234	6.16	+0.07	+0.04	3	1.01	01	6.52	01	+0.06	01	+0.03	01	5	1.73	03	2	HR5211. C is 28", 12".8. See note.
5242	6.20	+1.05	+0.81	1	3.77	02	7.53	01	+0.09	01	+0.07	01	4	6.48	05	2	
5362	5.55	+0.92	+0.60	3	2.41	02	6.23	01	+1.07	01	+0.88	01	3	3.64	07	3	
5371	4.78	+0.80	+0.39	12	2.15	01	10.01	02	+0.48	02	+0.00	02	6	(9.2)*			C is 20", 13".5. D is 45", 10".5.
5375	6.09	-0.13	-0.90	3	3.94	01	5.66	01	+0.99	01	+0.76	01	6	4.25	07	5	
5428	6.08	+1.03	+0.84	3	3.64	04	8.07	02	+0.41	01	+0.01	01	5	2.50	05	5	
5497	4.94	+0.34	+0.07	16	2.02	03	4.92	01	+0.87	01	+0.48	01	6	8.43	03	4	54 Hya. See note.
5559	5.627	-0.034	-0.260	18	0.79	01	7.12	02	+0.63	02	+0.09	02	3	(2.3)*			
5683	4.29	-0.03	-0.41	3	0.14	03	6.06	01	-0.02	01	-0.28	01	3	1.17	04	3	μ Lup. See note.
5697	6.47	-0.06	-0.29	3	2.71	02	6.85	01	-0.06	01	-0.22	01	6	5.68	06	4	
5756	6.20	+0.23	+0.12	3	2.76	04	9.27	02	+0.38	02	-0.03	02	7	(11.2)			
5781	4.54	-0.18	-0.69	2	1.91	01	6.28	01	+0.21	01	+0.13	01	4	2.19	03	6	d Lup.
5846	5.94	+0.00	-0.20	1	1.94	02	9.04	04	+0.58	02	+0.01	02	6	3.70	04	6	
5851/2	5.53	+0.23	+0.10	1	0.21	01	4.71	01	-0.20	01	-0.75	01	3	1.89	03	3	HR5851. See note.
							6.62	01	-0.08	01	-0.21	01	3	HR5852.			
							6.11	01	-0.04	01	-0.23	01	6				
							8.05	01	+0.27	01	+0.09	02	6				
							6.18	01	+0.22	01	+0.10	01	3				
							6.39	01	+0.24	01	+0.10	01	6				

HR	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	n	Remarks
5900	5.77	+0.36	+0.11	3	2.61	03	5.86	01	+0.34	01	+0.11	01	5	4.43	02	5	See note.
5904	4.60	-0.08	-0.64	2	2.35	02	8.47	02	+0.61	02	+0.19	02	7	2.25	05	7	2 Sco. See note.
5925/6	4.585	+0.09	+0.07	2	0.50	02	4.72	01	-0.08	01	-0.69	01	8	(10.3)*			ξ^1 Lup. HR5925.
5952	6.21	+0.01	-0.01	1	4.23	04	7.07	02	-0.06	05	-0.08	05	5	8.05	06	2	ξ^2 Lup. HR5926.
6006	6.18	+0.79	+0.45	3	0.75	02	5.12	01	+0.12	01	+0.08	01	5	8.05	06	2	AB 1:0 $\Delta m = 4.5$. See note.
6029	5.69	+0.02	-0.165	1,13	2.19	02	5.62	01	+0.05	01	+0.06	01	6	3.76	03	6	C
6097	6.46	+0.01	-0.02	3	0.45	01	6.23	01	+0.00	01			3	(6.2)			C is 92", 9 ^m .0.
6105/6	5.41	+0.59	+0.12	3	0.79	02	10.47	04	+0.60	04			7	(5.1)			HR6106.
6134	0.90	+1.83	+1.32	2	4.45	09	6.62	01	+1.05	01	+0.88	02	5	7.58	05	2	HR6105.
6236	6.45	+0.33	+0.07	3	0.21	04	7.37	01	+0.41	01	+0.12	01	6	3.76	03	6	Antares. See note.
6244	6.10	+0.12	-0.15	3	2.30	02	5.83	01	-0.03	01	-0.18	01	5	3.01	05	5	
6401/2	4.34	+0.855	+0.53	2	0.04	02	8.02	02	+0.50	01	-0.03	01	6	(6.7)*			
6416	5.474	+0.809	+0.348	18	3.25	05	7.01	01	-0.02	01	-0.06	01	5	4.50	06	4	36 Oph HR6402. See note.
6426	5.91	+1.04	+0.82	1	1.02	02	7.46	01	+0.05	01	+0.04	01	5	0.85	01	4	HR6401.
6477	5.280	-0.058	-0.339	18	0.77	01	5.84	01	+0.59	01	+0.13	01	6	(7.3)			C is 42", 12 ^m .5. D is 47", 14 ^m .0.
6622	5.66	-0.08	-0.64	4	3.80	05	7.31	02	+0.32	03	+0.05	01	3	2.19	06	3	C is 100", 7 ^m .6.
6645	6.46	+0.04	-0.04	3	1.48	01	6.22	01	+0.11	01	-0.17	01	7	(12.3)			V539 Ara. See note to Table II.
6693/4	4.98	+1.63	+1.52	3	1.89	03	5.37	09	-0.11	05	-0.55	04	3	(10.1)*			
							7.10	02	+0.34	02	+0.09	01	6	(5.5)*			
							7.10	02	+0.34	02	+0.09	01	6	(5.5)*			
							7.31	02	+0.32	03	+0.05	01	6	(5.5)*			
							6.22	01	+0.11	01	-0.17	01	6	(5.5)*			
							8.52	02	+0.24	01	+0.08	01	6	(5.5)*			
							5.07	01	+0.85	01	+0.53	01	6	(5.5)*			
							5.11	01	+0.86	01	+0.53	01	6	(5.5)*			
							5.53	01	+0.79	01	+0.33	01	6	(5.5)*			
							8.77	04	+1.43	01	+1.23	05	6	(5.5)*			
							6.27	01	+0.99	01	+0.75	01	5	(5.5)*			
							7.29	02	+1.19	02	+1.08	02	5	(5.5)*			
							5.72	01	-0.06	01	-0.37	01	3	(5.5)*			
							6.48	01	-0.06	01	-0.27	01	3	(5.5)*			
							5.69	01	-0.08	01	-0.65	01	7	(5.5)*			
							9.49	05	+0.07	04	+0.06	05	7	(5.5)*			
							6.71	01	+0.03	01	-0.05	01	3	(5.5)*			
							8.19	01	+0.09	01	+0.01	01	3	(5.5)*			
							5.16	01	+1.77	01	+1.95	02	6	(5.5)*			
							7.04	02	+1.06	01	+0.80	02	6	(5.5)*			

HR	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	n	Remarks
6751	5.85	+0.46	+0.05	1	3.08	05	5.91	01	+0.43	01	+0.03	01	3	2.46	05	3	See note
6780	5.52	+0.98	+0.70	3	2.34	01	8.99	04	+1.06	08	+0.74	08					
6832	3.04	+1.59	+1.79	4	5.28	07	5.64	01	+1.09	01	+0.92	01	6	(4.0)*			η Sgr. C is 33", 13 ^m .0. D is 93", 10 ^m .0. See note to Table II.
6855	4.36	+1.455	+1.54	2	4.87	05	7.98	01	+0.33	02	+0.08	01	7	3.58	05	8	ξ Pav. See note to Table II.
7226/7	4.205	+0.52	+0.00	2	0.06	01	3.05	01	+1.60	01	+1.84	01	6	3.26	06	6	γ Cr. A. HR7226. See note. HR7227.
7398	5.46	+1.10	+1.08	16	3.62	03	8.33	07	+0.79	04	+0.33	04	4	7.52	04	3	See note.
7959/60	5.67	+0.16	+0.07	3	0.30	01	4.37	01	+1.47	01	+1.65	01	5	2.48	02	5	HR7959. See note. HR7960.
7989	6.32	+0.88	+0.55	3	2.18	02	9.24	05	+0.53	02	-0.08	05	3	1.74	05	3	See note.
8140	4.385	+0.185	+0.11	2	2.58	05	4.93	01	+0.52	01	-0.00	01	4	6.19	03	4	θ Ind. See note.
8148	6.56	+0.73	+0.22	16	3.03	03	4.99	01	+0.52	01	+0.00	01	7	2.75	03	7	C is 80", 12 ^m .0. D is 250", 12 ^m .0. E is 180", 12 ^m .0. See note and note to Table II.
8202	5.50	+0.39	+0.15	3	2.63	03	5.50	01	+1.12	01	+1.17	01	6	(2.9)*			
8280	5.29	+0.75	+0.47	1	1.80	03	9.12	03	+0.59	01	+0.16	02	6	3.14	03	6	λ Oct. See note.
8386	5.43	-0.08	-0.34	3	1.09	02	6.28	01	+0.15	01	+0.08	01	6	1.82	04	6	η PsA.
8540	4.50	-0.01	-0.07	3	4.33	03	4.48	01	+0.16	01	+0.11	01	4	6.89	04	4	δ Tuc.
8602	5.86	+0.06	+0.05	3	4.12	09	7.06	05	+0.57	02	+0.05	02	3	2.70	07	3	
8635	5.987	+0.569	+0.065	18	4.89	03	6.63	01	+0.70	01	+0.20	01	4	7.56	05	5	See note.
8662	6.560	+0.305	+0.104	18	3.58	02	9.65	03	+1.33	03	+1.01	03	4	(10.5)			
							5.59	01	+0.38	01	+0.16	01	4	+0.10	01	4	+0.34
							8.22	03	+0.55	02	+0.06	01	5	+0.82	02	5	+0.34
							5.48	01	+0.91	01	+0.64	01	6	+0.10	01	6	+0.34
							7.28	02	+0.15	02	+0.12	01	6	+0.82	04	6	+0.34
							5.77	01	-0.08	01	-0.38	01	6	+0.82	04	6	+0.34
							6.86	02	-0.07	01	-0.22	01	6	+0.82	04	6	+0.34
							4.52	01	-0.02	01	-0.07	01	4	+0.82	04	4	+0.34
							8.85	03	+0.51	04	-0.02	02	3	+0.82	07	3	+0.34
							5.88	01					3	+0.82	07	3	+0.34
							10.01	09					4	+0.82	07	3	+0.34
							6.00	01	+0.56	01			4	+0.82	07	3	+0.34
							10.89	03	+1.36	05			4	+0.82	07	3	+0.34
							6.60	01	+0.29	01	+0.10	01	4	+0.82	07	3	+0.34
							10.18	02	+0.82	02	+0.34	05	4	+0.82	07	3	+0.34

HR	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	n	γ	PsA	Remarks
8695	4.47	-0.045	-0.14	2	3.69	04	4.51	01	-0.06	01	-0.14	01	4	(4.2)					
8760	6.46	+0.94	+0.71	3	2.90	02	8.20	03	+0.44	04	-0.08	03	3	2.07	05	3			
8793	5.82	+0.48	+0.01	3	0.79	02	6.25	01	+0.46	01	+0.01	01	7	(8.7)					
8956	6.51	+1.26	+1.21	3	3.57	05	7.04	02	+0.54	02	+0.02	02	6	(5.5)					
8966	6.08	+0.24	+0.09	3	0.79	01	6.55	01	+1.30	01	+1.38	01	5	4.02	03	4			
8999	6.18	+0.48	+0.08	3	3.41	05	10.12	05	+0.58	03	+0.03	02	5	(8.4)					
9044	6.34	+0.20	+0.00	19	0.67	05	6.51	01	+0.22	01	+0.11	01	5	(6.6)*					
							7.30	01	+0.29	01	+0.05	01							
							6.23	01	+0.47	01	+0.07	01	5						
							9.63	04	+0.77	01	+0.43	05							
							6.81	02	+0.11	01	+0.05	01	5						
							7.48	03	+0.39	01	-0.11	02							

TABLE Ib

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
HD	V	B-V	U-B	S	ΔV	ϵ	V	ϵ	B-V	ϵ	U-B	ϵ	N	d	ϵ	ρ	Remarks
6334	6.82	+0.47	+0.03	3	0.10	01	7.52	01	+0.48	01	+0.04	01	8	(5.0)*			A. C is 11 ^m .8, 100". B.
34088	7.51	+0.42	-0.05	4	0.18	05	7.62	01	+0.46	01	+0.02	01	4	(7.2)*			
41628	7.73	+0.10	+0.14	4	0.11	02	8.18	02	+0.39	02	-0.05	01	3	(4.6)*			See note to Table IIb.
85100	7.32	+0.26	+0.12	3	0.02	01	8.35	03	+0.46	02	-0.05	01	3	(4.3)*			
99279	7.19	+1.26	+1.18	17	1.20	01	8.43	01	+0.15	01	+0.18	01	5	(5.0)			
105563	7.20	+1.23	-0.17	4	2.28	02	8.54	01	+0.05	01	+0.10	01	3	(2.3)			See note to Table IIb.
134799	7.32	+0.23	+0.11	3	0.12	01	8.06	01	+0.24	01	+0.11	01	6	(6.4)*			
158320	6.66	+0.13	-0.77	20	3.14	04	8.08	01	+0.29	01	+0.13	01	7	4.48	04	4	See note to Table IIb.
							7.50	01	+1.20	01	+1.16	01					
							8.70	01	+1.46	01	+1.27	01					
							7.33	01	+1.53	02	+0.17	01					
							9.61	02	+0.07	02	-0.65	03					
							8.02	01	+0.30	01	+0.11	01					
							8.13	01	+0.16	01	+0.11	01					
							6.72	01	+0.13	01	-0.78	01					
							9.86	04	+0.22	03	-0.56	01					

Source references for Table I

1. Johnson et al. (1966)
2. Cousins (1971)
3. Hurly (1975)
4. Hurly, P.R. Unpublished.
5. Lake (1964)
6. Lake (1965)
7. Corben (1966)
8. Corben and Stoy (1968)
9. Corben (1971)
10. Cousins and Lagerwey (1970)
11. Alexander (1970)
12. Cousins (1970)
13. Carter et al. (1971)
14. Corben et al. (1972)
15. Cousins (1972)
16. Cousins (1973a)
17. Cousins (1973b)
18. Cousins (1973c)
19. Westerlund (1963)
20. Cousins (1973d)

Notes to Table I

- HR 377 The separation is for 1973.37.
- HR 486/7 1 measure of the separation is in agreement with the ephemeris calculated from van Albada's 1957 orbit by Muller and Meyer (1969) rather than the ephemerides calculated by Muller and Meyer from the orbits by Luyten-Ebbigh and Landi Dessy.
- HR 514 The separation is for 1974.55 and does not agree with the separation given by the orbit of Mourão (1969). Mourão's orbit has $i = 180^{\circ}$, $e = 0$ and $a = 4''.652$. Semi-major axis a is apparently based on mean of all observations quoted by Mourão. These range from $4''.04$ to $4''.91$. Photographic measures given by Thé (1970) for 5 seasons during 1951-8 have mean $4''.791 \pm 0''.022$.
- HR 963 The separation is for 1974.36 and does not agree with the ephemeris calculated from van den Bos's 1956 orbit by Muller and Meyer (1969) which has 1973.0 $2''.72$, 1974.0 $2''.77$ and 1975.0 $2''.82$. Worley (1972) obtained 1972.077 $3''.25$ $293''.5$ giving residuals of $+0''.57$, $-9''.6$ with the orbit. Holden (1975b) obtained 1975.100 $2''.41$ $293''.4$ giving residuals of $-0''.41$, $-10''.4$ with the orbit. Holden (1976) obtained 1975.135 $2''.39$ $294''.3$ giving residuals of $-0''.43$, $-9''.5$ with the orbit.
- HR 1405 The separation is for 1973.82.
- HR 1504 The separation is for 1974.12. Ephemeris calculated from Wierzbinski's 1957 orbit by Muller and Meyer (1969) has 1973.0 $2''.70$, 1974.0 $2''.73$, 1975.0 $2''.77$. We find a position angle of about 90° agreeing with this orbit rather than with Holden (1975b, 1976) who finds 270° approximately.
- HR 2158 The separation is for 1974.29.
- HR 2162 The separation is for 1973.97. Ephemeris calculated from Heintz's 1960 orbit by Muller and Meyer (1969) has 1973.0 $2''.40$, 1974.0 $2''.41$, 1975.0 $2''.42$. Measurements of combined light magnitude and colours during the present observations

agreed closely with the values quoted in the table. However Stoy (1968) gives $V = 6.66$, $B-V = +0.74$ and Johnson et al. (1966) gives $V = 6.57$, $B-V = +0.72$. The Johnson et al. result is based on observations made at the Cape during 1954. The present differential observations are not sufficiently accurate to confirm or deny variability.

- HR 2468 The separation for 1974.67.
- HR 3327/8 Jørgensen (1972) discovered A = HR 3327 to be an Algol type eclipsing binary with period 1.25686^d . He gives Δy (Stromgren) = 0.67^m out of eclipse. BC has very small separation (IDS gives $0''.1$ in 1956) and was not resolved. The combined light UB V is uncertain as it is based on only 1 observation by us but several unpublished observations of V and $B-V$ made at the Cape in 1962 and 1966 were used to improve the weights of V and $B-V$. See note to Table II.
- HR 3358 IDS gives $0''.1$ (1959) for AP. A is SB1. Another star C is $18''.8$ from A (1934) and was not included in combined light or differential photometry. See note to Table II.
- HR 3399 Corben (1966) gives range 0.09^m in V , 0.09^m in $B-V$ for combined light. Combined light UB V was not measured simultaneously with differential observations so star was assumed constant in the reductions. Errors quoted for primary in Table I may therefore be unrealistic. Range in ΔV greater than 0.09^m measured but this is partially due to observational errors due to the closeness of star. See note to Table II.
- HR 3574 The separation is for 1974.33.
- HR 3817 The separation is for 1974.15.
- HR 3831 The separation is for 1973.94.
- HR 4065 The separation is for 1973.93.
- HR 4370 The separation is for 1973.84.
- HR 4730/1 These 7 observations were made on only 3 nights. The separation is for 1974.41.

- HR 4819 The separation is for 1974.41 and does not agree with the ephemeris calculated from van den Bos's 1936 orbit by Muller and Meyer (1969) which has 1973.0 1^m'65, 1974.0 1^m'65, 1975.0 1^m'65. Holden (1974) obtained 1974.263 1^m'52 360^o.5 giving residuals of -0^o'13, +1^o.4 with the orbit. Later Holden (1976) obtained 1975.153 1^m'61 358^o.1 giving residuals of -0^o'04, -0^o.8 with the orbit.
- HR 4844 The separation is for 1974.43 and does not agree with the ephemeris calculated from Mourão's 1964 orbit by Muller and Meyer (1969) which has 1973.0 1^m'37, 1974.0 1^m'37, 1975.0 1^m'37. The residual with the orbit is thus -0^m'16. Mourão (1964) lists the observations used in the orbit calculation. Observations by Mourão in 1961 and by Heintz in 1955 give residuals of -0^m'16, -0^m'14 respectively. Holden (1975b) obtained 1975.248 1^m'31 21^o.5 and Holden (1976) obtained 1975.126 1^m'43 24^o.6 giving residuals of -0^m'05, -4^o.8 and +0^m'07, -1^o.7 respectively.
- HR 5234 The separation is for 1974.11.
- HR 5497 The separation is for 1974.61.
- HR 5683 C is 24", 7.2^m, common proper motion, and is not included in the photometry. The separation is for AB and is for 1973.96.
- HR 5851/2 The separation is for 1973.33.
- HR 5900 The separation is for 1973.79.
- HR 5904 The separation is for 1974.01.
- HR 5952 AB was not resolved visually. The presence of a close companion with such large magnitude difference should cause no significant error in our results.
- HR 6029 The separation is for 1973.98.
- HR 6134 The observations were made on 4 nights. The separation is for 1974.76 and is about 0^m'2 larger than the orbits by Hopmann (1957) predict. Recent measures by Holden (1974, 1975a) are 1974.269 2^m'81 and 1974.514 2^m'91. See note to Table II.

- HR 6401/2 The northern component SHJ 243 A is brighter. This appears to be HR6402 = HD155886 contrary to the normal numbering method of the HR and HD catalogues. The separation is for 1974.08. The ephemeris calculated from Broche's 1958 orbit by Muller and Meyer (1969) has 1973.0 4!55, 1974.0 4!57, 1975.0 4!58. A third star, C, K5 V, 6.7^m , approximately 700" away has common proper motion and parallax. There are two fainter companions.
- HR 6426 The separation is for 1974.44. One observation at 1973.28 gave $1!06 \pm 0.02$. The ephemeris calculated from Baize's 1952 orbit by Muller and Meyer (1969) has 1973.0 1!13, 1973.5 1!05, 1974.0 0!95, 1974.5 0!84. This system has been discussed by Hirst (1947). Component C was then 30" away with separation changing slowly. Eggen (1974a) gives $V_E = 10.26^m$, $B-V = +1.57^m$, $U-B = +1.17^m$ for C. Component D, 12.0^m , moves rapidly with respect to AB and is probably optical. Neither of these fainter components interfered with our observations of AB. Hirst gives the mass ratio $M_B / (M_A + M_B) = 0.411 \pm 0.027$. AB has large proper motion. Our estimate of ΔV agrees well with values given in Wierzbinski (1969) for photometric (1.02 ± 0.13^m) and visual (0.93 ± 0.07^m) observations. Estimates of 1.5^m from photographic plates by Stoy (Hirst 1947) and 2.5^m by Harvard observers (Eggen 1956) appear erroneous. See note to Table II.
- HR 6751 The separation is for 1974.93.
- HR 7226/7 The separation is for 1973.66. The ephemeris calculated from Heintz's 1963 orbit by Muller and Meyer (1969) has 1972.0 1!81, 1973.0 1!77, 1974.0 1!73, 1975.0 1!69. Worley (1972) and Holden (1974) have residuals of $3.2^0 - 4.7^0$ in position angle with respect to Heintz's orbit.
- HR 7398 The separation is for 1973.61. Van Albada (1958) has 7!757 (1951.7) and Luck (1972) has 7!654 (1967.6) so the pair may be closing quite rapidly.

- HR 7959/60 The separation is for 1973.92.
- HR 8140 The separation is for 1973.56. Pair widening.
- HR 8148 The separation is for 1973.94.
- HR 8280 The separation is for 1973.90.
- HR 8635 The separation is for 1974.11.

9.3 Some comments on the results

All the calculations were carried out to more significant figures than are quoted in the tables. Rounding was then done by hand. As a result of rounding some of the magnitude differences in column 6 differ by 0.01^m from the value obtained by subtracting the V magnitudes of the components given in column 8. All errors were rounded upwards to the next hundredth. It should be noted that no account was taken of possible errors in the combined light photometry. When using the results allowance should be made for this source of error. Since almost all the combined light photometry used was in fact done at the Cape or by us it seems reasonable to assume errors of 0.02^m in V and U-B and 0.01^m in B-V. Errors of more than 0.03^m in combined light magnitudes or colours are unlikely.

The method by which the magnitude differences and the magnitudes and colours of the components were calculated is explained in Section 7.6. Comments on the external errors of our magnitude differences are given in Section 11.2.

The method used to obtain the mean separations given in the table is explained in Section 7.7. The epochs of these separations are not given except in cases where there appears to be appreciable relative motion of the components. An epoch of 1974.2 may be assumed where none is given. All observations were made between November 1972 and May 1975.

The separations given in parentheses are based on values given in Luck (1972), van Albada (1958), Thé (1970, 1975) and the IDS and on our own observations. It has been explained in Section 7.7 why our own results are not always quoted. The separations in parentheses are very

inhomogeneous but we believe that none of them is in error by more than 0.2 arcsecs. For these separations epoch 1974.2 may also be assumed. See Section 11.4 for comments on the accuracy of the separations given to two decimal places.

CHAPTER 10

DISCUSSION OF THE PHOTOMETRY

10.1 Introduction

Table II which contains various estimates of the absolute magnitudes of the stars in Table I has been drawn up in order to discuss the astrophysical implications of the photometric results. We have also constructed colour-colour and magnitude-colour diagrams for the stars.

10.2 The absolute magnitudes

In Table II we make a comparison between the absolute magnitudes of the stars as estimated by various methods.

One method of estimating the absolute magnitude of a primary is to assume that its secondary is on the main sequence, estimate the absolute magnitude of the secondary by referring to a colour-magnitude diagram and then obtain an estimate of the absolute magnitude of the primary via the observed magnitude difference. We used this method for all systems where we had no reason to suspect that the (visual) secondary was not on the main sequence and also for some systems with class IV or IV-V secondaries. De-reddened colours were used where appropriate. A colour-colour diagram constructed using the colours given by Fitzgerald (1970) was used to estimate the reddening E_{B-V} . Fitzgerald's main sequence two-colour locus is shown in Figures 30 and 31 and representative points on it are given in Table III. A portion of the Class III locus from Fitzgerald (1970) is also shown in the figures. A slope $\frac{E_{U-B}}{E_{B-V}} = 0.72$ was used for the reddening lines. Only main sequence stars of spectral type A

TABLE III

Main Sequence Colours

B-V	U-B	B-V	U-B	B-V	U-B
-0.32	-1.19	+0.00	-0.01	+0.56	+0.04
-0.31	-1.14	+0.05	+0.05	+0.62	+0.08
-0.30	-1.09	+0.08	+0.08	+0.65	+0.12
-0.28	-1.00	+0.12	+0.09	+0.68	+0.20
-0.26	-0.95	+0.20	+0.10	+0.74	+0.30
-0.24	-0.81	+0.30	+0.08	+0.80	+0.42
-0.22	-0.72	+0.32	+0.03	+0.86	+0.48
-0.20	-0.68	+0.34	+0.00	+0.92	+0.67
-0.16	-0.58	+0.40	+0.00	+0.95	+0.73
-0.12	-0.40	+0.42	-0.01	+1.00	+1.00
-0.08	-0.23	+0.45	-0.02	+1.15	+1.06
-0.04	-0.10	+0.48	-0.01	+1.33	+1.21
		+0.50	+0.00	+1.47	+1.24

or earlier were used in determining reddening as it was considered unlikely, in view of their nearness, that any of the later type main sequence stars would be appreciably reddened. There is an uncertainty of several hundredths in the reddenings given in the table due to the errors of the combined and differential photometry, the finite width of the main sequence in the colour-colour diagram and the uncertainty in the slope used for the reddening lines. Since the reddenings are so small this uncertainty in the reddening is sometimes an appreciable fraction of the reddening itself. No blanketing corrections were made. The colour-magnitude locus used for the main sequence was based on the work of Balona and Feast (1975), Blaauw (Table 4 in Blaauw 1963), Upton (1970) and Gliese (1971). Representative points on this main sequence are given in Table IV and it is shown in Figures 32 and 33. Our sequence follows Balona and Feast for $-0.30 < B-V < -0.07$, Blaauw raised by about 0.15^m for $-0.07 < B-V < +0.45$,

Upton for $+0.45 < B-V < +1.30$ and Gliese for $1.30 < B-V < 1.50$.

TABLE IV

The Adopted Main Sequence Absolute Magnitudes

B-V	M_V	B-V	M_V	B-V	M_V	B-V	M_V
-0.30	-3.5	0.10	+1.9	0.55	+4.4	1.15	+7.4
-0.26	-2.3	0.20	+2.35	0.60	+4.75	1.25	+7.8
-0.13	-0.35	0.30	+2.8	0.70	+5.25	1.30	+8.0
-0.09	+0.4	0.40	+3.4	0.80	+5.75	1.35	+8.4
-0.07	+1.05	0.45	+3.7	0.90	+6.25	1.40	+8.9
0.00	+1.4	0.50	+4.05	1.00	+6.75	1.45	+9.5
				1.05	+7.0	1.50	+10.2

The absolute magnitude of the primary is also estimated from its own (B-V) colour if it is classified as luminosity class V. For stars with MK spectral type the absolute magnitude from Blaauw's calibration (Table 3 of Blaauw 1963) is given. Where necessary we interpolated between Blaauw's values.

Trigonometric parallaxes from the Catalogue of Stars within Twenty-Five Parsecs of the Sun (Woolley et al. 1970) and from the Catalogue of Bright Stars (Hoffleit 1964) were used to calculate absolute magnitudes of the primaries from their apparent magnitudes given in Table I. Trig. parallaxes of less than $0''.020$ were not used. Absolute magnitudes calculated using dynamic parallaxes quoted in the Catalogue of Bright Stars are also given for some stars. The magnitudes obtained from trigonometric and dynamic parallaxes were corrected for absorption assuming $R = 3.3$ for those stars for which we have estimated the reddening.

No allowance has been made for known or suspected duplicity of either component when calculating the absolute magnitudes in Table II. Some cases of duplicity are, however, discussed in the notes.

10.3 Explanation of Table II

The table is in two parts, Table II and IIb, in the same manner as Table I. The columns contain the following information for each star:-

- Col. 1 : The number of the star in the Catalogue of Bright Stars (Table II) or in the Henry Draper Catalogue (Table IIb).
- Col. 2 : The discoverer's number as in the Index Catalogue of Double Stars (Jeffers et al. 1963).
- Col. 3 : The spectral types of the components. These are taken from the literature. Spectral types given in the literature without mention of whether they refer to the primary or the secondary have been assigned to the primary. In some stars where the components are close and of similar brightness this is a risky procedure. The type of the secondary is given in the line below the type of the primary.
- Col. 4 : A code number indicating the source of the spectral type(s) in column 3. The sources are identified after the table.
- Col. 5 : The absolute magnitude of the primary (top line) and secondary (bottom line) obtained by assuming the secondary to be on the main sequence. See Section 10.2.

- Col. 6 : The absolute magnitude of the primary, based on its B-V colour, if it is class V. See Section 10.2.
- Col. 7 : The absolute magnitudes, according to Blaauw (1963), of the components for which MK spectral types are available. See Section 10.2.
- Col. 8 : The absolute magnitude of the primary if a parallax is available. See Section 10.2. Magnitudes based on trig. parallaxes from Woolley et al. (1970) are identified by a W alongside the value of the absolute magnitude, those based on dynamic parallaxes from the Catalogue of Bright Stars by a D, whereas those not accompanied by a letter are based on trig. parallaxes from the Catalogue of Bright Stars.
- Col. 9 : Remarks and references to notes. Unacknowledged remarks are mostly by us or from the Catalogue of Bright Stars. A value for reddening entered in the line corresponding to the primary implies that both components were reddened.

TABLE II

Analysis of Photometry

(1) HR	(2) Name	(3) Spectrum	(4) S	(5) M _v	(6) M _v	(7) M _v	(8) M _v	(9) Remarks
24	BU 391	F2 V	15	3.3	3.7	2.8		
199	COO 3	F5 III-IV	5	3.4 1.9		1.4		
251	WNO 1	F6 IV-V	12	3.7 2.3		2.8	0.4D	
377	HJ 3423	G3 IV F5 V	5	4.8 3.4	3.7	3.2	3.4W	F6 IV from Malaroda (1975).
380	HJ 3426	A0 V	5	6.0 1.4	1.4	0.7	1.4D	
436	BU 1230	gK4	1	3.2 -0.1		-0.1		Colours suggest K3-4 III.
479	DUN 4	F5 IV-V	5	4.8 2.9		2.8		
486/7	DUN 5	K0 V	7	4.3 6.2	6.1	5.9	6.7W	
514	HJ 3461	K0 V F1 V	1	6.3 3.0	3.2	2.6	2.7	
749	HJ 3506	B9 V	16	6.3 -0.8	1.1	0.3		Optical?
848	HJ 3536	A8 V K0	1	2.2 0.6		2.1		Primary apparently G5 III.
897/8	PZ 2	A3 V	24	5.1 0.7	2.1	1.5	0.5	See note.
963	HJ 3555	A2 F6 IV	1 15	1.8 2.9		1.9	3.3W	See note.
1058	I 58	A0	1	6.0 1.2				Colours suggest A4 V.
1157	HJ 3589	K1 III	11	5.0 2.0		0.8		
1168	HJ 3592	K1 III	5	5.0 2.1		0.8		^m 0.10 below two colour main seq.
1189/90	DUN 16	A0	1	5.2 0.8				Colours suggest B9.5. See note.
1271	R 38	A0 B9.5 IV	5	1.5 0.6		0.0	1.2D	Colours suggest A1. B9V from Buscombe (1969).
1359	HJ 3642	A2	1	2.2 1.5			0.7D	Colours suggest A3.
1372	RMK 3	B9 V	13	3.7 0.2	0.3	0.3		Houk and Cowley have B9 III-IV. See note.
1405	RMK 4	G4 V	11	1.9 4.9	4.9	5.0	4.9W	
1504	HJ 3683	G6 V G5 V	5	5.3 5.0	5.2	5.1	6.2W	
1505/6	STF 590	G8 III F2p III	25	5.2 0.4		1.9D		See note.

HR	Name	Spectrum	S	M_V	M_V	M_V	M_V	Remarks
1652	JC 9	g K3	1	1.1 5.0		0.1		Colours suggest K3 III
1771	HJ 3752	G7 II-III A7 IV-V	17			-1.0 1.8		
2158	HJ 3834	F4 V	12	4.3 7.4	3.8	3.1	3.0	
2162	DUN 23	G5	1	5.2 5.6				Colours suggest G6 V. See note to Table I.
2412	HJ 3874	B9 V	5		1.0	0.3		See note.
2468	I 5	G1-2 V	5	4.3 6.7	4.6	4.6		
2482	DUN 32	A3	1	2.0 3.4			-1.1D	Colours suggest F0.
2497	COO 44	B8 IV	26	-0.9 2.7		-0.7		Thackeray et al. (1973) have B5 III.
2501	HJ 3891	B2 III	6			-3.6	-0.6D	See note.
2546	I 159	K5 III	12	1.4 6.0		-0.3		See note.
2674	DUN 39	B9 IV	5	-1.1 -0.1		-0.2	1.6D	
2677	HJ 3928	F0	1	2.7 4.0				Colours suggest F0 V.
2726	BU 757	B3 V	6	-1.3 1.1	-1.6	-1.7	-1.1D	$E_{B-V} = 0.06$ based on primary. See note.
2735/6	DUN 42	G8 III dF4	1	1.5 3.4		0.4		Sp. Bin. See note.
2813/4	RMK 6	F2	1	4.0 4.7			3.6	Colours suggest F3 V. Colours suggest G0 V.
2842/3	HJ 3966	A3	1	2.4 2.5			-0.8D	Colours suggest A8. Colours suggest A7.
2870/1	DUN 49	B3 V B4 V	6	-2.1 -1.4	-1.6	-1.7 -1.3		$E_{B-V} = 0.05$.
3079	HWE 65	F5 V	15	3.6 6.8	3.6	3.2	4.4W	
3205	DUN 63	A0	1	0.0 1.2			2.5D	$E_{B-V} = 0.07$, dereddened colours indicate B7.
3223	RMK 7	B5 III	5	-1.6 1.4		-2.2		Sp. Bin. B6 IV by Hiltner et al. (1969).
3251	BU 454	G5	1	1.7 3.5				
3260	RMK 8	A2 V	5	1.0 3.5	1.8	1.2	2.2	
3267	HJ 4073	A0	1	0.3 1.1			1.9D	Observations suggest F6 III.
3327/8	HJ 4093	A0 A0	1	1.1 1.8			0.0D	See note.

HR	Name	Spectrum	S	M_V	M_V	M_V	M_V	Remarks
3358	HJ 4104	B2 III	14	-2.8		-3.6		$E_{B-V} = 0.06$ based on secondary. See note.
		B5 V	12	-1.0		-1.0		
3359	DUN 70	B2 IV	6	-2.9		-3.3		SB1. Buscombe (1969) gives B3 III.
				-1.0				
3373	HJ 4107	B4 V	6	-1.9	-0.6	-1.3		See note.
				-0.1				
3399	I 195	K5	1	3.9				See note.
				6.3				
3432	HJ 4125	K0 III	5	0.1		0.8		
				4.8				
3439	COO 74	B9 V	26	0.7	1.3	0.3		
				4.4				
3455	HJ 4130	A3 V	5	3.3	2.0	1.5	3.2D	Discordant. Optical double?
				5.2				
3489	RMK 9	B7 III	5			-1.6	0.8D	If primary is giant, then secondary also giant.
								Observations suggest B9 V.
3542	CPO 9	A0	1	1.1				
				2.6				
3574	R 87	B5 V	6	-0.7	-0.5	-1.0	1.3D	SB1.
				2.4				
3661	HJ 4188	B8 V	8	-0.2	-0.9	-0.2	-0.6D	$E_{B-V} = 0.03$. See Table I remark.
				0.6				
3715	HJ 4200	B9.5 V	13	0.9	1.2	0.5		$E_{B-V} = 0.04$.
				1.5				
3780/1	DUN 78	A0	1	1.1			-3.8D	Colours suggest A1.
		A0		1.9				Colours suggest A3.
3817	HJ 4220	B4 Vn	18	-1.7	-0.9	-1.3	1.3D	$E_{B-V} = 0.05$. See note.
		B8 V		-1.0		-0.2		
3831	R 125	F0 p	29	2.1			2.9D	
				5.0				
3890/1	RMK 11	A7 II	9			-2.6	-0.5	See note.
		F0	1					
3925	DUN 81	B4 V	18	-1.4	-0.9	-1.3		$E_{B-V} = 0.03$. See note.
		B9 V		1.0		+0.3		$E_{B-V} = 0.13$.
4065	HJ 4306	A1 V	5	1.6	1.7	1.1		
				1.8				
4074	RMK 13	B3 IVe	27	-3.6		-2.5	-1.4D	$E_{B-V} = 0.11$. See note.
				0.3				
4118	H 50	B9.5 Vn	13	1.3	1.2	0.5	-2.9D	Double-lined spectr. bin. See note.
				5.3				
4135/6	PZ	B6 II	28			-4.2		See note.
	(DUN 88)	B8 II				-3.9		
4262	HJ 4383	B6 V	5	-1.2	-0.9	-0.7	-0.9D	$E_{B-V} = 0.14$. H_α emission (Kucewicz 1975).
				-0.5				
4370	HJ 4423	F3 V	15	3.2	3.3	3.0	2.9D	
				3.5				

HR	Name	Spectrum	S	M_V	M_V	M_V	M_V	Remarks
4401	HJ 4432	B5 V	6	0.1	-0.9	-1.0	0.2D	$E_{B-V} = 0.06$ based on primary only. See note.
		B	5	1.3				Colours suggest B9.5 or A0.
4443/4	H 96	dF6	1	4.2	4.3	3.7	1.3D	Colours suggest F8 V
		dF7		4.3		4.0		Colours suggest F8 V
4469	HJ 4455	K0	1					Colours suggest K0 III. See note.
4577	HJ 4484	K0	1					Colours suggest K0 III. See note.
4615	HJ 4498	Composite		1.2				See note.
		F0	19	3.2				
4628	JC 17	A0	1	0.7			0.2D	Colours suggest A0.
				2.5				
4636	I 423	K0	1	0.8				See note.
				4.8				
4652	RMK 14	gM0	1			-0.4		See note.
4718	HJ 4518	K0	1	1.7				Colours suggest K3 III. $E_{B-V}^m = 0.06$ below 2 colour diag. main sequence. Evolved?
				4.4				See note.
4730/1		B0.5 IV	6	-2.7		-4.7	-4.2D	
		B1 V		-2.3		-3.6		
4804	I 296	B8 Ve	28	-0.3		-0.2		$E_{B-V}^m = 0.14$. See note.
				2.3				
4819	HJ 4539	A0 III	1			-0.6	-0.2D	See note.
4844	R 207	B2 V	6	-2.1	-2.0	-2.5	-0.6D	$E_{B-V}^m = 0.04$.
				-1.6				
4952	RMK 16	B0 Ia	6			-6.2		See note.
		WC5						
5120	H 69	A7 III	19			0.3		Binary.
		A7 IV-V				1.8		
5122	R 223	K1 III	5	0.7		0.8		
				4.2				
5141	DUN 141	B8 V	28	0.3	0.7	-0.2	-2.3D	
		A0 V		1.7		+0.7		
5189	HWE 94	G3 IV-V	8	4.3		3.8	4.0	See note.
				7.9				
5210/1	H 101	B5 IIIp	20	-0.3		-2.2	0.7D	See note.
		B8 Vn		1.2		-0.2		
5234	R 227	A1 V	5	0.6	1.4	1.1	1.7D	$E_{B-V} = 0.06$
				1.6				
5242	HJ 4632	K0 III	5	0.2		0.8		
				4.0				
5362	HJ 4672	G5	1	1.1				Colours suggest K0 III.
				3.5				
5371	DUN 159	G8 III	19	1.2		0.4		Primary is double-lined spectr. bin.
		F5 V		3.4		3.2		
5375	R 244	B1 III	6	-3.6		-4.4		$E_{B-V} = 0.09$ based on secondary. See note.
				0.3				
5428	BU 1112	K0	1	1.9			0.0D	Colours suggest K0 III.
				5.5				

HR	Name	Spectrum	S	M_V	M_V	M_V	M_V	Remarks
5497	H 97	F0 III G3 IV?	21	2.9 4.9		0.7	3.5W	See note.
5559	HJ 4715	B9 V	26	-0.7	1.0	0.3		$E_{B-V} = 0.05$. Single lined spectr. bin. cpm?
5683	HJ 4753	B8	1	0.1 -0.2 -0.1			0.2D	$E_{B-V} = 0.09$. See note.
5697	HWE 76	A0p	29	0.6 3.3				
5756	S 672	A8 V	30	1.8	2.4	2.2		Double-lined spectr. bin. (Wilson and Joy, 1950).
		dF5	31	4.6		3.2		Single-lined spectr. bin. (Wilson and Joy, 1950).
5781	HJ 4788	B3 IVp	6	-1.2		-2.5	0.4D	See note.
		B8 V	18	0.7		-0.2		
5846	HWE 79	A0	1	0.8 2.7				cpm. Colours suggest B9.5.
5851/2	RMK 20	A5 III-IV A5 III-IV	5			0.6? 0.6?		cpm.
5900	HJ 4813	Am	32	2.2 4.8			3.1D	See note.
5904	BU 36	B2.5 Vn	6	-1.2 1.2	0.7	-2.1	-1.4D	See note.
5925/6	PZ (DUN 196)	A3 V B9 V	34	1.2 1.7	2.0	1.5 0.3		Colours suggest A2 V.
5952	COO 190	A0 V	13	0.5 4.7	1.4	0.7		See note to Table I.
6006	BSO 11	dG2 G5	1 2					Colours suggest K0 III. Colours suggest F3 III.
6029	HJ 4839	B9 Vn F2 V	12 22	1.5 3.7	1.3	0.3 2.8	2.3D	$E_{B-V} = 0.05$. See note.
6097	HJ 4848	A0	1	1.2 1.7			1.8D	Colours suggest A0.
6105/6	H 39	G0 IV G0 IV	7			2.6 2.6	3.6D	Binary.
6134	Antares	M1 Ib dB4	1	-5.4 -0.9		-4.8 -1.3		See note.
6236	COO 201	g?AB	1	2.7 2.9			1.6D	May both be giants.
6244	HJ 4889	B9 V B9 V, B9 V	28	-0.9 1.4	-0.5	0.3 0.3	-0.7D	$E_{B-V} = 0.25$. See note.
6401/2	SHJ 243	K0 V K1 V	7 8	6.0 6.0	6.0	5.9 6.1	6.5W	
6416	BSO 13	G8 V M0 V	7 8	6.0 9.3	5.7	5.5 8.7	6.1W	See note.
6426	MLO 4	K3 V K5 V	33	6.6 7.6	6.7	6.5 7.2	7.0W	See note.
6477	HJ 4949	B8 V	28	-0.5 0.3	0.3	-0.2	0.3D	$E_{B-V} = 0.04$. See note.
6622	HJ 4978	B3 V, B4 V	6	-2.0 1.8	+0.7	-1.7		See note.

HR	Name	Spectrum	S	M_V	M_V	M_V	M_V	Remarks
6645	PZ (STN 37)	A0 Vn A0 V	19	-0.1 1.4	1.1	0.7 0.7		$E_{B-V} = 0.09$. Optical?
6693/4	PZ (HJ 5003)	M2 Ib-II G8 II	17			-3.6 -2.3		See note.
6751	HDO 284	F8 IV-V	11	3.9 7.0	3.6	2.9	2.8	
6780	BU 245	K1 II F0 IV	12			-2.3 1.8	-1.3D	Binary.
6832	BU 760	M3.5 III	23	0.4 5.7		-0.5	1.3W	See note.
6855	GLE 2	K4 III	5	-0.6 4.3		-0.1		See note.
7226/7	HJ 5084	F8 V F8 V	7	4.1 4.2	4.2	4.0 4.0	3.6W	See note.
7398	H 119	K3 III	10	1.1 4.7		0.1	3.7W	See note.
7959/60	RMK 26	A2 V A2 V	11	1.9 2.2	2.1	1.2 1.2	1.1D	See note.
7989	HJ 3003	SgG5	1	2.4 4.6		-6.2		See note.
8140	HJ 5258	A5 V	3	1.9 4.5	2.2	1.8	2.5W	A3-5 IV-V by Houk & Cowley (1975)
8148	BU 271	G5 V K4	14 1	5.2 8.2	5.3	5.1	5.3W	See note.
8202	MLO 6	Am	32	1.8 4.4				
8280	HJ 5278	G8 - K0 III A3-5	5	0.3 2.1		0.6 1.5	0.7D	Colours suggest A5.
8386	BU 276	B6 Vne	13	-0.7 0.4		-0.7	0.9D	$E_{B-V} = 0.02$. Variable rad. vel. (Buscombe et al., 1961).
8540	HJ 5334	B8 Vn	13	-0.2 4.1	1.3	-0.2		cpm.
8602	BU 771	A2	1					
8635	COO 252	G1 V M1	7 1	3.6 8.5	4.5	4.5	5.1W	See note.
8662	HJ 5362	F0 III	10	2.3 5.9		0.7		See note.
8695	HJ 5367	A0 V	1	0.0 3.7	1.1	0.7	2.7W	See note.
8760	BU 1011	g?G9	1	1.4 4.3		0.6	-1.1D	Colours suggest G8 III.
8793	DUN 246	dF7	1	3.6 4.4	3.8	3.7		Colours suggest F5 V.
8956	HWE 93	G8 - K0 III	5	1.0 4.6		0.6	-1.1D	
8966	DUN 251	A3	1	2.0 2.8			1.0D	Colours suggest A7.
8999	HJ 5417	F8 V G8 IV-V	11 4			4.0 4.2		See note.
9044	LAL 192	A5 m F2 IV	9				0.7D 1.9	See note.

TABLE IIb

(1) HD	(2) Name	(3) Spectrum	(4) S	(5) M_V	(6) M_V	(7) M_V	(8) M_V	(9) Remarks
6334	HJ 3416	F5 V	7	3.7	3.9	3.2		See note.
		F5 V		3.8		3.2		
34088	HJ 3735	F2	2	3.6	3.3			
				3.8				
41628	ARG 12	A0	2	1.6	2.1			See note.
				1.7				
85100	HJ 4249	A3	2	2.8	2.5			Colours suggest A7.
				2.8				
99279	BSO 5	K7 V	7	8.5	7.6	8.1	7.3	
		M0 V	8	9.7		8.7		
105563	HRG 74	B + M1e	5	-4.5				$E_{B-V} = 0.32$. See note.
		B2 V	35	-2.2		-2.5		
134799	COO 179	A3	2	2.1	2.8			Colours suggest A9.
				2.2				
158320	HWE 39	B0.5 II	36	-5.3		-5.2		$E_{B-V} = 0.47$. See note.
				-2.2				

Source references for Table II

1. Bright Star Catalogue (Hoffleit 1964)
2. Index Catalogue of Double Stars (Jeffers et al. 1963)
3. Jaschek et al. (1964)
4. Kennedy and Buscombe (1974)
5. Houk and Cowley (1975)
6. Hiltner et al. (1969)
7. Evans et al. (1957)
8. Evans et al. (1959)
9. Wayman (1961)
10. Evans et al. (1961)
11. Evans et al. (1964)
12. Evans (1966)
13. Buscombe (1969)
14. Evans (1961)
15. Malaroda (1975)
16. Murphy (1969)
17. Stephenson (1960)
18. Thackeray (1966)
19. Wayman (1962)
20. Andrews and Thackeray (1973)
21. Struve and Franklin (1955)
22. Garrison (1967)
23. Landi Dessy and Keenan (1966)
24. Woods (1955)
25. Bidelman (1958)
26. Morris (1961)
27. de Vaucouleurs (1957)
28. Hube (1970)
29. Jaschek and Jaschek (1959)
30. Cowley et al. (1969)
31. Wilson and Joy (1950)
32. Jaschek and Jaschek (1960)
33. Cousins and Stoy (1963)

34. Levato (1975)
35. Lyngå (1973)
36. Penny et al. (1975)

Notes to Table II

- HR 897/8 Primary is double-line spectroscopic binary. Allowance for this would bring the absolute magnitudes into better agreement. Spectral type A3 III given by Gascoigne (1950) is also by Miss Woods. This star is listed as possible variable GCVS 100250 because it was suspected to vary by Gould (1879a). The present observations do not indicate variability.
- HR 963 Jaschek et al. (1964) gives F8 IV (Evans et al. 1957), F6 V (Woods 1955) and F7 V. Eggen (1956) has discussed this star. It is listed as a probable variable GCVS 6016. Baize (1962) quotes a long series of observations by van den Bos and Finsen claiming that Δm varies from 2.8 to 5.2 with periods when the companion is invisible. Van Albada (1958) gives $\Delta m = 5$, 1 plate, doubtful. The present observations were made in August and October 1973, in November and December 1974 and in January 1975. They give no positive evidence for variability. It should be noted however that measures of the combined light U-B for this star vary from 0.00 to +0.05 (Cousins 1971).
- HR 1189/90 Possible variable GCVS 100352. Suspected as variable by Gould (1879b). The present observations do not indicate variability.
- HR 1372 Possible variable GCVS 100382. Suspected as variable by Gould (1879c). The present observations do not indicate variability.
- HR 1505/6 Common proper motion. Probable variable GCVS 6130. Suspected as variable by Eggen (1959). Eggen (1969) suggests HR 1505 (component B) may be a δ Scuti. Eggen (1974b) claims HR 1505 varies by several hundredths on a very short time scale. The present observations have high error in ΔV but this is believed to be mainly observational and should not be taken to confirm variability. HR 1506 has variable radial velocity (Abt 1970). HR 1505 lies well below the class III, IV and V sequences in the two colour diagrams.

- HR 2412 The primary falls right on the two colour main sequence but the secondary falls much farther off this sequence than can be accounted for by errors in the photometry. We suspect that this system is optical despite its closeness, the secondary being a reddened B star.
- HR 2501 The secondary appears 0.06^m bluer in B-V than the two colour main sequence. This is possibly due to errors in the photometry. De Vaucouleurs (1957) gives spectral type B3 V for the double.
- HR 2546 Probable variable GCVS 6511 but an E region standard (Cousins 1973c). Variation, if any, must be small and hence unmeasurable at such large magnitude difference using the present technique.
- HR 2726 Possible variable GCVS 102551. Listed by Baize (1962) as possible variable on grounds of discordant visual estimates of magnitude difference. The present observations do not indicate variability.
- HR 2735/6 Possible variable GCVS 100831. Suspected as variable by Gould (1879d). The present observations do not indicate variability.
- HR 3327/8 See note to Table I. IDS has $\Delta m = 0.2$ for BC. Jørgensen (1972) suggests A is B9 V. Colours indicate B8 for A, A3 for BC. The absolute magnitudes in column 5 are not inconsistent with a physical relation between A and BC if we allow for duplicities.
- HR 3358 See note to Table I. IDS has $\Delta m = 0.0$ for AP. Hiltner et al. (1969) has B2 IV. Evans (1966) suggests physical relation between A and B.
- HR 3373 Hiltner et al. (1969) say He I lines asymmetrical on one plate indicating possible companion.
- HR 3399 Primary probably an M giant or supergiant. Secondary is right on two colour main sequence but could be class IV, III or II. If star is a physical double secondary unlikely to be class V. See note to Table I.

- HR 3817 Buscombe (1969) has B5 III. Jaschek and Aguilar (1969) have B5 IV p and report spectrum similar to 3 Cen A. A has variable radial velocity (Thackeray 1966). Peculiar (diffuse weak) lines seem to be in faint component and there is no sign of He³ in the brighter component (Thackeray 1969). Probable member Sco - Cen Association.
- HR 3890/1 Houk and Cowley (1975) give A8 Ib, de Vaucouleurs (1957) gives A9 II. Colours of secondary indicate reddened B star rather than F0. Common proper motion. M_v based on trig. parallax is of low weight.
- HR 3925 A is a possible double-lined spectroscopic binary, B's radial velocity possibly variable (Thackeray 1966). Member of Sco - Cen Association (Gutierrez-Moreno and Moreno 1968). AB binary. Reddenings of components seem different. Dereddened colours agree with spectral types.
- HR 4074 Secondary appears reddened by 0.11^m , primary by much less. Optical? - in a rich field. Hiltner et al. (1969) have B3 III, Houk and Cowley (1975) have B5 II. Hoffleit (1953) has B5 III-V and comments that two earliest plates (1893, 1895) show emission, 22 later plates do not. Slettebak (1975) found "most of lines asymmetrical with rather steep violet edges". Binary? (Hoffleit 1964).
- HR 4118 Possible variable GCVS 101131. Claimed to be variable by Stanley Williams (1897). The present observations do not indicate variability - the high errors are observational.
- HR 4135/6 Hube (1970) says radial velocity of B is variable.
- HR 4401 Single-line spectroscopic binary? Hoffleit (1953) gives B5 I-III, Houk and Cowley (1975) give B5 III-V.
- HR 4469 The secondary may be on the main sequence but the colours and magnitude difference suggest it is class IV.
- HR 4577 The colours of the secondary suggest it is on the main sequence but the magnitude difference suggests it is class IV.

- HR 4615** Primary is double, sep. = 0".1, $\Delta m = 0.0$. Houk and Cowley (1975) give G8 - K0 III and A3 - 5 V for the components. Wayman (1962) gives F7 IV for the primary. AB lies well below main sequence and giant sequence in two colour diagram. A K0 III star (6.59 +1.01 +0.84) and an A5 V star (7.14 +0.15 +0.09) give combined light photometry (6.08 +0.60 +0.35) near that for AB. C is double-lined spectroscopic binary with both components about F0 (Wayman 1962). Our photometry suggests F2 V. Allowing for this our magnitude difference between AB and C suggests $M_v = 1.0$ for the K0 III star and $M_v = 1.5$ for the A5 V star in good agreement with the values given by Blaauw (1963). The HD catalogue implies that HD 105151 and HD 105152 are the designations of the 8".7 pair whereas Houk and Cowley have 105152 as the secondary of the 0".1 pair.
- HR 4636** Primary lies 0.18^m above giant sequence in two colour diagram. Secondary has 0.15^m U-B excess. M_v 's calculated assuming secondary on main sequence at B-V = +0.62. Primary probably a K0 giant.
- HR 4652** Colours suggest primary is K5 III. Colours and magnitude difference suggest secondary is K2 III.
- HR 4730/1** Thackeray and Hill (1974) suggest this is a physical system but that radial velocities differ by more than slow apparent orbital motion would suggest. A is a single-line spectroscopic binary. Thackeray and Hill say radial velocity of B is constant.
- HR 4804** Primary seems reddened by 0.18^m , secondary by 0.10^m .
- HR 4819** This possible member of the Hyades group has been discussed by Rodgers (1967). Our results (Table I) show that the components have almost identical magnitudes and colours. Rodgers states that the spectrum does not appear composite. The dynamical parallax used is by van den Bos (1936).
- HR 4952** It is not clear in the literature whether the primary is the B0 star, or the WC star, or whether it is a spectroscopic binary.

The present interpretation with the WC 5 star as the secondary implies $M_V \approx -4.2$ for the WC 5 star if the system is physical. Our results (Table I) show that the components have almost identical colours. We did not detect any variation during our observations (made during 1974). Fitzgerald (1973) suspected variability as a result of a copying error in the Washington Photoelectric Catalogue (Blanco et al. 1970) - see Hurly (1975).

- HR 5189 Space velocity $\approx 90 \text{ km s}^{-1}$. Wayman (1962) gets very similar magnitudes and colours for the components except that he gets $+1.24^m$ (range $> 0.06^m$) for U-B of the secondary. Probably U-B of the secondary lies between Wayman's and our values and is consisted with a dwarf of spectral type about K5.
- HR 5210/1 No reddening has been allowed for as we find the secondary to be on the two colour main sequence. Andrews and Thackeray (1973) have used $E_{B-V} = 0.03$. Probably a member of Sco-Cen Association and almost certainly a physical pair (Jones 1970). Cluster parallax of $0.008''$ (Jones 1970) gives $M_V = -0.9$ for primary. Slettebak (1963) gives spectral types B5 V p and B9 V. A has high abundance of He^3 (Sargent and Jugaku 1961). Rad. vel. of B may be variable (Thackeray 1966).
- HR 5375 Radial velocity probably varies (Neubauer 1930).
- HR 5497 Malaroda (1975) has F2 III-IV for AB. However our M_V 's based on secondary (assumed to be on main sequence) and on trig. parallax indicate primary is dwarf. Hoffleit (1964) has dF1 and dF9 for components and says star is binary. Our colours suggest A9 V and G2 V.
- HR 5683 H_α emission (Kucewicz 1967). $E_{B-V} = 0.09$ based on secondary. Colours indicate B8 for primary.
- HR 5781 Probably a physical pair and member of Sco-Cen Association (Jones 1970, Gutierrez-Moreno and Moreno 1968).
- HR 5900 Binary. Possible variable GCVS 101532. Suspected as variable by Gould (1879e). The present observations do not indicate

variability. However B falls 0.13^m below the two colour main sequence. Houk and Cowley (1975) give composite spectrum G5 II-III + A3 for primary.

- HR 5904** High errors probably observational but U-B measures of combined light vary from -0.63 to -0.67 (Cousins 1971). Possibly reddened by about 0.10^m but no de-reddening applied as our colours for secondary put it slightly the wrong side of two colour main sequence. Probably member of Sco-Cen Association (Gutierrez-Moreno and Moreno 1968).
- HR 6029** Binary. $E_{B-V} = 0.05$ based on primary. Possible variable GCVS 101558. Suspected as variable by Gould (1879f). The present observations do not indicate variability. The de-reddened colours suggest F5 V for secondary.
- HR 6134** The errors quoted in Table I for the UBV of the components are highly misleading in this case. No simultaneous combined light UBV photometry was done although the combined light magnitude and probably the colours varied during the year over which the observations were made. The values we used for reducing all our observations are quoted in Table I. [Antares varies in V by about 0.9^m (Baize 1962)]. There is also the possibility of large errors in our transformations to the UBV system for such a red star. In Table I therefore the value for ΔV is really a time average, the values for V_A and V_B are almost meaningless, and the values for the colours may have errors up to 0.1^m larger than indicated. However it is worth noting that our value of ΔV is larger than values obtained by many other authors. Kooreman (1946), Garrison (1967), van Albada (1958), Wieth-Knudsen (1957) and Piccirillo (1974) all obtain ΔV (or Δm) in a surprisingly small range from 4.0^m to 4.25^m . Muller (1951) obtains a Δm of 4.4^m . Our colours for B as they stand suggest $E_{B-V} = 0.06^m$ and a spectral type of B4 for B. Allowing for larger errors as discussed above we get a type for B between B2 and B8. Several authors have

classified Antares B as B3 or B4 (Stone and Struve 1954). Garrison (1967) gives B2.5 V. E_{B-V} as large as the 0.25^m suggested by Garrison (1967) seems unlikely. Antares is almost certainly a physical pair (Jones 1970) and a member of the Sco-Cen Association (Jones 1970, Gutierrez-Moreno and Moreno 1968). Cluster parallax of 0!006 by Jones (1970) gives $M_V -5.2$ for Antares A whereas dynamical parallax of 0!004 by Russell and Moore (1940) gives $M_V -6.1$. See note to Table I.

- HR 6244** B has broad double lines, components both B9 V (Hube 1970). Jaschek and Jaschek (1960) have type B9 p for the system. Assuming that all stars are on main sequence we get E_{B-V} of 0.21^m for primary, 0.29^m for secondary. Observed magnitude difference much larger than indicated by the spectral types and by the de-reddened colours when allowance is made for the duplicity of the secondary. Possibly optical or luminosity class of primary wrong.
- HR 6416** Wayman (1962) has $U-B = 0.87$ (1 observation) for B. He gives $B-V = +1.03$ for C and remarks that it is probably optical. Johnson et al. (1968) has HR 6416 as a subdwarf with ultraviolet excess 0.24^m - this seems to be an error as their photometry shows it to be on the main sequence. Our photometry shows both A and B to be very close to the main sequence and the agreement between the absolute magnitudes in the table is good.
- HR 6426** Eggen's magnitude and colours for C (see note to Table I) suggest it is an M5 dwarf with distance modulus almost identical to that of AB. This, together with the slowness of the motion of C relative to AB, suggests a physical relationship of C with AB.
- HR 6477** Binary. Variable radial velocity (Hube 1970). Possible variable GCVS 101649. Suspected as variable by Gould (1879g). The present observations do not indicate variability.
- HR 6622** V539 Ara. Primary is an eclipsing spectroscopic binary, period 3.17^d . Ephemeris, eclipse duration, orbital elements, estimated masses etc. are given by Knipe (1971). All our observations

were outside the eclipses predicted by Knipe's ephemeris. The combined light photometry (i. e. including the visual companion) listed in Table I is of low weight. However V and B-V agree with values given by Knipe (1971). Knipe has $U-B = -0.74$ whereas we get -0.64 . Unpublished Cape photometry (1967-9) gives $V = 5.66$, $B-V = -0.10$, $(U-B)_{\text{Cape}} = +1.26$ outside eclipses. This $(U-B)_{\text{Cape}}$ corresponds to $U-B = -0.61$. Knipe (1971) obtained $V = 9.22$, $B-V = +0.05$ for the visual companion (2 observations, 50 cm reflector). He also suggests that there is intrinsic variability in the system. Our observations give $V = 9.49$ for the companion. The difference of 0.27^m in V may be due to errors but it must be noted that the errors in our V and B-V results for the secondary are larger than would be expected from a pair of constant stars. De-reddening the primary gives $E_{B-V} = 0.15$, $(B-V)_0 = -0.23$ corresponding to B2.5V. Our colours put the secondary near the two colour main sequence but allowing for the errors in the colours a reddening of 0.15^m is possible. Making a reasonable assumption about $(B-V)_0$ for the secondary, using $(B-V)_0 = -0.23$ for the primary and allowing for the primary being a double with $\Delta V = 0.5$ removes the large discrepancy between the absolute magnitudes in the Table.

HR 6693/4

Binary. Probable variable GCVS 7736. The present observations do not indicate variability.

HR 6832

The errors quoted in Table I for the UBV of the components are misleadingly small in this case. The combined light photometry quoted in Table I and used in the reduction is of low weight but we have preferred it because it is based on observations made simultaneously with our differential observations. It appears from our work and unpublished combined light Cape photometry that V varies by about 0.1^m . The U-B (combined light) used is redder than values found in the literature by $0.05^m - 0.10^m$. However the secondary falls on the two colour main sequence (within the quoted errors).

- HR 6855 Suspected variable GCVS 102863. Spectroscopic binary. The present observations are not sufficiently accurate to confirm or deny variability. Physical (Eggen 1966b).
- HR 7226/7 Malaroda (1975) has F7 IV-V.
- HR 7398 Binary (Hoffleit 1964). See note to Table I. Secondary falls 0.11^m below two colour main sequence. M_V based on trig. parallax is in marked disagreement with other M_V 's.
- HR 7959/60 Houk and Cowley (1975) have A2-3 IV-V for each component. Binary.
- HR 7989 Primary very unlikely to be a supergiant as then proper motions and radial velocity in Hoffleit (1964) would imply a very large space velocity. Colours suggest G6 II or G6 III. G6 III would give a reasonable space velocity but gives M_V for primary 2 magnitudes brighter than value obtained by placing secondary on main sequence.
- HR 8148 Binary. Primary is single-line spectroscopic binary. The error for U-B of secondary in Table I is misleadingly small. For such a close star with magnitude difference in U so large (4.5^m) an error of $0.10^m - 0.15^m$ would be normal. An unweighted mean gave $+1.08 \pm 0.13$ for U-B of secondary. The secondary probably lies on the two colour main sequence.
- HR 8635 Probable variable GCVS 8783. Cousins and Stoy (1962) suspected it to vary but it is now used as a standard (Cousins 1973c). Estimates of magnitude of B vary widely. Cousins and Stoy (1962) give 9.8^m , Wayman (1962) give 11.10^m (1 observation) and says Kuiper gave 10.0^m , IDS (Jeffers et al. 1963) gives 10.3^m , whereas we get 10.89^m . B-V of B suggests spectral type about M0.
- HR 8662 Common proper motion. Our observations suggest A9 V. Hoffleit (1964) has A5 m.
- HR 8695 Suspected variable GCVS 102214. Suspected as variable by Gould (1879h). The present observations do not indicate

variability. Binary. Sirius group. M_V based on trig. parallax is in marked disagreement with other M_V 's. Radial velocity probably variable (Campbell 1928).

HR 8999

Hoffleit (1964) gives dF5, Malaroda (1975) gives F4 V. The colours for the primary do not agree with any of these types but suggest that it is a giant F7. The colours for the secondary are compatible with the type given. If the primary is a dwarf the companion is probably optical.

HR 9044

The secondary is 0.14^m above the class IV locus in the two colour diagram (0.10^m above the two colour main sequence) although, according to Wayman (1961), it has a normal F2 IV spectrum. Buscombe (1963) says that the radial velocity (of the primary?) varies.

Notes to Table IIb

- HD 6334 Houk and Cowley (1975) have F6-8 III-IV for primary and say secondary is of similar type. Our colours agree better with this type than with F5 V but they might be affected by reddening.
- HD 41628 The combined light photometry in Table I is of low weight. Errors of 0.06^m in V and 0.03^m in the colours of the components would be more realistic.
- HD 105563 This star has been discussed by Lyngå (1973). The primary is of VV Cephei type and varies slightly in magnitude and colours. We did not obtain combined light UBV simultaneously with each of the 3 observations forming the mean. The combined light photometry used (see Table I) was based on 1 observation only and the star was assumed non-variable. In Table I the errors in the magnitude and colours for the primary should thus be larger and the rather large errors for the secondary do not imply that it varies. The colours of the secondary suggest $E_{B-V} = 0.32$ and $(B-V)_0 = -0.25$. Lyngå obtained mean $E_{B-V} = 0.29$ for three other stars in the group and our $(B-V)_0$ agrees with his type for the secondary. However B is 1.3^m brighter than D which has almost identical colours.
- HD 158320 This star has been discussed by Penny et al. (1975). The values of the magnitude and colours of the secondary and of the separation given there were preliminary and differ slightly from those in Table I which suggest $E_{B-V} = 0.47$, $(B-V)_0 = -0.25$ and spectral type B1.5 V. The primary is a single-line spectroscopic binary.

10.4 Comment on Table II

The agreement between the absolute magnitudes in the various columns is generally good. Some of the disagreement between the magnitudes based on the (B-V) colours and those based on the spectral types is undoubtedly due to differences between the adopted M_V versus B-V relation for the main sequence and Blaauw's calibration. It should be noted however that there may well be a selection effect in the case of Class III, II and I stars. This is because we tend to observe stars with small magnitude difference and hence discriminate against the brighter of the giants which have main sequence companions. It is possible that there may also be a small selection effect for dwarf primaries at the blue end of the main sequence. We were not able to estimate absolute magnitudes via main sequence secondaries for any of the class II primaries in Table II and only obtained such an absolute magnitude for one class I primary (HR 6134).

None of the estimated reddenings are anomalously high when compared with the reddenings for the appropriate distance and direction as given by Fitzgerald (1968).

There are surprisingly few doubles which appear to be optical. Probably some optical doubles included in the table remain undetected.

The absolute magnitudes based on dynamical parallaxes give extremely poor agreement. It should be noted, however, that the dynamical parallaxes used were all small, only a few being above 0.020 arcsecs and about half being less than 0.010 arcsecs. They appear too high and too low with about equal frequency. Bearing in mind the relatively large errors in trig. and dynamical parallaxes less than 0.040 arcsecs (see for example fig. 2 in Cester 1963) the agreement between the absolute magnitudes based

on trig. or dynamical parallaxes in this range and the other absolute magnitudes is fair. For the absolute magnitudes based on trig. parallaxes over 0.040 arcsecs taken from Woolley et al. (1970) the agreement is rather poor. The absolute magnitudes based on Woolley's parallaxes are $0.7^m \pm 0.2^m$ (s.e.) greater (i.e. fainter) than the absolute magnitudes of the primaries in column 5. The absolute magnitude based on the Woolley parallax is brighter for only 1 of the 17 stars for which the comparison was made. This suggests that the parallaxes in Woolley's catalogue are systematically too large. Figures 1 and 2 in Woolley et al. (1970) show that this is indeed the case except for stars with well-determined parallaxes. A main sequence fitted to the dwarf stars shown in their figure 1 would lie $0.5^m - 1.0^m$ below the main sequence locus shown in the figure.

10.5 Colour-colour and magnitude-colour diagrams for the stars

Figure 30 is a (U-B) versus (B-V) plot for the stars in Table II which have MK spectral types and Figure 31 is a (U-B) versus (B-V) plot for the stars in Table II which do not have a luminosity calibration. In both plots the main sequence and giant sequence shown are from Fitzgerald (1970). Most of the few apparently anomalous stars have been discussed in remarks in Table II or in the Notes to Table II.

In Figure 30 several class V stars with $0.40 \leq B-V \leq 0.45$ are well below the main sequence. These stars are rather far off the main sequence to be undetected binaries with main sequence components. Reddening is very unlikely. An error in the U-B colours is possible but unlikely. In Figure 31 the secondaries with $0.2 \leq B-V \leq 0.7$ are widely scattered about the main sequence. Duplicity, reddening and errors in the colours cannot explain this scatter. It is possible some of the stars

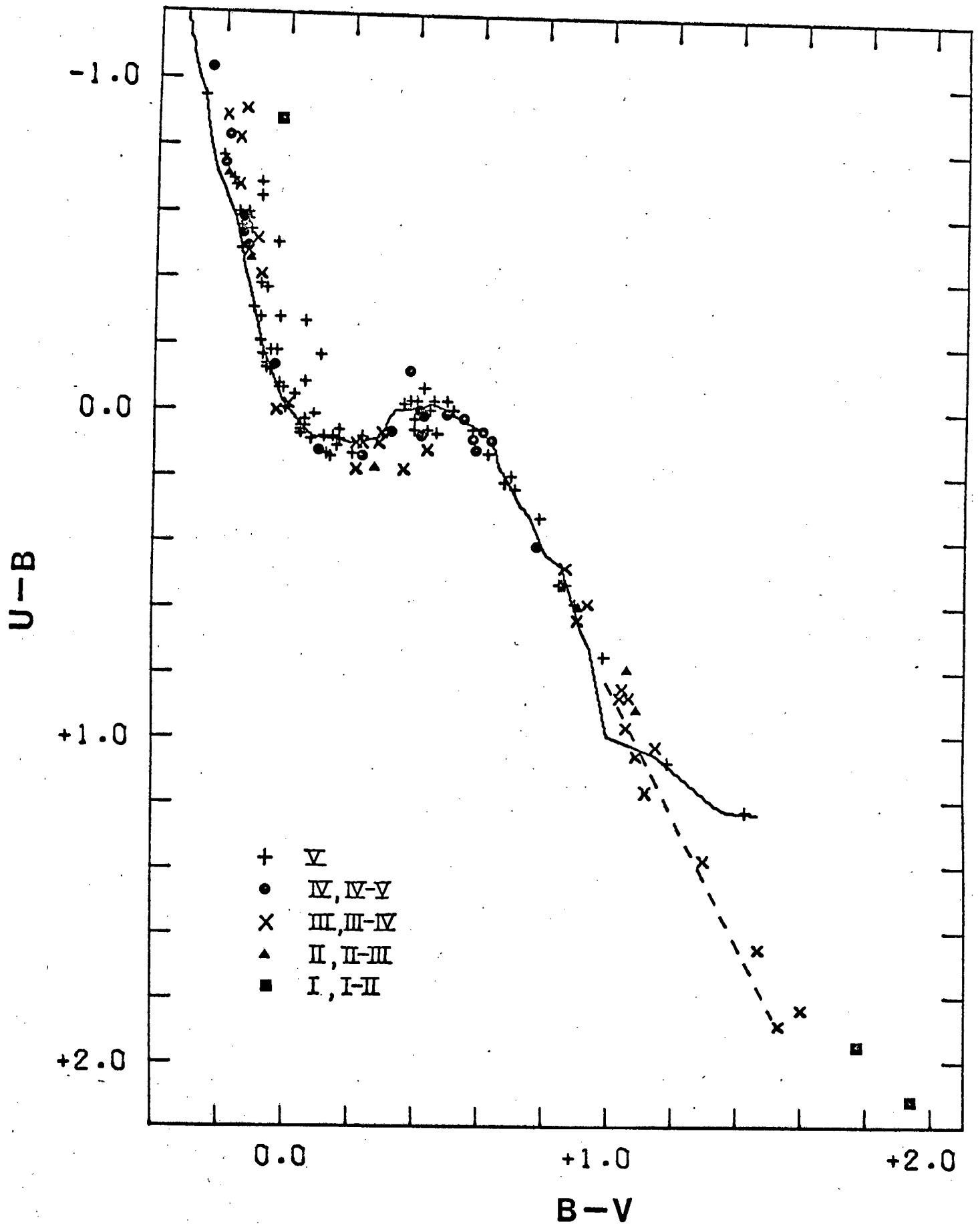


Figure 30. U-B versus B-V plot of the stars with MK spectral types.

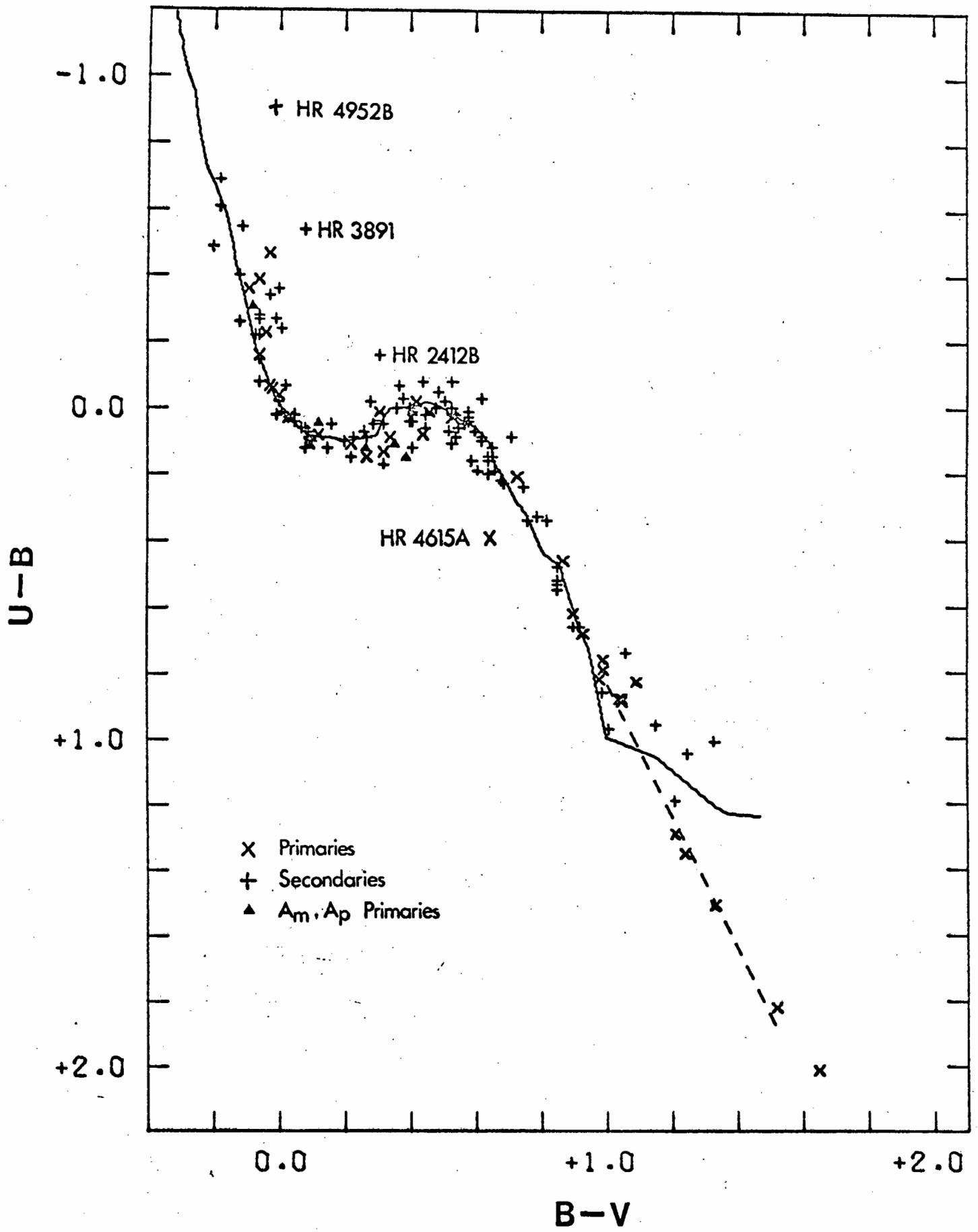


Figure 31. U-B versus B-V plot of the stars without luminosity classifications.

are Am or Ap stars but it seems that the main sequence two-colour locus really is wide for this range of B-V values. The two-colour diagrams given by Woolley et al. (Figs. 3 and 4 in Woolley et al. 1970) for the nearby stars show widening in the same region. In both figures 30 and 31 there is a striking absence of stars in a narrow band which crosses the main sequence at $0.30 < B-V < 0.35$. This feature is not so pronounced in the two-colour diagrams of Woolley et al. (1970).

Figure 32 is a magnitude-colour diagram for the stars for which we have assigned absolute magnitudes in column 5 of Table II. Figure 33 is a magnitude-colour diagram for the primaries only. In this diagram the luminosity class of each star is shown. In both diagrams the main sequence shown is the one to which the secondaries were fitted. It is given in Table IV. De-reddened B-V colours have been used where appropriate.

It is noticeable that very few primaries fall below the main sequence. There is a marked Hertzsprung gap. It should be noted that the shape of the giant branch is likely to be affected by observational selection. In Figure 33 it is seen that almost all the primaries without luminosity classifications are evolved stars, many of them being giants. In our sample there seem to be as many class III primaries without luminosity classifications as there are with classifications. Antares is the only star classified as class I or II which is included in Figure 33. The other class I and II primaries in Table II do not have main sequence secondaries.

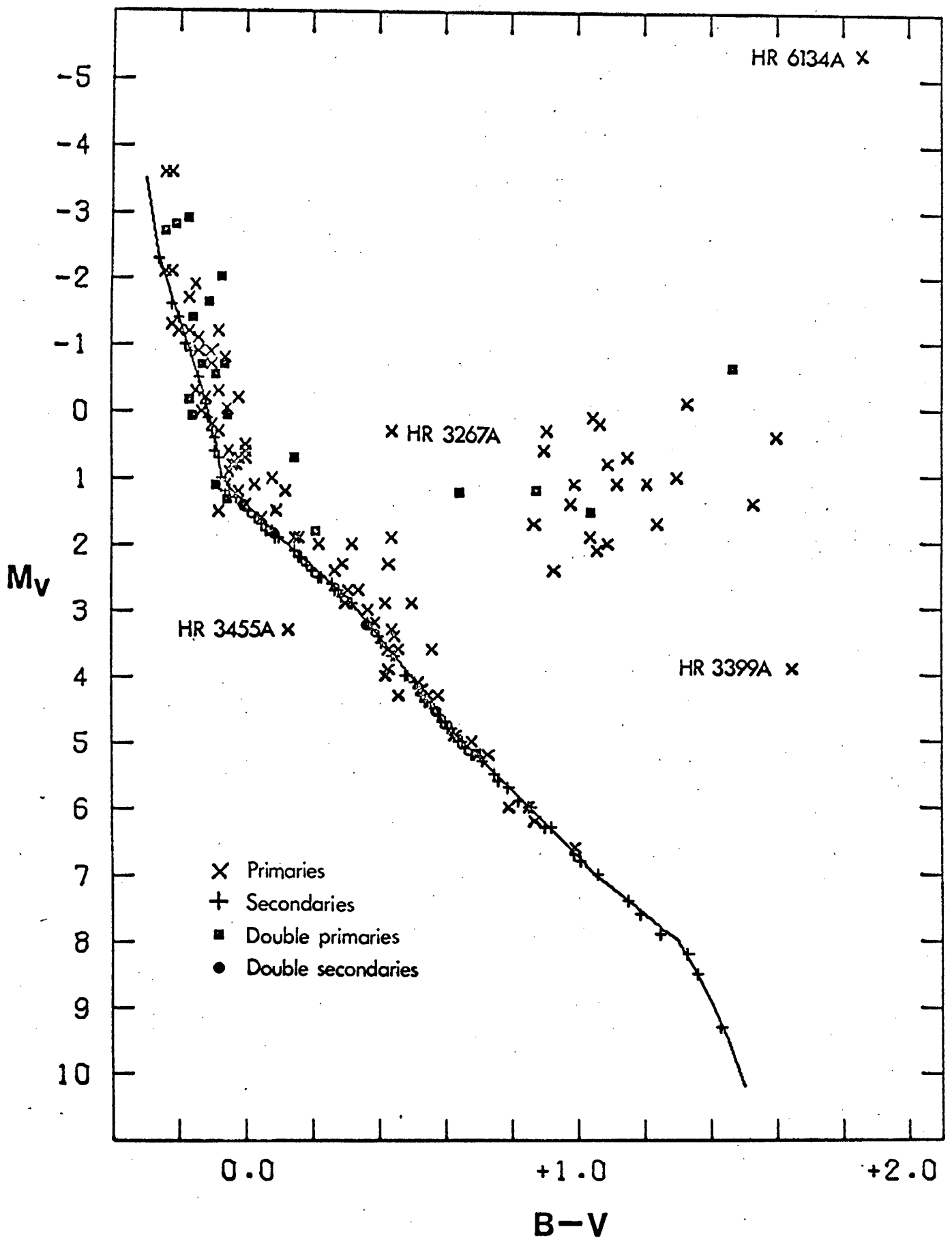


Figure 32. Magnitude-colour plot of all the stars to which we have assigned absolute magnitudes in column 5 of Table II.

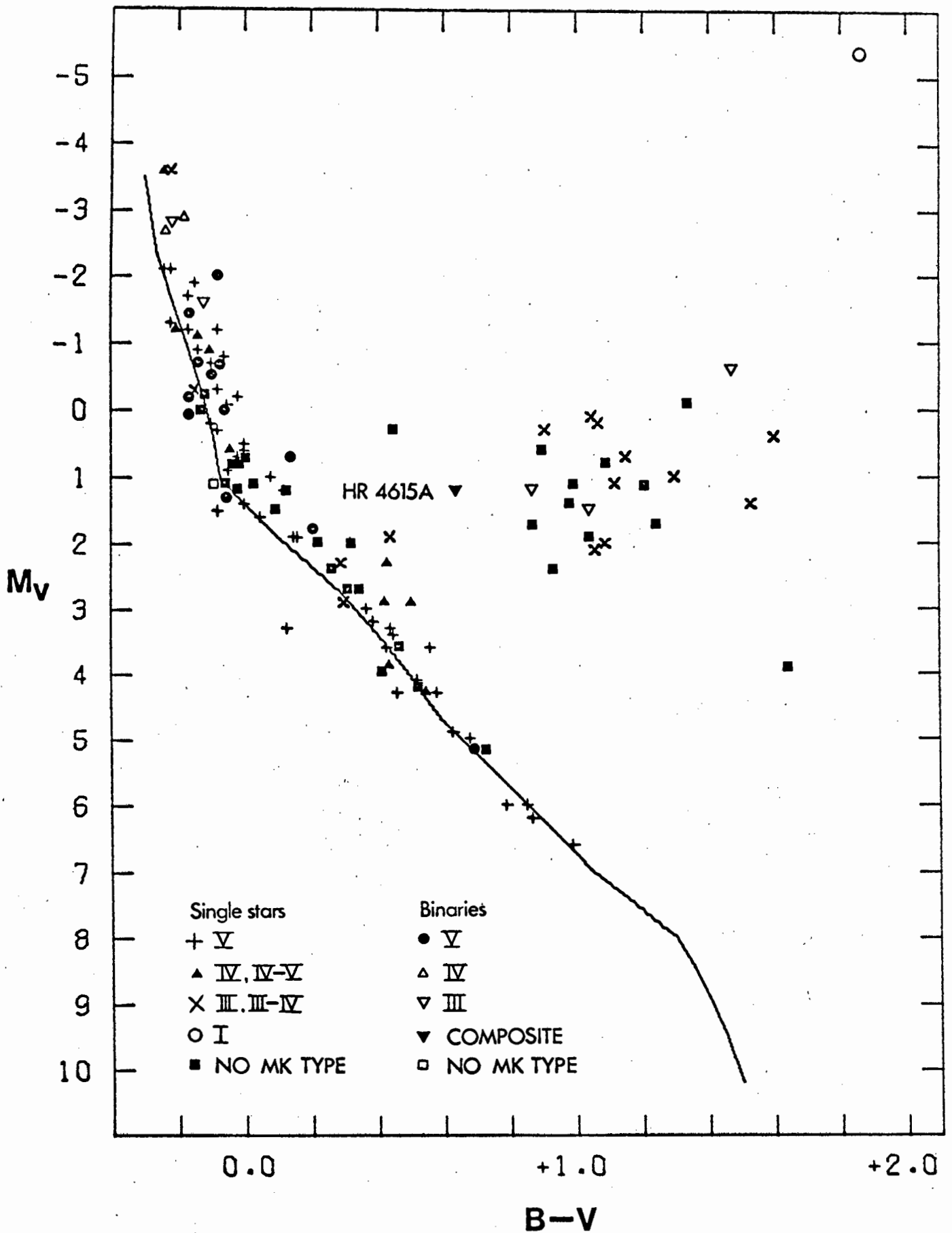


Figure 33. Magnitude colour plot of the primaries to which we have assigned absolute magnitudes in column 5 of Table II. Primaries which are themselves binaries are indicated by special symbols.

CHAPTER 11DISCUSSION OF THE ACCURACY OF OUR RESULTS
AND THOSE OF OTHER AUTHORS11.1 Comparison with other area scanner results

Only Rakos (1972) has published magnitude differences of constant stars measured using an area scanner. Unfortunately none of Rakos's 11 stars were observed by us. No comparison of our magnitude differences with other area scanner magnitude differences is therefore possible.

Various workers have given estimates of the (internal) errors for single measures of magnitude difference made with their scanners. We have found the error of a single measure to vary extremely widely depending on the seeing, and on the separation, magnitudes and magnitude difference of the double. The errors may be much larger for observations with the U filter due to much lower photon count rates and/or worse seeing than for V or B. Errors also depend of course on the size of the telescope used. We feel therefore that comparison of error estimates for single measures would be meaningless.

11.2 Comparisons of magnitude differences obtained by various workers

Very few magnitude differences on the UBV system have been published for southern visual doubles. The position is especially bad for closer doubles. Hardly any of the stars observed in our program have published magnitude differences on the UBV system, the only published photometry with which a meaningful comparison is possible being that of Wayman (1962). For 9 stars we find a systematic difference, this work

minus Wayman, of $+0.034 \pm 0.029$ with the root mean square of the single comparisons (after correction for systematic difference) being 0.083 . All the 9 stars are "wide", between 7 and 12 arcsecs, and their magnitude differences are fairly uniformly distributed between 0.0 and 5.0 . Our magnitude difference differed by more than 0.10 from that given by Wayman for only one star, HR 8635, which has a magnitude difference of about 5.0 . The sample is unfortunately very small but does not show evidence for any dependence of the differences, this work minus Wayman, on magnitude difference. For the same 9 stars the systematic difference between our B-V colours for the secondaries and Wayman's is -0.009 ± 0.008 . The largest difference was only -0.05 , for HR 8635 which has ΔB about 5.8 . For 8 stars the systematic difference for the U-B colours of the secondaries is $+0.033 \pm 0.055$. The U-B colours for 2 of the 8 secondaries, HR 5189 for which $\Delta u = 5.3$ and HR 6416 for which $\Delta u = 4.8$, differ by more than 0.10 . Neither we nor Wayman could obtain a U-B colour for the secondary of HR 8635.

Wieth-Knudsen (1957) and van Albada (1958) have published many magnitude differences on the photovisual system. These results were obtained as a by-product of the astrometric work done at Lembang. In this work objective gratings were used on a 60 cm visual refractor where necessary so as to minimize the magnitude difference between the central image of each secondary and the first or a higher order diffraction image of its primary on multiple exposure plates - the Hertzsprung method. Both authors used modified versions of the Argelander step method to estimate the magnitude differences from the plates obtained. Wieth-Knudsen used Lembang plates from 1949.7 to 1952.4 whereas van Albada used plates

from 1949 to 1957. As magnitude differences for a considerable proportion of our stars were published by Wieth-Knudsen and van Albada a comparison of their values with ours has been made. As a check on the accuracy of their results a comparison between van Albada's and Wieth-Knudsen's results for the stars for which we have obtained results has also been made. These comparisons are summarized in Table V.

In constructing Table V the stars were divided into groups in order to facilitate the recognition of systematic differences. The limits of these groups were somewhat arbitrarily chosen in order to obtain roughly equal numbers of stars in each group. However 3.0 arcsecs is about the separation below which the Hertzsprung photographic technique would not be expected to give accurate results and below which stars of non-negligible magnitude difference become difficult for us to observe. Few photoelectric observations have been published for stars with separations less than 6.0 arcsecs. No stars with $\Delta m > 4.0^m$ were included in the comparison as three of the four such stars which could have been included were known or suspected variables. The differences between the results of the various authors, in the senses indicated in the column headings, were calculated for each of the stars. For each group of stars the systematic difference was calculated, then the root mean square of the differences after allowing for the systematic difference and finally the standard error of the systematic difference. The values for the summed groups and for all the compared stars were calculated similarly.

The agreement between our magnitude differences and those of Wieth-knudsen and van Albada is in general fairly good but there is a marked tendency for our magnitude differences to be larger. Taking all

TABLE V

Comparison with magnitude differences obtained at Lembang

Separation in arcsecs	$\Delta m < 1.0$			$1.0 \leq \Delta m \leq 2.5$			$2.5 < \Delta m \leq 4.0$			$\Delta m \leq 4.0$		
	H-WK	H-VA	WK-VA	H-WK	H-VA	WK-VA	H-WK	H-VA	WK-VA	H-WK	H-VA	WK-VA
$d < 3.0$	$\begin{matrix} -0.004 \\ +0.023 \\ 7 \end{matrix}$	$\begin{matrix} +0.002 \\ +0.022 \\ 14 \end{matrix}$	$\begin{matrix} +0.007 \\ +0.041 \\ 7 \end{matrix}$	$\begin{matrix} +0.064 \\ +0.091 \\ 5 \end{matrix}$	$\begin{matrix} -0.012 \\ +0.028 \\ 9 \end{matrix}$	$\begin{matrix} -0.040 \\ +0.102 \\ 5 \end{matrix}$	-	$\begin{matrix} +0.090 \\ +0.021 \\ 3 \end{matrix}$	-	$\begin{matrix} +0.006 \\ +0.040 \\ 13 \end{matrix}$	$\begin{matrix} +0.007 \\ +0.016 \\ 26 \end{matrix}$	$\begin{matrix} +0.015 \\ +0.051 \\ 13 \end{matrix}$
$3.0 \leq d \leq 6.0$	$\begin{matrix} +0.004 \\ +0.021 \\ 7 \end{matrix}$	$\begin{matrix} +0.003 \\ +0.026 \\ 8 \end{matrix}$	$\begin{matrix} +0.019 \\ +0.026 \\ 7 \end{matrix}$	$\begin{matrix} +0.015 \\ +0.027 \\ 12 \end{matrix}$	$\begin{matrix} +0.016 \\ +0.023 \\ 17 \end{matrix}$	$\begin{matrix} +0.040 \\ +0.033 \\ 12 \end{matrix}$	$\begin{matrix} -0.023 \\ +0.061 \\ 6 \end{matrix}$	$\begin{matrix} +0.055 \\ +0.055 \\ 13 \end{matrix}$	$\begin{matrix} +0.188 \\ +0.075 \\ 6 \end{matrix}$	$\begin{matrix} +0.003 \\ +0.020 \\ 25 \end{matrix}$	$\begin{matrix} +0.027 \\ +0.022 \\ 38 \end{matrix}$	$\begin{matrix} +0.070 \\ +0.027 \\ 25 \end{matrix}$
$d > 6.0$	$\begin{matrix} +0.048 \\ +0.018 \\ 13 \end{matrix}$	$\begin{matrix} +0.026 \\ +0.013 \\ 14 \end{matrix}$	$\begin{matrix} -0.016 \\ +0.020 \\ 13 \end{matrix}$	$\begin{matrix} +0.027 \\ +0.020 \\ 6 \end{matrix}$	$\begin{matrix} +0.081 \\ +0.047 \\ 8 \end{matrix}$	$\begin{matrix} +0.033 \\ +0.055 \\ 6 \end{matrix}$	$\begin{matrix} +0.213 \\ +0.040 \\ 7 \end{matrix}$	$\begin{matrix} +0.141 \\ +0.047 \\ 8 \end{matrix}$	$\begin{matrix} -0.091 \\ +0.051 \\ 7 \end{matrix}$	$\begin{matrix} +0.088 \\ +0.021 \\ 26 \end{matrix}$	$\begin{matrix} +0.072 \\ +0.020 \\ 30 \end{matrix}$	$\begin{matrix} -0.025 \\ +0.023 \\ 26 \end{matrix}$
All separations	$\begin{matrix} +0.023 \\ +0.013 \\ +0.064 \\ 27 \end{matrix}$	$\begin{matrix} +0.012 \\ +0.012 \\ +0.069 \\ 36 \end{matrix}$	$\begin{matrix} -0.001 \\ +0.015 \\ +0.079 \\ 27 \end{matrix}$	$\begin{matrix} +0.029 \\ +0.025 \\ +0.115 \\ 23 \end{matrix}$	$\begin{matrix} +0.024 \\ +0.019 \\ +0.106 \\ 34 \end{matrix}$	$\begin{matrix} +0.021 \\ +0.031 \\ +0.144 \\ 23 \end{matrix}$	$\begin{matrix} +0.082 \\ +0.050 \\ +0.179 \\ 14 \end{matrix}$	$\begin{matrix} +0.088 \\ +0.034 \\ +0.161 \\ 24 \end{matrix}$	$\begin{matrix} +0.059 \\ +0.059 \\ +0.214 \\ 14 \end{matrix}$	$\begin{matrix} +0.038 \\ +0.015 \\ +0.117 \\ 64 \end{matrix}$	$\begin{matrix} +0.036 \\ +0.012 \\ +0.115 \\ 94 \end{matrix}$	$\begin{matrix} +0.020 \\ +0.018 \\ +0.143 \\ 64 \end{matrix}$

Note: H = present work,

WK = Wieth-Knudsen (1957),

VA = van Albada (1958)

Each box contains the systematic difference with its standard error, the number of comparisons on which it is based, and the root mean square of the single comparisons after removal of the systematic error. See text.

the stars together the systematic differences are small but significant. For the closer stars the agreement is very good but for separations greater than 6.0 arcsecs the systematic differences are significant. By far the greatest systematic difference is for the group of stars with separation greater than 6.0 arcsecs and magnitude difference between 2.5^m and 4.0^m . A systematic error (or errors) seems likely as will be discussed below. The root mean squares of the single comparisons H-WK and H-vA (after removal of systematic differences) show no obvious trend with separation but do increase rapidly with magnitude difference. The root mean squares for the comparisons WK-vA show, as might be expected, a decrease as separation increases. The root mean squares 0.117^m , 0.115^m and 0.143^m obtained for H-WK, H-vA, WK-vA respectively for all the stars suggest that Wieth-Knudsen's and van Albada's random errors are similar. The root mean square of the errors quoted by Wieth-Knudsen for the 64 stars compared in Table V is 0.102^m and van Albada claims a standard error of a single estimate of 0.11^m for his magnitude differences. Thus both Wieth-Knudsen's and van Albada's error claims appear realistic and the errors we quote for our Δv 's in Table I are roughly the correct size. Rather surprisingly in view of the fact that Wieth-Knudsen's results are based on a subset of the plates used by van Albada there are some fairly large systematic differences in the WK-vA comparisons. However these average out giving a barely significant systematic difference when summed over all the compared stars. The overall systematic differences and root mean square differences are very similar for H-WK and H-vA despite the greater care used by Wieth-Knudsen in obtaining his magnitude differences and despite the fact that his measures are quoted to 0.01^m whereas van Albada's

are only quoted to 0.05^m . As already mentioned however, van Albada had a larger number of plates at his disposal.

In order to obtain a better idea of the source of the systematic difference between our magnitude differences and those from Lembang for the wider stars we compared conventional UBV photoelectric results by Eggen (1963, 1966a) with those of Wieth-Knudsen and van Albada. Very few of the stars observed by Eggen had separations less than 6.0 arcsecs so this comparison is perforce only possible for the wider stars. The results are given in Table VI which is similar to Table V but the restriction to $\Delta m \leq 4.0^m$ has been relaxed. Despite the small number of stars included in this comparison there is a close correspondence between the systematic differences and root mean squares found for E-WK and E-vA and those found for H-WK and H-vA (see Table V). In particular the systematic differences for the $2.5^m < \Delta m \leq 4.0^m$ group agree very well. A comparison with the work of Wayman (1962) is also given in Table VI. This comparison shows a very similar pattern. This suggests a systematic error in the magnitude differences from Lembang.

A comparison between Eggen's magnitude differences and those of Strand (1969) was also made and the results included in Table VI. While there are significant systematic differences between the results of Eggen and those of Strand they are small. The systematic difference for the stars in the group $\Delta m > 2.5^m$ is only $+0.036^m \pm 0.018^m$. If this group is split into two groups with $2.5^m < \Delta m \leq 4.0^m$ and $\Delta m > 4.0^m$ the resulting systematic differences are $+0.021^m \pm 0.022^m$ (22 stars) and $+0.071^m \pm 0.029^m$ (7 stars) respectively. Splitting the E-WK and E-vA groups in the same way does not produce such a difference in either case. It therefore appears

TABLE VI

Comparison of magnitude differences obtained by various workers

Authors compared and separation in arcsecs	Magnitude difference			
	$\Delta m < 1.0$	$1.0 \leq \Delta m \leq 2.5$	$\Delta m > 2.5$	All Δm 's
E-WK $d > 6.0^*$	+0.025 _± 0.068 4 +0.119	+0.020 _± 0.040 5 +0.080	+0.202 _± 0.023 4 +0.040	+0.078 _± 0.034 13 +0.119
E-vA $d > 6.0^*$	-0.018 _± 0.018 10 +0.054	+0.064 _± 0.046 9 +0.130	+0.194 _± 0.066 7 +0.161	+0.068 _± 0.024 26 +0.118
W-WK $d > 6.0$	-0.054 _± 0.059 7** +0.143	- -** -	+0.183 _± 0.051 4 +0.088	+0.032 _± 0.054 11 +0.170
W-vA $d > 6.0$	-0.020 _± 0.029 5 +0.058	+0.067 _± 0.035 6 +0.078	+0.114 _± 0.037 7 +0.091	+0.061 _± 0.023 18 +0.096
E-S $d > 6.0$	-0.044 _± 0.016 27 +0.080	-0.002 _± 0.016 37 +0.096	+0.036 _± 0.018 29 +0.098	-0.006 _± 0.009*** 103*** +0.095***
E-S $3.0 \leq d \leq 6.0$	-0.043 _± 0.019 10 +0.058	- - -	- - -	- - -

E = Eggen (1963, 1966a),

WK = Wieth-Knudsen (1957)

vA = van Albada (1958),

W = Wayman (1962),

S = Strand (1969)

See note beneath Table V

* 3 (possibly 4) of stars used are actually in range $3.0 \leq d \leq 6.0$ ** 2 stars with $1.0 \leq \Delta m \leq 2.5$ have been included with 5 stars with $\Delta m < 1.0$. One WK measure in this group seems erroneous hence high errors. The "All Δm " result for W-WK would be $+0.074 \pm 0.037$ (10 stars) without this measure.*** The 10 stars with $3.0 \leq d \leq 6.0$ have been included in these totals which should agree with those given in Table I of Strand (1969). Strand however used only 97 stars for his comparison and the other results differ slightly as a result, the systematic difference Strand obtained being -0.001 ± 0.010 .

as if a small systematic difference between Eggen's and Strand's magnitude differences occurs for $\Delta m \gtrsim 4.0^m$ whereas a large systematic difference between Eggen's and Wieth-Knudsen's and van Albada's results occurs for $\Delta m \gtrsim 2.5^m$. A direct comparison between Strand's (1969) results and those of Wieth-Knudsen and van Albada is made in Table VII. The differences evident for $\Delta m < 1.0^m$ are probably the result of errors in the work of Strand (see Section 11.3), those for $1.0^m \leq \Delta m \leq 2.5^m$ probably indicate underestimates by Wieth-Knudsen and van Albada and the large differences for $\Delta m > 2.5^m$ once again suggest a large underestimation of magnitude differences by Wieth-Knudsen and van Albada for this group.

It seems probable that a systematic underestimation of magnitude difference occurs for large magnitude differences obtained using refractors and the Hertzsprung method. The higher order images (spectra) of the primaries are probably measured too faint in these cases. This was suggested by Kooreman (1946). It might be expected that this underestimation depends on the colour of the primary or on the colour difference between the components. However, using the B-V and U-B of the components as measured by us, the differences H-WK and H-vA do not show any significant dependence on the B-V or U-B colour of the primary or on the difference in the B-V or U-B colours of the components. Thus there is no evidence that the differences between the wavelength response curves of the photovisual V and the photoelectric V cause significant systematic differences in the magnitude differences obtained. As our conclusions concerning doubles with large magnitude difference are based in all cases on very small samples they ought to be verified by doing conventional UVB photometry on wide (say separation > 15 arcsecs) doubles of large magnitude

TABLE VII

Comparison of magnitude differences obtained by Strand with those obtained at Lembang

Separation in arcsecs	$\Delta m < 1.0$		$1.0 \leq \Delta m \leq 2.5$		$\Delta m > 2.5$		All Δm 's	
	S-WK	S-VA	S-WK	S-VA	S-WK	S-VA	S-WK	S-VA
$d \leq 6.0$	+0.020	+0.025	+0.093	+0.089	-	+0.190	+0.040	+0.051
	+0.020	+0.014	+0.024	+0.035	-	+0.166	+0.017	+0.018
	16	28	6	8	-	3	22	39
$d > 6.0$	+0.079	+0.075	+0.054	+0.093	-	+0.234	+0.080	+0.111
	+0.057	+0.053	+0.035	+0.071	+0.170	+0.075	+0.069	+0.062
	+0.027	+0.020	+0.039	+0.037	+0.052	+0.079	+0.022	+0.018
All separations	14	16	4	9	3	4	21	29
	+0.096	+0.077	+0.067	+0.104	+0.073	+0.137	+0.098	+0.096
	+0.037	+0.035	+0.070	+0.079	+0.170	+0.124	+0.054	+0.056
All separations	+0.017	+0.012	+0.022	+0.025	+0.052	+0.079	+0.014	+0.013
	30	44	10	17	3	7	43	68
	+0.089	+0.077	+0.066	+0.099	+0.073	+0.194	+0.090	+0.105

S = Strand (1969)
 WK = Wieth-Knudsen (1957)
 VA = van Albada (1958)
 See note beneath Table V

difference already observed at Lembang.

11.3 Attempts to put magnitude differences on a homogeneous system

Various attempts have been made to transform magnitude differences measured visually and by a variety of photometric methods onto a uniform system. Early efforts by Öpik (1923), Baize and Romani (1943) and Baize (1951) were superseded by the catalogue of Wallenquist (1954). Wierzbinski's (1969) catalogue is based on Wallenquist (1954).

Wallenquist's catalogue is based on photovisual magnitude differences obtained using the Hertzsprung method by Kooreman (1946) and Strand (1969) although only a part of the Strand (1969) results was available to Wallenquist. Wallenquist found that, for the 69 pairs he compared, there was a systematic difference, Strand minus Kooreman, of $+0.02^m$ and that there was no scale error. He therefore used the mean of the values obtained by the two authors as the basis of his catalogue. However the comparisons made by Strand (Table I in Strand 1969) with extensive photoelectric results by Eggen (1963, 1966a) and Johnson show that Strand's results have negligible zero point difference with the V magnitude differences on the UBV system and suggest that Kooreman's results are not on the system. We have already shown (see Table VI) that the apparently perfect agreement between Strand's and Eggen's results is fortuitous. We have also examined the differences, Strand minus Kooreman, for the 93 stars in common between Strand (1969) and Kooreman. We find a systematic difference, Strand minus Kooreman, of $+0.031^m \pm 0.009^m$ (s.e.) for 62 stars with $\Delta m < 1.0^m$ and $+0.009^m \pm 0.015^m$ (s.e.) for 31 stars with $\Delta m \geq 1.0^m$. There does not appear to be any dependence of the systematic difference on separation. It appears that

Strand's results for $\Delta m < 1.0^m$ are $0.03^m - 0.04^m$ larger than Eggen's and Kooreman's but that his results for larger magnitude differences are in fair agreement with those of the other two authors. Figures 1a, 2a and 4a of Strand (1969) illustrate the tendency of Strand's magnitude differences to be too large for $\Delta m < 1.0^m$. Strand however does not comment on this point. Similarly Wieth-Knudsen (1957) has compared his results with those in Wallenquist's (1954) catalogue and claims that the differences, Wieth-Knudsen minus Wallenquist, do not depend on the magnitude difference whereas his fig. 2 shows that for stars with $\Delta m > 2.5^m$ there is a tendency for these differences to be negative.

Wierzbinski (1969) does not refer to Eggen (1963) or Eggen (1966) and appears to have been unaware of the various systematic differences between the results of Strand (1969), Kooreman (1946), Wieth-Knudsen (1957) and van Albada (1958). His catalogue should therefore be used with caution. We have not compared our results with those in Wierzbinski's catalogue because, for virtually all the stars in common, the results in Wierzbinski are based on authors whose results we have already discussed. The external errors of Parts One and Three of Wierzbinski's catalogue are certainly not less than 0.10^m and that for Part Two is probably much higher. Systematic errors are extremely likely especially for large magnitude differences. It should be noted that Wierzbinski identifies the double star observer Δ as Dembowski whereas most if not all the results given as being by Δ are in fact by Dunlop whose abbreviation in the Southern Double Star Catalogue (Innes 1927) is Δ .

Heintz (1969) comments concerning Δm observations by visual observers: 'Large Δm 's are overestimated on the average.... Correction

formulae for the Δm have been given by Öpik.... as is now generally agreed-in Öpik's results the systematic correction is underdone....'.

We find to the contrary. For 27 stars the differences, This work minus Öpik, have a mean of $+0.^m.24 \pm 0.^m.05$ (s.e.) with no dependence on magnitude difference. The root mean square difference, after correction for the systematic difference is $0.^m.27$.

11.4 Some comments on the accuracy of the separations obtained

The differences between the separations assumed for the separation standard stars when calculating the scales and the values obtained for these stars when treated as program stars were examined. It was found that the systematic difference (measured separation-standard separation) was $-0.^m.022 \pm 0.^m.021$ (s.e.) arcsecs with root mean square difference 0.10 arcsecs. This small systematic difference reflects the fact that some of the stars were used as standards very much more often than others. The high root mean square difference is caused by some large differences for wider separation standards (because of the erroneous wobble plate centring). The mean separation of the standards was 6.1 arcsecs whereas that for the other stars was 3.8 arcsecs.

For stars for which the separations in Table I are given to two decimal places and which are not known to have significantly changing separation a comparison was made with the separations given in the Index Catalogue of Double Stars (IDS) (Jeffers, van den Bos and Greeby 1963). Five of the 54 stars in the sample showed differences greater than 0.3 arcsecs, one difference being over 1 arcsec. On investigation it was found that, in each of these 5 cases, the separation given in the IDS was based

on a few poor measures. Considering only the remaining 49 stars a systematic difference, This work minus IDS, of $+0.006 \pm 0.014$ (s.e.) arcsecs was found, the root mean square of a single difference being 0.10 arcsecs. When these 49 stars were divided into groups with separations greater than 3.0 arcsecs, less than 3.0 arcsecs, respectively, no significant difference was found between the two groups. Thus our separations do not appear to be systematically wrong or to have errors depending on separation whereas it was expected that scaling errors (see Sections 7.4 and 7.7) which are essentially percentage errors would ensure that the errors would be largest for the widest stars. The overlapping of the profiles probably increases the error of the separations for the closer stars. The root mean square difference of 0.10 arcsecs with the IDS is satisfactory when it is remembered that the IDS separations are only quoted to one decimal place. It seems that the internal mean errors quoted in Table I, the root mean square of which is 0.045 arcsecs, are comparable with the external errors of the corresponding separations.

CHAPTER 12CONCLUSIONS AND RECOMMENDATIONS12.1 Improvements to the UCT Area Scanner

There are many ways in which the efficiency, accuracy and usefulness of our area scanner can be improved. Most of these concern the hardware, the ASHCAN program and the observing procedure.

The most urgent improvement required is to the gearing system used between the stepping motor and the wobble plate shaft. Large backlash in the gears allowed incorrect motion of the wobble plate resulting in large errors in separation and magnitude difference as has been discussed in Chapter 7. This problem can be tackled in two ways. Gears with minimal backlash can be used for the approximately 4:1 gearing between the motor and the wobble plate shaft. Alternatively, or perhaps in addition, a trigger and sensing mechanism can be built into the photometer and the ASHCAN program to ensure that the scans are all centred on the correct "flat" position of the wobble plate. Beside the elimination of the errors caused by the wrong centring of the wobble plate it is likely that the minimising of backlash will improve the shapes of the accumulated scan profiles resulting in better fits and another decrease in error.

The addition of a 360° circle to the scanner and a change in the observing procedure would enable measurements of the position angle of the doubles to be made. There are three ways in which the position angle of a star could be obtained. The most accurate way would be to observe the star at several (6 or 8?) different scanning angles and fit a sine curve (see Rakos 1972) to the separations at the various scan angles. This method

should yield the most accurate separation. However it would not be justified using our scanner because of inaccuracy in the rotation of the bearing in our turntable module (see Section 3.2). The large number of extra observations required is also a disadvantage. At the other extreme one could merely set the turntable so that the stars, as viewed through the eyepiece, are in the position previously described as horizontal. This would result in a random error of several degrees in the position angle and possibly a systematic error too. Another method which might be more accurate without being too time-consuming would be to rotate the turntable till the images of both components are simultaneously on the slit. This should be relatively quick and accurate and could easily be done before rotating by 90° or some other measured angle to do the main part of the observation. The separations obtained should then be more accurate than those obtained by the procedure used for the present observations. Using the methods outlined above it should be possible to measure the position angles and separations of stars with separations up to about 20 arcsecs without making any further changes to the equipment.

If magnetic tape is used for output of the data the resulting decrease in output time for each accumulated scan will result in a slightly decreased time being needed for each observation as discussed in Sections 3.4.4 and 4.4. The hardware and ASHCAN program could be altered to enable inclusion of extra information on the punched (or magnetic) tape. Items such as filter used, wobble plate used, observation sequence number, star name etc. could be automatically/semi-automatically recorded in this way so as to speed up the observations and make the subsequent reduction easier, faster and more accurate. The author is not convinced that these goals

would be achieved.

Several alterations to the ASHCAN program however would be worthwhile. The bins on either end of the scan should be corrected for the losses resulting from shifting during the summing process. This can be done by counting the number of times each bin of the accumulated scan does not receive an increment and, knowing the total number of scans made, multiplying the total in each bin by the appropriate ratio immediately before outputting the data. It would be much easier to judge the quality of the peaks of faint components in the accumulated scans if the accumulated scan could (optionally) be displayed instead of the mean scan. There is scope for experimentation in the correlation part of the ASHCAN program. The maximum shift allowed before rejection could be set at 8 or 10 instead of 16 bins. This might improve the profile shapes. The actual function which is maximised in the correlation procedure could possibly be altered. Criteria could be introduced to reject scans made in worse than average seeing (see Section 4.5). It is expected that it will be possible to improve the resolution of the scanner in this way by decreasing the width of the profiles of the components. There is however the danger that systematic errors could be introduced at the same time.

For very bright stars neutral filters will be used in future to reduce the amount of light reaching the photomultiplier tube. Once the absorption of the neutral filters and the colour equations for the system including the neutral filters have been found then very bright stars could be scanned using the full aperture of the telescope and simultaneous or near simultaneous UVB photometry could be made without any coincidence loss problems.

The observing procedure could be improved in several ways. More care could be taken to avoid having internal reflection image profiles of the primary near the profile of the secondary (see Section 5.6). Observations with the turntable rotated so that the viewing eyepiece is on the north side of the telescope could be made more frequently as checks (see Section 4.4). Conventional UBV observations of standards should be made more frequently so as to improve the accuracy of the transformation of the magnitude differences to the UBV system. The accuracy of the separations obtained would be improved by making more frequent observations of separation standards.

A very careful check of the parallelity of each new slit should be made before it is taken into use.

Two sources of error in the magnitude differences should be more thoroughly investigated. These are systematic wrong fitting of magnitude differences in the case of badly overlapping profiles and the incorrect centreing of the scans. These are discussed in Sections 7.4 and 7.6. In the case of incorrect centreing an experiment should be performed in which the centreing is set wrong by measured amounts in order to verify the conclusions of Sections 7.4 and 7.6.

Several minor changes in the reduction programs could improve the accuracy of our results very slightly.

12.2 Moving the slit versus moving the image

A key feature in the design of any area scanner is the method by which the scanning is achieved. The method we use, namely scanning the image across a slit by wobbling a quartz plate in the converging light beam,

caused complications in our reduction process because of the non-linearity of the image shift and the dependence of the shift on the wavelength of the light (see Section 6.2). It also sometimes gave rise, by internal reflection in the wobble plate, to troublesome extra images (see Section 5.6). Problems also occurred with the gears between the driving motor and the wobble plate shaft. However we prefer these problems to those which might occur as a result of non-linearities in the motion of the slit in the arrangement as used by Franz and Rakos (see Chapter 2). Moving the image across a slit by rocking a double mirror in the light beam as described by Høg (1971) seems to be the simplest scanning method used up to the present time. Unfortunately we cannot compare our experiences with those of Rakos, Franz and Høg as they have not yet described their work in detail.

12.3 Range of applicability of the area scanner to double star observations

Figure 34 is a plot of magnitude difference versus separation for the stars in Table I. The original limits set for the observing program are indicated. The stars with separation greater than 10 arcsecs were added in a slight extension of the program. Most of the stars with separation less than 2 arcsecs were included in the program because the separations given for them in the Catalogue of Bright Stars were over 2 arcsecs. With the scanner in its present state stars with separation less than 1 arcsec can be measured, using the 1 metre telescope, only on nights of exceptional seeing and then only if their magnitude differences are less than about 1 magnitude. Stars with separation between 1 and 3 arcsecs and small magnitude difference can quite frequently be measured at

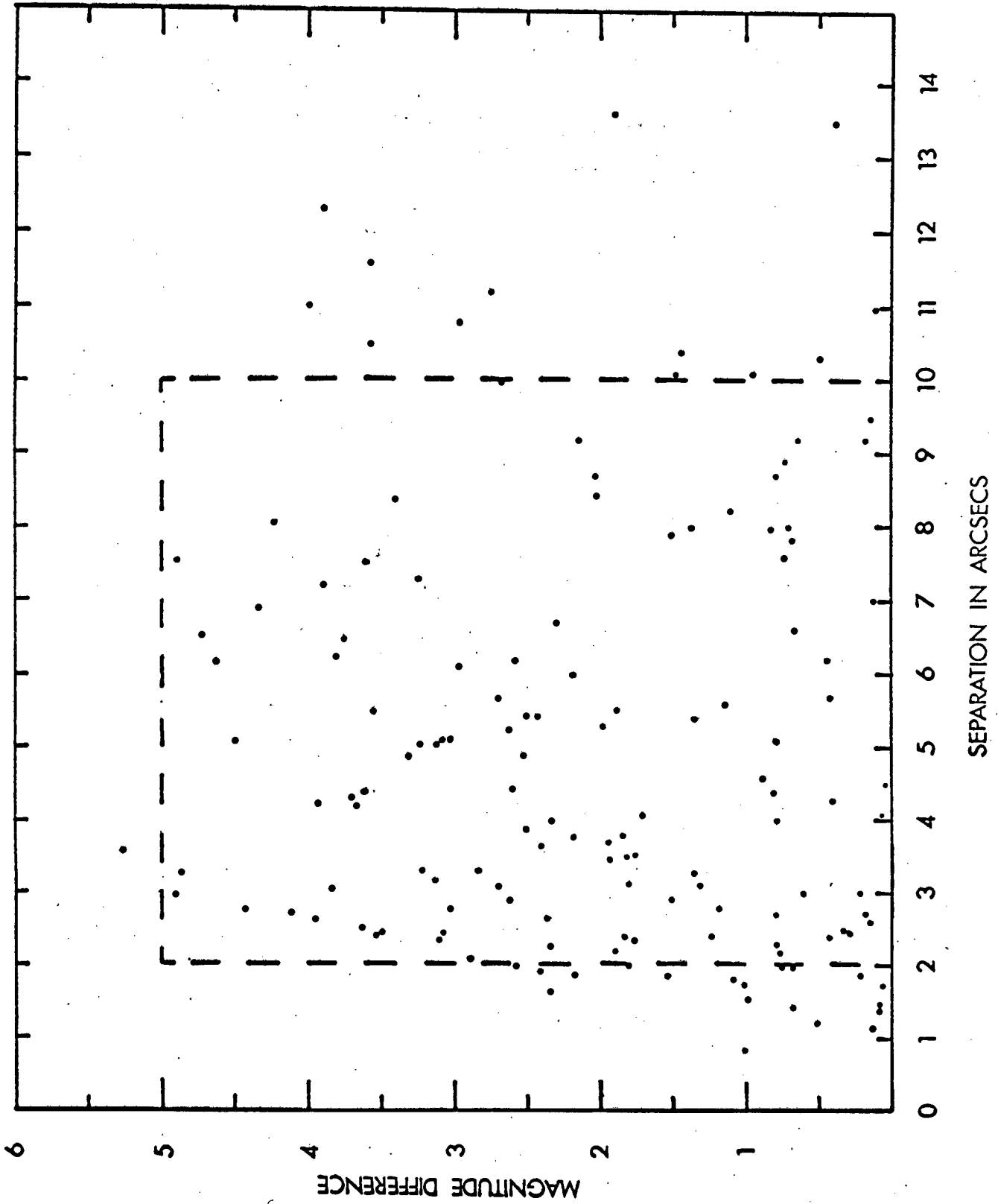


Figure 34. V Magnitude difference versus separation for the stars in Table I. The original limits of our program are indicated by broken lines.

Sutherland but exceptional seeing is required for those with magnitude difference greater than about 3 magnitudes. Observation of still wider stars is routine except for those with very large magnitude differences. The improvements described in Section 12.1 should increase the accuracy of all observations and enable worthwhile observations of the closer stars to be made in slightly worse seeing than is currently possible. Observations on fainter stars take longer and require slightly better seeing than those on bright stars because of the lower totals of counts recorded in each bin. On the 1 metre telescope the scanner requires a primary brighter than about 11th magnitude for the correlation process to be reliable and a secondary brighter than about 12th magnitude in order to complete the observation in a reasonable time. Observations on stars with components fainter than these limits are possible for stars wider than about 4 arcsecs but they would be time consuming and not very accurate. If our scanner were to be used on a larger telescope these magnitude limits would be adjusted accordingly.

The stars observed in our program are only a small fraction of those on which our scanner could be used to obtain UBV photometry and separations (and position angles). Among the southern bright stars there are a number with separations of 0.5 - 2.0 arcsecs which should be observed and also a number of wider stars with very large magnitude differences which it might be possible to observe. There are a great many fainter doubles which could be observed.

No (or very little) uvby photometry is available for components of southern close visual doubles. Because of the smaller amount of light passed by the uvby filters observations using our scanner would take longer

and be restricted to brighter stars than is the case for UBV photometry. However in view of the greater astrophysical usefulness of uvby photometry it would seem worthwhile to make uvby observations.

Our scanner can be used to obtain the light curves of variable components of double stars. However, due to the highly variable, sometimes rather large, errors of single measures of magnitude difference it would not be worthwhile observing variables with range less than several tenths of a magnitude except in cases of stars with rapid periodic variations for which a significant portion of the light curve can be obtained in a single night. The tendency of random (and systematic?) errors to be larger for larger magnitude differences must always be considered when using area scanners on variable components of doubles.

12.4 Future work in the field of double star photometry and astrometry

There is still very little photometry available for the components of visual double stars especially for southern doubles. Not much astrometric work is currently being done on southern close visual doubles either. Astrophysical studies are greatly hampered by this lack of basic data. Murphy (1969), for example, in a study of visual binaries with B-type primaries used Δm 's from Wallenquist (1954), Öpik (1924), Aitken (1932), and the Harvard Revised photometry as well as photoelectric Δm 's by authors such as Eggen (1963) and Tolbert (1964). He adjusted Eggen's measures (which we have discussed in Chapter 11) by -0.27^m to bring them onto the system of Wallenquist (1954)! This is a very undesirable procedure.

Techniques which yield photometric and astrometric results should therefore be vigorously used, in the southern hemisphere in particular. The area scanning technique seems to be the best one for stars with separations 1-10 arcsecs. The electronographic camera can be used for a similar range of separations with perhaps a slightly lower minimum separation. Both these techniques can yield UBV or uvby photometry, separations and position angles if suitably applied. The reduction of the area scanner observations is simpler whereas the telescope time used for the electronographic camera observations is shorter. The Hertzsprung photographic method has been shown to yield reasonably reliable visual Δm 's up to $\Delta m = 2.5^m$ for stars as close as 2 arcsecs (see Chapter 11). It should be possible by this method to obtain Δm 's for blue light which could be transformed into the B of the UBV system. It might also be worthwhile to pay more attention to the accuracy of the Δm 's estimated from the plates taken primarily for astrometric purposes.

The area scanning technique can be used for stars much wider than 10 arcsecs. It has an advantage over conventional photometry for all separations for which the wings of the images of the components overlap and the further advantage of being usable in non-photometric conditions. However we feel that the much longer observation and reduction times using the scanner as opposed to a conventional photometer preclude the use of the scanner for such stars except perhaps in the case of very large magnitude differences (say 5 magnitudes or more). For stars wider than 10 arcsecs conventional photometers should rather be used. Franz (1970) has illustrated how the light level midway between the two components falls virtually to the background level for stars as close as 7 arcsecs when the

seeing is good. We have found this to be the case at Sutherland, sometimes for stars much closer than 7 arcsecs. We have described (Chapter 2) the use of conventional photometers for UBV photometry of close visual doubles. Eggen (1963, 1966a) has observed stars as close as 4 arcsecs, apparently by conventional methods. However the techniques of Wayman (1962), Tolbert (1964) and Kron (1964) are likely to be more accurate. This photometry requires small diaphragms and hence telescopes with accurate tracking and good fine setting. Good seeing is of course also a requirement. For sites such as Sutherland and Cerro Tololo the seeing would be adequate on at least half the photometric nights. Some non-photometric nights could be used to measure magnitude differences. Photometric nights with bad seeing could be used to make combined light measures of the doubles.

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I wish to thank Professor Brian Warner who suggested this project to me and was my supervisor during its execution. I much appreciate his assistance. Dr. R. Edward Nather was mainly responsible for the hardware development and assembler programming which brought the area scanner to a usable condition. Perhaps one day I will meet him. Dr. Warner, Dr. Alistair Walker, Dr. Wayne van Citters, Dr. P.A.T. Wild and Dr. Mike Breger made area scanner or conventional UBV observations for this project. Mrs. Rhona Banfield reduced many conventional UBV observations. Mrs. Nancy Warner helped with clerical work. I also thank Dr. A.D. Thackeray, Dr. A.W.J. Cousins and Dr. L. Balona for useful discussions and Mr. H. Jenkner of Vienna and Mr. H.W. Dürbeck of Bonn for their advice.

The observations were made using the 20 inch (50 cm), 30 inch (75 cm) and 40 inch (1 metre) telescopes at the Sutherland station of the South African Astronomical Observatory. I thank the director Sir Richard Woolley, and his staff both at Observatory and at Sutherland for their assistance. In particular I would like to thank Ms Helen Kingwill, librarian, and her assistants for their invaluable help. I am also grateful for the assistance given by the technical staff of the Physics Department at U.C.T. and by the secretaries especially Mrs. Penny Dobbie who typed this thesis.

During the execution of part of the work I held a Research Associateship at U.C.T. I also received a bursary from the Council for Scientific and Industrial Research.

Finally, I thank the numerous other people who have helped me,
perhaps unknowingly or unintentionally, to produce this thesis.

APPENDIX IOperating instructions for ASHCAN programLoading the program via the teletype

Position the program tape on the teletype reader. Select 17777 on the front panel switches. Push RESET and START. A block of code at location 17777 reads in the program.

Starting the program

Select 400. Push RESET and START.

Altering the backlash constant

The backlash constant is stored in location 326. To change it stop the program, select 326, push EXAMINE, select new value on the switches, push DEPOSIT, restart the program. The value of the backlash constant after reading in the program is 12.

The functions of the switches

↑ means up, ↓ means down in this description.

- 0 ↑ The data for the accumulated scan are transferred to a buffer and printing and punching of the data in the buffer is started.
- 0 ↓ Aborts printing and punching of the buffer.
- 1 ↑ Starts the wobbling of the plate.
- 1 ↓ Parks the wobble plate in the position from which it started.
- 2 ↑ Disables normal functions of switches 4-15. Causes a pause in printing and punching. Prepares program to accept a new value of SCANS/INTEGRATION i.e. the number of scans added together before correlation. The new value is selected on switches 4-15

and inserted by 3 ↑ , 3 ↓ . 2 ↓ then returns program to its normal state.

- 3 ↑ See 2 ↑.
- 4-8 Not used.
- 9 ↑ Mean accumulated scan is displayed on the right side of the screen.
- 9 ↓ Return scan displayed on right side of screen.
- 10 ↑ Used in conjunction with 12. Magnifies the x axis point spacing by a factor of 2 or rolls the points (i.e. moves the points across the screen). This switch is not normally operated as the functions are not required during area scanning.
- 10 ↓ Stops the rolling.
- 11 ↑ Used in conjunction with 12. Magnifies the y axis point spacing by 2 or rolls the points upwards.
- 11 ↓ Stops the rolling.
- 12 ↑ Magnify.
- 12 ↓ Roll.
- 13 ↑ Reset display to unit magnification and zero roll.
- 14 ↑ No correlation.
- 14 ↓ Correlation.
- 15 ↑ Starts data recording after clearing the appropriate memory.
- 15 ↓ Stops data recording.

APPENDIX IIScale factors used in determining separations

Telescope →	50cm	75cm	100cm
4:1 gearing, 3mm plate	0.06565	-	0.03893 arcsecs/unit
4.032:1 gearing, 3mm plate	0.06565	0.05390	0.04210 arcsecs/unit
4.032:1 gearing, 5mm plate	0.09655	0.07925	0.06200 arcsecs/unit

For one observing run on the 100 cm telescope using the 4.032:1 gearing scale factors of 0.04050 and 0.05970 arcsecs/unit were used for the 3 mm and 5 mm plates respectively.

APPENDIX IIISUMMARY OF REDUCTION PROCEDURE

1. Read the paper tapes into elements of a file using TPREAD. Call the elements .TAPE x where x is the tape number.
2. Edit the tape elements on the file. It is best to use the @ELT processor. Correct all obvious data errors, delete where appropriate. Refer to teletype printout and observing log where necessary. Make sure all data is in 14 line blocks in the format: dummy line, SCANS/INTEGRATION line, 12 data lines.
3. Combine file elements into larger ones if some are very small.
4. Make identification cards for each 14 line data block. Normally each star is observed once with each of the 3 filters so a simple program can be used to have the computer punch these cards.

For observations where extra accumulated scans were recorded the extra identifying cards can be punched by hand. The identification card for sequence number 1079, B filter is 3RUN 1079-2. The 3 is a check number and is fixed. The code for U is a 1, for B a 2, for V a 3 and for R a 4. Another two digits may follow the colour code. The first digit indicates repeats using the same filter e.g. -2 indicates the first accumulated scan in B, -21 the second, -22 the third. The next digit is used to give information on the scan angle in abnormal cases. A zero (or blank) is used for normal scans. A 1 indicates that a repeat non-horizontal observation had the ordering of the components along the slit reversed by rotating the turntable by somewhat less than 180° . A 9 indicates that the

observation was made with the viewing eyepiece on the north side of the telescope i.e. with the turntable rotated 180° from the position in which it would normally be set for observing the star.

5. Use prepunched editing cards -1,1; -15,15; etc. and the identification cards just punched to insert the identification in the data.
6. Run the graph-printing program GRPRNT. Normally use option 2 i.e. print graphs of all runs between two run numbers given in the runstream.
7. Inspect the graphs for errors in the data and cases where start parameters need to be inserted by hand because the automatic initialization may fail. The automatic initialization will nearly always work if there is a peak for the secondary and it is separated from the primary peak by a trough at least 6 bins wide.
8. Run the curve-fitting program (see Appendix IV).
9. Examine the summary of fitted parameters, errors etc. Look for any abnormal termination and INPAR failed messages. Also look for runs with abnormally large magnitude differences, very small separations or very large (greater than approximately 10%) percentage errors in the fitted heights - all these are indicative of an incorrect fit. High percentage error in the fitted background suggests an unreliable magnitude difference. Examine the graphs of the fits and the graphs of the residuals. The graphs may point to many different errors and abnormalities. Where the automatic initialization of parameters failed, no fit was obtained, or a wrong fit was obtained the data should be rerun with better estimates of the start parameters. Where the fit of the secondary or of the background seems poor

because the secondary is very close to the edge of the scan or there are insufficient background bins then the data can be rerun with more bins included. This is a matter of fine judgement as the magnitude difference can be severely affected by inclusion of bins which have in fact suffered losses of counts because of the correlation shifting process. For reruns of data option 1 of the program is normally used with each set of data specifically identified on a run information card.

10. Arrange the output cards in order selecting the card corresponding to the best fit in cases where more than one 'correct' fit was made.
11. List the cards and punch another copy. This can easily be done on the UNIVAC.
12. File one copy of the output cards in order of stars.
13. Keep the second copy in observing log sequence number and use the MAGCHK program on each night's observations separately. Record rough combined light UBV of known and apparent variables if the night appears photometric. Record the scale factors given by the separation standards.
14. Use the UBVCN program on the results for the individual stars using the starwise arranged copy of the output cards.
15. Examine the printouts from UBVCN carefully. Rerun UBVCN if necessary.
16. Prepare the results in a form suitable for publication.

APPENDIX IV

Listing of Program CONTRL

ASHCAN•PROGS.CONMAP
1 IN PROGS.CONTRL
2 IN PROGS.INPAR
3 IN PROGS.FIT/NEW
4 IN PROGS.JACORD/ORIG
5 IN PROGS.FRANZ
6 IN PROGS.GRAPH
7 IN PROGS.GREER

.CONTRL

C

C THIS PROGRAM CONTROLS THE EXECUTION OF INPAR,FIT,GRAPH AND GREER

C

C IF IOP.EQ.1 ONLY THOSE RUNS EXPLICITLY MENTIONED ON RUN INFORMATION
C CARDS ARE PROCESSED. ONLY 20 SUCH CARDS ARE PERMITTED.

C IF IOP.EQ.2 ALL RUNS BETWEEN A FIRST AND LAST RUN MENTIONED ON TWO RUN
C INFORMATION CARDS WILL BE PROCESSED. STARTING PARAMETERS ETC MAY STILL
C BE GIVEN FOR UP TO (20-2) INDIVIDUAL RUNS ON RUN INFORMATION CARDS
C PLACED BETWEEN THE CARDS FOR THE FIRST AND LAST RUNS.

C IN EITHER CASE THE LAST RUN INFORMATION CARD MUST BE FOLLOWED BY A
C CARD WITH 0000 IN COLUMNS 1-4 UNLESS THERE ARE 20 INFORMATION CARDS.

C THIS CARD MUST ALSO BE FOLLOWED BY A BLANK CARD

C

C BEWARE THE FORMAT OF RUN INFORMATION CARDS - EACH RUN INFORMATION CARD
C IS ACTUALLY TWO CARDS. THE VALUES OF KKA,KKK AND IT ARE GIVEN ON A
C SECOND CARD SO IF THEY ARE NOT TO BE EXPLICITLY GIVEN A BLANK CARD MUST
C BE INSERTED. THIS MUST BE DONE AFTER THE 0000 CARD ALSO

C

C IERR IS AN OPTION CONTROLLER,THIS OPTION MAKES A ROUGH DETERMINATION
C OF THE PERCENTAGE ERRORS OF THE FITS OF THE PORTIONS OF PROFILE DUE TO
C EACH SEPARATE STAR IN CASES OF WIDE SEPARATION(LITTLE OVERLAP)

C THIS IS DONE BY COMPARING TOTALS OF OBSERVED AND CALCULATED VALUES FOR
C THE 25 CHANNELS CENTRED ON THE PEAK

C IF IERR.NE.0 THEN THE OPTION IS PERFORMED.

C

```

DIMENSION X(120),Y(120),FO(120),F1(120,11)
DIMENSION XU(120),XB(120),XV(120),XR(120)
DIMENSION D(11),PO(11),P(11),COV(11,11),U(11,11)
DIMENSION A(120),B(120),ISTRUN(20),ISTCOL(20),STPA(11,20),ISTKKA(2
50),ISTKKK(20),ITST(20),POS(6),IPV(3)
DIMENSION AXU(60),BXU(60),AXB(60),BXB(60),AXV(60),BXV(60)
DIMENSION AXR(60),BXR(60)
DIMENSION IERRST(20)

```

C NOTE THAT THE ARRAY PO IS PEE-NOUGHT WHEREAS POS IS PEE-OH-ESS

EQUIVALENCE (A(1),F1(1,1)),(B(1),F1(1,2))

EQUIVALENCE (XU(1),AXU(1)),(XU(61),BXU(1))

EQUIVALENCE (XB(1),AXB(1)),(XB(61),BXB(1))

EQUIVALENCE (XV(1),AXV(1)),(XV(61),BXV(1))

EQUIVALENCE (XR(1),AXR(1)),(XR(61),BXR(1))

LOGICAL IL

C IL IS SET FALSE IF INPAR FAILS

EXTERNAL FRANZ

DATA AXU/.000, 3.518, 7.013, 10.486, 13.935,

• 17.363, 20.770, 24.155, 27.520, 30.864,

• 34.189, 37.494, 40.780, 44.048, 47.298,

• 50.530, 53.744, 56.942, 60.123, 63.288,

• 66.438, 69.572, 72.691, 75.796, 78.887,

• 81.965, 85.029, 88.080, 91.119, 94.145,

• 97.161,100.165,103.158,106.140,109.113,

• 112.076,115.029,117.974,120.910,123.838,

• 126.758,129.671,132.577,135.477,138.370,

• 141.257,144.139,147.016,149.888,152.755,

• 155.619,158.479,161.337,164.191,167.043,

• 169.892,172.740,175.587,178.433,181.278/

DATA BXU/184.123,186.969,189.815,192.661,195.509,

• 198.359,201.211,204.065,206.922,209.783,

• 212,646,215,514,218,386,221,263,224,145,
 • 227,032,229,925,232,825,235,731,238,643,
 • 241,564,244,492,247,428,250,373,253,326,
 • 256,289,259,262,262,244,265,237,268,241,
 • 271,256,274,283,277,322,280,373,283,437,
 • 286,515,289,605,292,710,295,830,298,964,
 • 302,114,305,279,308,460,311,658,314,872,
 • 318,104,321,354,324,621,327,908,331,213,
 • 334,538,337,882,341,247,344,632,348,038,
 • 351,466,354,916,358,388,361,884,365,402/
 DATA AXB/,000, 3,489, 6,954, 10,396, 13,816,
 • 17,213, 20,589, 23,944, 27,279, 30,592,
 • 33,886, 37,161, 40,416, 43,653, 46,872,
 • 50,072, 53,256, 56,422, 59,572, 62,706,
 • 65,824, 68,927, 72,015, 75,088, 78,148,
 • 81,193, 84,226, 87,245, 90,252, 93,247,
 • 96,231, 99,203,102,164,105,115,108,056,
 • 110,986,113,908,116,821,119,725,122,621,
 • 125,509,128,390,131,264,134,131,136,993,
 • 139,848,142,697,145,542,148,382,151,218,
 • 154,050,156,878,159,703,162,525,165,344,
 • 168,162,170,978,173,793,176,606,179,419/
 DATA BXB/182,232,185,045,187,859,190,674,193,490,
 • 196,307,199,127,201,949,204,774,207,602,
 • 210,434,213,270,216,109,218,954,221,804,
 • 224,659,227,520,230,388,233,261,236,142,
 • 239,031,241,927,244,831,247,744,250,665,
 • 253,596,256,537,259,487,262,449,265,421,
 • 268,404,271,399,274,406,277,426,280,458,
 • 283,504,286,563,289,637,292,725,295,828,
 • 298,946,302,080,305,229,308,396,311,579,
 • 314,780,317,999,321,236,324,491,327,765,
 • 331,059,334,373,337,707,341,062,344,438,
 • 347,836,351,256,354,698,358,163,361,652/
 DATA AXV/,000, 3,464, 6,905, 10,323, 13,718,
 • 17,091, 20,443, 23,773, 27,082, 30,371,
 • 33,640, 36,890, 40,120, 43,332, 46,525,
 • 49,701, 52,859, 56,000, 59,125, 62,233,
 • 65,326, 68,403, 71,466, 74,513, 77,547,
 • 80,567, 83,574, 86,568, 89,549, 92,519,
 • 95,476, 98,423,101,358,104,283,107,198,
 • 110,103,112,999,115,885,118,764,121,634,
 • 124,496,127,351,130,199,133,041,135,876,
 • 138,705,141,529,144,347,147,161,149,971,
 • 152,777,155,579,158,378,161,174,163,968,
 • 166,759,169,549,172,338,175,125,177,913/
 DATA BXV/180,699,183,487,186,274,189,063,191,853,
 • 194,644,197,438,200,234,203,033,205,835,
 • 208,641,211,451,214,265,217,083,219,907,
 • 222,736,225,571,228,413,231,261,234,116,
 • 236,978,239,848,242,726,245,613,248,509,
 • 251,414,254,329,257,254,260,189,263,136,
 • 266,093,269,063,272,044,275,038,278,045,
 • 281,065,284,098,287,146,290,209,293,286,
 • 296,379,299,487,302,612,305,753,308,911,
 • 312,087,315,280,318,492,321,722,324,972,
 • 328,241,331,530,334,839,338,169,341,521,

```

•          344.894,348.289,351.707,355.148,358.612/
DATA      AXR/.000:  3.437,  6.850, 10.240, 13.607,
•          16.952, 20.275, 23.577, 26.859, 30.119,
•          33.360, 36.581, 39.782, 42.965, 46.130,
•          49.277, 52.406, 55.519, 58.614, 61.694,
•          64.757, 67.806, 70.839, 73.858, 76.862,
•          79.853, 82.831, 85.795, 88.747, 91.687,
•          94.616, 97.533,100.439,103.334,106.220,
•          109.095,111.962,114.819,117.668,120.509,
•          123.341,126.167,128.985,131.797,134.603,
•          137.402,140.197,142.986,145.770,148.550,
•          151.327,154.099,156.868,159.635,162.399,
•          165.161,167.921,170.680,173.438,176.196/
DATA BXR/178.953,181.711,184.469,187.228,189.988,
•          192.750,195.514,198.281,201.050,203.823,
•          206.599,209.379,212.163,214.953,217.747,
•          220.547,223.352,226.164,228.982,231.808,
•          234.641,237.481,240.330,243.188,246.054,
•          248.930,251.815,254.711,257.617,260.534,
•          263.462,266.402,269.354,272.319,275.296,
•          278.287,281.292,284.310,287.344,290.392,
•          293.456,296.535,299.631,302.743,305.872,
•          309.019,312.184,315.367,318.569,321.790,
•          325.030,328.291,331.572,334.874,338.197,
•          341.542,344.910,348.300,351.713,355.149/

C SET UP DIMENSIONS
  N=120
  M=11
C IO IS THE NUMBER OF THE DATA FILE TO BE USED FOR STORING RESULTS
  IO=25
C ASSIGN READER AND PRINTER UNIT NUMBERS
  IR=8
  IRR=0
  IW=5
  WRITE(IO,103)
103 FORMAT('  RUN',6X,'DM',5X,'SEP',4X,'L',3X,'VAR',2X,'PERA',1X,'PE
•RB P5/P2 P5/P4 P(6) P(7) S RMAG')
C READ IN VALUES OF KKA,KKK,IT TO BE USED IN ABSENCE OF EXPLICIT VALUES
C OF THESE VARIABLES ON A RUN INFORMATION CARD
  READ(IR,104)KKAS,KKKS,ITS,IOUT,KOV,STOP
104 FORMAT(5I5,F10.4)
C READ IN VALUES OF PO(6) TO PO(11) TO BE USED IF NOT EXPLICITLY GIVEN
C DEPENDING ON IPV THE LAST FITTED VALUES OF THE PARAMETERS MAY OVERRIDE
C THESE VALUES
  READ(IR,105)POS,IPV
105 FORMAT(4F5.2,2F5.1,2X,3I1)
  WRITE(IW,106)KKAS,KKKS,ITS,POS,IOUT,KOV,STOP,IPV
106 FORMAT('1'//////////' DEFAULT VALUES'/' KKA = ',I4/' KKK = '
•,I4/' IT = ',I5/' PO(6) = ',F6.2/' PO(7) = ',F6.2/' PO(8) = ',F6.2
•/' PO(9) = ',F6.2/' PO(10) = ',F5.1/' PO(11) = ',F5.1////////' VALUES
•OF OUTPUT CONTROL PARAMETERS'/' IOUT = ',I2/' KOV = ',I2/' OVALUE 0
•F STOPPING PARAMETER STOP = ',F8.4////////' IPV = ',3I1)
  READ(IR,107)IOP
107 FORMAT(I1)
C READ THE RUN INFORMATION CARDS
  NR=0
  5 NR=NR+1

```

```

      READ(IR,108)ISTRUN(NR),ISTCOL(NR),(STPA(I,NR),I=1,11),ISTKKA(NR),I
      *STKKK(NR),ITST(NR),IERRST(NR)
108  FORMAT(I4,1X,I3,2X,2(F5.1,F10.0),F10.0,6F5.0/415)
      IF(ISTRUN(NR).EQ.0)GO TO 6
      IF(NR-20)5,7,7
      6  NR=NR-1

```

```

C
C FIND THE REQUIRED RUN ON THE FILE AND READ IN THE OBSERVED VALUES
C ALSO SET THE PARAMETERS AS SPECIFIED BY IPV AND THE RUN INFORMATION
C CARDS

```

```

C
      7  I=0
      8  I=I+1
          IERR=0
          IF(I.GT.NR)GO TO 80
          KKA=KKAS
          KKK=KKKS
          IT=ITS

```

```

C
C IPV(1),IPV(2),IPV(3) RESPECTIVELY NON-ZERO CAUSE LAST FITTED VALUES OF
C P(6)&P(7),P(8)&P(9),P(10)&P(11) RESPECTIVELY TO BE USED INSTEAD OF THE
C DEFAULT VALUES POS(1) ETCETERA AS START VALUES OF RESP. PARAMETERS

```

```

C
      DO 12 IJ=1,3
          IF(IPV(IJ).NE.0.AND.I.GT.1)GO TO 10
          PO(4+2*IJ)=POS(2*IJ-1)
          PO(5+2*IJ)=POS(2*IJ)
          GO TO 12
      10  PO(4+2*IJ)=P(4+2*IJ)
          PO(5+2*IJ)=P(5+2*IJ)
      12  CONTINUE
      13  READ(IR,114)ICHECK
114  FORMAT(I1)
          IF(ICHECK-3)13,15,13
      15  READ(O,116)IRUN,ICOL
116  FORMAT(5X,I4,1X,I3)
          IF(IRUN-ISTRUN(I))17,18,17
      17  IF(I.NE.1.AND.IOP.EQ.2)GO TO 37
          GO TO 13
      18  IF(ICOL-ISTCOL(I))19,20,19
      19  IF(I.NE.1.AND.IOP.EQ.2)GO TO 37
          GO TO 13
      20  DO 21 MI=1,5
      21  PO(MI)=STPA(MI,I)
          DO 23 MI=6,11
          IF(STPA(MI,I)-0.1)23,23,22
      22  PO(MI)=STPA(MI,I)
      23  CONTINUE
          IERR=IERRST(I)
          IF(ISTKKA(I).EQ.0)GO TO 33
          KKA=ISTKKA(I)
      33  IF(ISTKKK(I).EQ.0)GO TO 34
          KKK=ISTKKK(I)
      34  IF(ITST(I).EQ.0)GO TO 40
          IT=ITST(I)
          GO TO 40
      37  DO 38 MI=1,5

```

```

38 PO(MI)=0.0
   I=I-1
40 READ(IR,141)ISCAN,ITOTSC
141 FORMAT(22X,IS,T45,I5)
   IF(ISCAN.LT.100)GO TO 1039
   READ(IRR,1141)ISCAN,ITOTSC
1141 FORMAT(21X,I4,14X,I4)
1039 READ(IR,142)Y
   142 FORMAT((T3,10F7,0))
   IF(ICOL-200)42,41,41
   41 IF(ICOL-300)44,1041,1041
1041 IF(ICOL-400)46,1042,1042
   42 DO 43 IK=1,N
   43 X(IK)=XU(IK)
   GO TO 48
   44 DO 45 IK=1,N
   45 X(IK)=XB(IK)
   GO TO 48
   46 DO 47 IK=1,N
   47 X(IK)=XV(IK)
   GO TO 48
1042 DO 1043 IK=1,N
1043 X(IK)=XR(IK)
   48 IF(IOUT.LT.4)GO TO 1048
   WRITE(IW,143)IRUN,ICOL,ISCAN,ITOTSC
143 FORMAT('1',/////' RUN',I4,'-',I3,' SCANS/INTEGRATION=',I5,'
* TOTAL SCANS=',I5)
   WRITE(IW,144)
144 FORMAT('0PARAMETERS PASSED TO INPAR'/' J',6X,'PO(J)')
   WRITE(IW,145)((IJ,PO(IJ)),IJ=1,11)
145 FORMAT((1X,I2,E12.5))
   WRITE(IW,146)KKA,KKK
146 FORMAT('OKKA = ',I3/' KKK = ',I3)
1048 IL=.TRUE.

C
C INITIALISE PARAMETERS PO(1) TO PO(5) IF NOT ALREADY INITIALISED
C
   CALL INPAR(X,Y,PO,KKA,KKK,IL)
   IF(IOUT.LT.4)GO TO 1049
   WRITE(IW,149)
149 FORMAT('0',/////' PARAMETERS RETURNED BY INPAR'/' J',6X,'PO(J)')
   WRITE(IW,145)((IJ,PO(IJ)),IJ=1,11)
1049 IF(IL)GO TO 50
   WRITE(IW,147)
147 FORMAT('0INPAR FAILED TO FIND TWO PEAKS')
   WRITE(10,148)IRUN,ICOL
148 FORMAT(' ',I4,'-',I3,5X,'INPAR FAILED')
   GO TO 8

C
C CALL SUBROUTINE FIT WHICH FITS CURVE TO DATA AND PRINTS RESULTS
C
   50 CALL FIT(X,Y,FRANZ,FD,F1,D,PO,P,COV,U,N,M,KOV,IOUT,IT,STOP,KKA,KKK
   * ,IRUN,ICOL,ISCAN,ITOTSC)

C
C OPTIONALLY CALCULATE ROUGH PERCENTAGE ERROR OF FITS OF PEAKS
C
   IF(IERR.EQ.0)GO TO 59

```

```

    ICHPA=INT(P(1)/3.5)
    ICHPB=INT(P(3)/3.5)
51  ICHPA=ICHPA+1
    IF(X(ICHPA)-P(1))51,51,53
53  ICHPB=ICHPB+1
    IF(X(ICHPB)-P(3))53,53,54
54  SUMO=0,
    SUMC=0,
    ITEK=ICHPA-12
    ITEM=ICHPA+12
    DO 55 IEI=ITEK,ITEM
    SUMO=SUMO+Y(IEI)
55  SUMC=SUMC+FO(IEI)
    ERRA=100.0*(SUMO-SUMC)/(SUMO-25.0*P(5))
    SUMO=0,
    SUMC=0,
    ITEK=ICHPB-12
    ITEM=ICHPB+12
    DO 56 IEI=ITEK,ITEM
    SUMO=SUMO+Y(IEI)
56  SUMC=SUMC+FO(IEI)
    ERRB=100.0*(SUMO-SUMC)/(SUMO-25.0*P(5))
    WRITE(IW,156)ERRA,ERRB
156  FORMAT('1'////////// ' ERRA =',F6.1,' 0/0'/' ERRB =',F6.1,' 0/0')

```

```

C
C PLOT GRAPHS OF THE FIT AND THE RESIDUALS
C

```

```

59  NOP=2
    MOP=0
    KB=12
    IF(P(2)-P(4))60,,
    MINORP=4
    MAJORP=2
    GO TO 61
60  MINORP=2
    MAJORP=4
61  ICHMIP=INT(P(MINORP-1)/3.5)
    IF(P(MINORP)-0.2*P(MAJORP)),,65
    MOP=1
62  ICHMIP=ICHMIP+1
    IF(X(ICHMIP)-P(MINORP-1))62,62,65
65  CALL GRAPH(X*Y*FO,NOP,MOP,ICHMIP*KB,KKA,KKK,IRUN*ICOL,ISCAN*ITOTSC
*)
    CALL GREER(A*B*KKA*KKK,IRUN,ICOL,ISCAN*ITOTSC)
    GO TO 8
80  WRITE(IW,181)
181  FORMAT('1',//// ' I GREATER THAN NR')
    END

```

```

.INPAR
  SUBROUTINE INPAR(X,Y,PO,KKA,KKK,IL)
C
C THIS SUBROUTINE SETS INITIAL VALUES OF THE PARAMETERS 1 TO 5 UNLESS
C THESE INITIAL VALUES ARE EXPLICITLY READ IN BY CONTRL FROM DATA CARDS
C
C BOTH PARAMETERS 1 AND 3 CAN BE READ IN OR ELSE NEITHER BUT NOT ONLY
C ONE OF THEM
C
  DIMENSION X(120),Y(120),PO(11)
  LOGICAL IL
  IA=0
  IB=0
  IF(ABS(PO(1)).GT.0.5.AND.PO(3).GT.0.5)GO TO 30
  IC=1
  N=KKA-4
  DIFFB=0.5
  OSUM=0.0
11 N=N+4
  IF(N+3.GT.KKK)GO TO 24
  SUM=0.0
  NN=N+3
  DO 12 J=N,NN
12 SUM=SUM+Y(J)
  DIFFA=SUM-OSUM
  IF(DIFFA*DIFFB)15,15,16
15 IF(DIFFA)17,16,16
16 OSUM=SUM
  DIFFB=DIFFA
  GO TO 11
17 IF(IC.NE.1)GO TO 20
  IA=N-2
  PO(1)=X(IA)
  IC=2
  GO TO 16
20 IF(IC.NE.2)GO TO 25
  IB=N-2
  PO(3)=X(IB)
  IC=3
  GO TO 16
24 IF(IC.EQ.3)GO TO 30
  IL=.FALSE.
  RETURN
25 IQ=N-2
  IF(Y(IA)-Y(IB))127,127,128
127 IF(Y(IA)-Y(IQ))129,129,16
128 IF(Y(IB)-Y(IQ))130,130,16
129 IA=IB
  IB=IQ
  PO(1)=X(IA)
  PO(3)=X(IB)
  GO TO 16
130 IB=IQ
  PO(3)=X(IB)
  GO TO 16
30 IL=.TRUE.
  IF(PO(5).GT.0.5)GO TO 40

```

```
SUM=0.0
NN=KKA+1
DO 31 J=KKA,NN
31 SUM=SUM+Y(J)
SUMB=0.0
NN=KKK-1
DO 32 J=NN,KKK
32 SUMB=SUMB+Y(J)
IF(SUM.GT.SUMB)SUM=SUMB
PO(5)=SUM/3.0
40 IF(PO(2).GT.0.5)GO TO 45
IF(IA.NE.0)GO TO 43
DO 41 I=KKA,KKK
IF(PO(1)-X(I))42
41 CONTINUE
42 IA=I
43 PO(2)=Y(IA)-PO(5)
45 IF(PO(4).GT.0.5)GO TO 50'
IF(IB.NE.0)GO TO 48
DO 46 J=I,KKK
IF(PO(3)-X(J))47
46 CONTINUE
47 IB=J
48 PO(4)=Y(IB)-PO(5)
50 RETURN
END
```

```

.FIT/NEW
  SUBROUTINE FIT(X,Y,FRANZ,FO,F1,D,PO,P,COV,U,N,M,KOV,IOUT,IT,STOP,K
  •KA,KKK,IRUN,ICOL,ISCAN,ITOTSC)
C
C -----
C
C SOME OF THE COMMENTS MAY NOT BE VERY APPROPRIATE ANY LONGER, THIS IS
C BECAUSE EXTENSIVE CHANGES HAVE BEEN MADE TO THE ORIGINAL PROGRAM.
C
C -----
C
C OPTIONALLY THE COVARIANCE MATRIX OF THE ERRORS OF THE FITTED
C PARAMETERS COV(J,K) IS CALCULATED
C   KOV = 0 : ONLY DIAGONAL ELEMENTS ARE CALCULATED
C   KOV = 1 : ALL ELEMENTS ARE CALCULATED
C   KOV = 3 : THE COVARIANCE MATRIX IS ALSO PRINTED
C THE PRINTOUT DURING EXECUTION OF FIT CAN BE CHOSEN BY IOUT:
C   IOUT = 0 OR SMALLER: NO PRINT
C   IOUT = 1 OR GREATER: ERROR MESSAGES
C   IOUT = 2 OR GREATER: FITTED PARAMETERS WITH ERRORS
C   IOUT = 3 OR GREATER: MEASURED + CALCULATED VALUES FOR ALL ABSCISSAS
C   IOUT = 4 OR GREATER: VALUES OF DM,SEP,VAR AFTER EACH ITERATION.
C
C           ALSO MAIN PROGRAM PRINTS PARAMETERS PASSED TO
C           AND RETURNED BY INPAR.
C
C   IOUT = 5 OR GREATER: CHANGES IN PARAMETERS WITH EACH INTEGRATION
C STOP DETERMINES THE PRECISION AND IT THE MAX. NUMBER OF ITERATIONS
C THE DIMENSION OF THE DUMMY ARRAY U AND OF ALL MENTIONED ARRAYS MUST BE
C SPECIFIED ACCORDING TO
      DIMENSION X(N),Y(N),FO(N),F1(N,M),D(M),PO(M),P(M),COV(M,M)
      DIMENSION U(M,M)
      DIMENSION W(120),DMD(10)
C INTERNALLY USED ARRAYS ARE SPECIFIED FOR A MAXIMUM OF 12 PARAMETERS
      DIMENSION Q(12),Z(12),E(12),DD(12)
      LOGICAL LA,LB,LD,OK
C LA IS SET FALSE WHEN VAR>VARS.
C LB IS SET TRUE WHEN THE TOTAL OF 10 SUCCESSIVE ABSOLUTE CHANGES IN DM
C IS LESS THAN .002, THUS LB=.TRUE. WHEN PROCESS 4 STOPS ITERATIONS.
C LD IS SET FALSE WHEN THE LINEARITY RANGE IS EXCEEDED.
C OK IS SET TRUE FOR ANY NORMAL TERMINATION.
      DATA BLANK,STAR/IH ,IH*/
C ASSIGN CHANNEL NUMBERS
      IW=5
      IP=9
C IO IS FILE RESULTS
      IO=25
C
C TEST FOR REASONABLE N AND M
C
      IF(M,GE,N) GOTO 500
C THE FOLLOWING TEST HAS TO BE MODIFIED, IF THE DIMENSIONS OF Q, Z AND
C E ARE ALTERED
      IF(M,GT,12) GOTO 510
C
C INITIALIZATION
C
      LB=.FALSE.
      DMD(10)=1.0

```

```

      XM=M
      XNM=KKK-KKA-M+1
      B=1./SQRT(XM)
C L IS THE NUMBER OF ITERATIONS
      L=0
C OK IS A FLAG INDICATING NORMAL TERMINATION
      OK=.FALSE.
C ID IS THE NUMBER OF ITERATIONS WITH ALTERATIONS GREATER THAN THE
C LINEARITY RANGE
      ID=0
C IN IS THE NUMBER OF ITERATIONS WITH REDUCED LINEARITY RANGE
      IN=0
C II IS THE NUMBER OF ITERATIONS WITH ILL CONDITIONED NORMAL EQUATIONS
      II=0
C IAMAX GIVES THE MAX. REDUCTION FACTOR OF THE LINEARITY RANGE
      IAMAX=1
C IS IS A COUNTER USED IN THE STOPPING PROCESS.
      IS=0
C IR IS A COUNTER USED IN THE STOPPING PROCESS
      IR=0
C IM IS AN INDICATOR USED TO INDICATE HOW THE ITERATIONS WERE STOPPED
      IM=1
C IM=1 WHEN STOP CRITERION STOPS ITERATIONS
C IM=2 WHEN VAR DECREASES BY LESS THAN .0005 OR INCREASES BY LESS THAN
C .001 THREE TIMES
C IM=3 WHEN IR.GT.1, THAT IS, WHEN IT HAS TWICE OCCURRED THAT VAR HAS
C DECREASED BY LESS THAN .005 DESPITE REDUCTION OF THE LINEARITY RANGE.
C IM=4 WHEN THE TOTAL OF 10 SUCCESSIVE ABSOLUTE CHANGES IN DM IS LESS
C THAN .002
C
C START WITH ESTIMATIONS
      DO 1 J=1,M
      1 P(J)=P0(J)
      IF(IOUT.LT.4)GO TO 100
      WRITE(IW,1600)
1600 FORMAT('1',,////,' WITH ESTIMATED VALUES OF PARAMETERS')
      DM=2.5*ALOG10(P(2)/P(4))
      SEP=P(3)-P(1)
      WRITE(IW,1433)DM,SEP
C
C ITERATIVE LOOP
C
      100 CALL FRANZ(X,FO,F1,P,D,N,M,W)
C CALCULATION OF VAR = CHI-SQUARED/DEGREES OF FREEDOM
      VAR=0.
      DO 101 I=KKA,KKK
      101 VAR=VAR+(FO(I)-Y(I))**2*W(I)
      VAR=VAR/XNM
      IF(IOUT.GE.4)WRITE(IW,1431)VAR
1431 FORMAT(' VAR=' ,F9.4//)
C BEGIN IMMEDIATELY WITH THE FIRST ITERATION
      IF(L.EQ.0) GOTO 104
C TEST IF CHI-SQUARED INCREASES
      IF(VAR.GT.VARS) GOTO 200
C IF THE SUM OF MAX. AND MIN. EIGENVALUE IS WITHIN MACHINE PRECISION
C EQUAL TO THE MAX.EIGENVALUE, THE NORMAL EQUATIONS ARE ILL CONDITIONED
      IF(E1M.EQ.E(1)) II=II+1

```

```

      IF(LA) GOTO 102
C LINEARITY RANGE REDUCED, DO NOT STOP
      IN=IN+1
      ID=ID+1
      IF(VARS-VAR-0.006)1101,105,105
1101 IR=IR+1
      IF(IR-2)105,300,300
102 DO 10001 JC=1,9
10001 DMD(JC)=DMD(JC+1)
      DMD(10)=ABS(DM-DM0)
      DMDS=0,0
      DO 10002 JC=1,10
10002 DMDS=DMDS+DMD(JC)
      IF(DMDS-0.002)10004,10004,10009
10004 LB=.TRUE.
10009 IF(LD) GOTO 103
C ALTERATION GREATER THAN LINEARITY RANGE, DO NOT STOP
      ID=ID+1
      GO TO 1102
C NO TERMINATION BEFORE 3 ITERATIONS ARE EXECUTED
103 IF(L.LE.2) GOTO 105
C TEST IF ALTERATION IS SMALL ENOUGH
      IF(IOUT,GE,4)WRITE(IW,3001)STP
3001 FORMAT(' STP = ',F10,4//)
1102 IF(VAR+0.0015-VARS)1103,,
      IS=IS+1
      IF(IS.GT.2) GO TO 300
1103 IF(LD) GO TO 1104
      GO TO 105
1104 IF(STP-ST0P) 300,300,105
C STORE INITIAL CHI-SQUARED FOR PRINT OUT AT THE END
104 VARI=VAR
C RESET REDUCTION FACTOR (IA) AND FLAGS INDICATING REDUCED LINEARITY
C RANGE (LA) OR ALTERATION GREATER THAN LINEARITY RANGE (LD)
105 IF(LB) GO TO 300
      IA=1
      LA=.TRUE.
      LD=.TRUE.
      L=L+1
C SAVE CHI-SQUARED/DEGREES OF FREEDOM FOR LATER COMPARISON
      VARS=VAR+0,001
C TEST IF THE NUMBER OF ITERATIONS IS TOO BIG
      IF(L.GT.IT) GOTO 520
C SET-UP NORMAL EQUATIONS, THE MATRIX OF COEFFICIENTS IS STORED
C TEMPORARILY IN COV, THE COLUMN MATRIX OF CONSTANTS IN Q
      DO 107 J=1,M
      DD(J)=B*D(J)
      TEMP=0,
      DO 106 I=KKA,KKK
      F1(I,J)=DD(J)*F1(I,J)
106 TEMP=TEMP+F1(I,J)*(FO(I)-Y(I))*W(I)
107 Q(J)=TEMP
      DO 109 J=1,M
      DO 109 K=1,J
      TEMP=0,
      DO 108 I=KKA,KKK
108 TEMP=TEMP+F1(I,J)*F1(I,K)*W(I)

```

```

109 COV(K,J)=TEMP
C THE SUBROUTINE JACORD COMPUTES FOR A GIVEN QUADRATIC MATRIX COV WITH
C DIMENSIONS M THE EIGENVECTORS (STORED AS COLUMNS IN U) AND THE EIGEN-
C VALUES E (STORED AT THE EXIT OF JACORD IN THE MAIN DIAGONAL OF COV)
    CALL JACORD(M,COV,U)
C CALCULATION OF ALTERATIONS Z IN THE PRINCIPAL AXIS SYSTEM
    DO 112 J=1,M
    Z(J)=0.
    DO 110 K=1,M
110 Z(J)=Z(J)+U(K,J)*Q(K)
    E(J)=COV(J,J)
    IF(ABS(Z(J)).LT.E(J)) GOTO 111
C REDUCE Z IF THE LINEARITY RANGE IS EXCEEDED
    Z(J)=SIGN(1.,Z(J))
    LD=.FALSE.
    GOTO 112
111 Z(J)=Z(J)/E(J)
112 CONTINUE
    EIM=E(1)+E(M)
C STP IS THE SQUARE SUM OF PARAMETER ALTERATIONS DIVIDED BY THEIR ERRORS
C AND IS USED IN THE STOP CRITERION
113 STP=0.
C CALCULATION OF ALTERATIONS OF PARAMETERS Q AND DIAGONAL ELEMENTS OF
C THE COVARIANCE MATRIX COV
    DO 115 J=1,M
    Q(J)=0.
    TEMP=0.
    DO 114 K=1,M
    TEMP=TEMP+U(J,K)**2/E(K)
114 Q(J)=Q(J)+U(J,K)*Z(K)
    IF(LD) STP=STP+Q(J)**2/TEMP
    Q(J)=Q(J)*DD(J)
C CALCULATE NEW PARAMETERS
    P(J)=P(J)-Q(J)
    TEMP=TEMP*IA**2
115 COV(J,J)=TEMP*DD(J)**2
    SEP=P(3)-P(1)
    IF(LA)DM0=DM
    IF(P(2).LE.0)P(2)=1.
    IF(P(4).LE.0)P(4)=1.
    DM=2.5*ALOG10(P(2)/P(4))
    IF(IOUT.LT.4)GO TO 100
    WRITE(IW,1430)L
1430 FORMAT(' L =',I3)
    IF(IOUT.LT.5)GO TO 121
    WRITE(IW,1432)
1432 FORMAT(' J',T15,'Q(J)')
    DO 120 JJ=1,M
120 WRITE(IW,1406)JJ,Q(JJ)
121 WRITE(IW,1433)DM,SEP
1433 FORMAT(' MAG DIFF=',F8.4,5X,'SEP=',F10.5)
    GOTO 100
C
C REDUCTION OF LINEARITY RANGES BECAUSE OF INCREASE OF THE CHI-SQUARED
C
C RESET P(J) TO THE VALUES BEFORE THE LAST ITERATION
200 DO 201 J=1,M

```

```

      P(J)=P(J)+Q(J)
C D IS HALVED, AND Z IS DOUBLED AND TESTED AGAIN
      Z(J)=Z(J)*2.
      IF(ABS(Z(J)).GT.1.) Z(J)=SIGN(1.,Z(J))
201 DD(J)=DD(J)*0.5
      LA=.FALSE.
      IA=IA*2
C SAVE MAX. REDUCTION FACTOR FOR PRINTOUT
      IAMAX=MAX0(IAMAX,IA)
C TEST IF LINEARITY RANGE IS HALVED MORE THAN 13 TIMES
      IF(IA.GT.10000) GOTO 530
      GOTO 113

C
C CALCULATION OF THE COVARIANCE MATRIX
C
300 IF(IS.GT.2) IM=2
      IF(IR.GT.1) IM=3
      IF(LB) IM=4
      DO 301 J=1,M
301 COV(J,J)=COV(J,J)*VAR
      IF(KOV.LT.1) GOTO 400
      DO 303 J=1,M
          J1=J-1
          DO 303 K=1,J1
              TEMP=0.
              DO 302 I=1,M
302 TEMP=TEMP+U(J,I)*U(K,I)/E(I)
303 COV(K,J)=TEMP*D(J)*D(K)/XM*VAR

C
C OUTPUT SECTION
C
400 OK=.TRUE.
      IF(IOUT.LT.2.AND.KOV.LT.2) RETURN
      WRITE(IW,1000) IRUN,ICOL,ISCAN,ITOTSC,KKA,KKK
      WRITE(IW,1400) L
401 IF(II.GT.0) WRITE(IW,1401) II
      IF(ID.GT.0) WRITE(IW,1402) ID
      IF(IN.GT.0) WRITE(IW,1403) IN,IAMAX
      WRITE(IW,1404) VARI,VAR
      IF(IOUT.LT.2) GOTO 410
      WRITE(IW,1405)
      IF(OK) GOTO 405
      DO 404 J=1,M
404 WRITE(IW,1406) J,PO(J),P(J)
      WRITE(IO,2000) IRUN,ICOL,DM,SEP,L,VAR
      WRITE(IP,2000) IRUN,ICOL,DM,SEP,L,VAR
2000 FORMAT(' ',I4,'-',I3,F8.4,F8.3,I3,F7.2,' ABNORMAL TERMINATION')
      GOTO 420
405 DO 406 J=1,M
      AE=SQRT(COV(J,J))
      RE=AE/ABS(P(J))*100.
406 WRITE(IW,1406) J,PO(J),P(J),AE,RE
      PERA=100.0*SQRT(COV(2,2))/ABS(P(2))
      PERB=100.0*SQRT(COV(4,4))/ABS(P(4))
      WRITE(IW,1407) DM,SEP
1407 FORMAT(' OMAGNITUDE DIFFERENCE =',F8.4/' SEPARATION =',F7.2)
      AV=0.0

```

```

DO 407 IJ=1,120
407 AV=AV+FO(IJ)
   AV=(AV/120.0-P(5))/ITOTSC
   RMAG=2.5*ALOG10(AV)
   WRITE(IW,1408)RMAG
1408 FORMAT(' RELATIVE MAGNITUDE =',F6.2)
410 IF(KOV.LT.2) GOTO 420
   WRITE(IW,1410)
   DO 412 I=1,M,6
     I1=MINO(I+5,M)
     WRITE(IW,1412) (K,K=I,I1)
     DO 411 J=I,M
       J1=MINO(I1,J)
411 WRITE(IW,1411) J,(COV(K,J),K=I,J1)
412 CONTINUE
420 IF(IOUT.GE.3)WRITE(IW,1420)
   DO 421 I=1,N
     ERR=Y(I)-FO(I)
     RE=ERR*SQRT(W(I))
     F1(I,1)=ERR
421 F1(I,2)=RE
   IF(IOUT,LT.3)GO TO 423
   DO 422 I=1,N
     REX=BLANK
     IF(ABS(F1(I,2)).GT.2.3265) REX=STAR
     WRITE(IW,1421)I,x(I),Y(I),FO(I),F1(I,1),F1(I,2),REX
     IF(I.EQ.KKA)GO TO 424
     IF(I.EQ.KKK)GO TO 425
422 CONTINUE
423 BKGR1=P(5)/P(2)
   BKGR2=P(5)/P(4)
   IF(OK) WRITE(IO,2001)IRUN,ICOL,DM,SEP,L,VAR,PERA,PERB,BKGR1,BKGR2,
   *P(6),P(7),ISCAN,RMAG,IM
   IF(OK) WRITE(IP,2001)IRUN,ICOL,DM,SEP,L,VAR,PERA,PERB,BKGR1,BKGR2,
   *P(6),P(7),ISCAN,RMAG
2001 FORMAT(' ',I4,'-',I3,F8.4,F8.3,I3,F7.2,2F5.2,2F6.3,2F6.2,I2,F5.2,I
   *4)
431 RETURN
424 WRITE(IW,1440)
   GO TO 422
425 WRITE(IW,1441)
   GO TO 422
1440 FORMAT('+',T75,'FIRST CHANNEL USED')
1441 FORMAT('+',T75,'LAST CHANNEL USED')

```

```

C
C ABNORMAL TERMINATION

```

```

C
500 IF(IOUT,LT.1) GOTO 431
   WRITE(IW,1000)IRUN,ICOL,ISCAN,ITOTSC,KKA,KKK
   WRITE(IW,1500)
   GOTO 431
510 IF(IOUT,LT.1) GOTO 431
   WRITE(IW,1000)IRUN,ICOL,ISCAN,ITOTSC,KKA,KKK
   WRITE(IW,1510)
   GOTO 431
520 IF(IOUT,LT.1) GOTO 431
   WRITE(IW,1000)IRUN,ICOL,ISCAN,ITOTSC,KKA,KKK

```

```

WRITE(IW,1520) IT
GOTO 401
C COMPUTE THE FUNCTION WITH THE PARAMETERS BEFORE THE NON-EXECUTABLE
C ITERATION
530 CALL FRANZ(X,FO,F1,P,D,N,M,W)
VAR=VARS
IN=IN+1
IF(IOUT.LT.1) GOTO 431
WRITE(IW,1000) IRUN,ICOL,ISCAN,ITOTSC,KKA,KKK
WRITE(IW,1530) L
GOTO 401
1000 FORMAT('1'///' RUN',I4,'-',I3,5X,'SCANS/INTEGRATION =',I2,5X,'TOTA
*L SCANS =',I5///' CHANNELS USED-',I4,' TO',I4)
1400 FORMAT(22H NUMBER OF ITERATIONS:',I5/)
1401 FORMAT(3H IN,I4,53H ITERATIONS THE NORMAL EQUATIONS WERE ILL CONDI
TIONED/)
1402 FORMAT(3H IN,I4,63H ITERATIONS THE CALCULATED ALTERATION OF PARAME
TERS WAS GREATER/35H THAN THE ESTIMATED LINEARITY RANGE/)
1403 FORMAT(3H IN,I4,63H ITERATIONS THE LINEARITY RANGE WAS REDUCED BEC
AUSE OF INCREASE/41H OF THE CHI-SQUARED (MAX.REDUCTION FACTOR,I6,
21H)/)
1404 FORMAT(58H CHI-SQUARED/DEGREES OF FREEDOM WITH ESTIMATED PARAMETER.
1S:',F11,4,1H, /32X,23HWITH FITTED PARAMETERS:',3X,F11,4/)
1405 FORMAT(6HD NR.,11X,9HPARAMETER,23X,5HERROR/10X,9HESTIMATED,7X,
16HFITTED,8X,8HABSOLUTE,9X,8HRELATIVE/)
1406 FORMAT(3X,I2,3E15.5,F12.4,4H 0/0)
1410 FORMAT(///42HCOVARIANCE-MATRIX OF ERRORS OF PARAMETERS)
1411 FORMAT(1X,I3,1X,6E11.3)
1412 FORMAT(//6I11)
1420 FORMAT('1'////////' ',T2,'CHAN',T12,'ABSCISSA',T23,'MEASURED',T34,'C
*ALCULATED',T46,'DIFFERENCE',T59,'NORMALISED'/' ',T4,'I',T14,'X(1)'
*,T26,'Y(1)',T37,'FO(I)',T46,'Y(I)-FO(I)',T59,'DIFFERENCE'/)
1421 FORMAT(1X,I4,4F12.1,F12.2,1X,A1)
1500 FORMAT(67H THE NUMBER OF DATA HAS TO BE GREATER THAN THE NUMBER OF
1 PARAMETERS)
1510 FORMAT(32H MAX.NUMBER OF PARAMETERS IS 12./43H CHANGE THE DIMENSIO
IN SPECIFICATIONS IN FIT)
1520 FORMAT(16H NO RESULT AFTER,15,11H ITERATIONS/)
1530 FORMAT(67H NO RESULT, CHI-SQUARED STILL INCREASES AFTER HALFING TH
IE LINEARITY/28H RANGE 13 TIMES IN ITERATION,15/)
END

```

```

.JACORD/ORIG
  SUBROUTINE JACORD(M,A,U)
C
C COMPUTATION OF PRINCIPAL VALUES OF A MATRIX A OF ORDER M BY THE
C CYCLIC JACOBI METHOD
C INPUT: SUPER-DIAGONAL ELEMENTS OF A. A IS DESTROYED
C OUTPUT: EIGENVALUES AS DIAGONAL ELEMENTS OF A
C         EIGENVECTORS AS COLUMNS OF U
C
  DIMENSION A(M,M),U(M,M)
  XM=M
C INITIALIZE U AS UNIT MATRIX
  DO 2 J=1,M
  DO 1 K=1,M
    1 U(J,K)=0.
    2 U(J,J)=1.
    IF(M.LE.1) RETURN
  DO 201 L=1,50
C SS IS THE SQUARE SUM OF OFF-DIAGONAL ELEMENTS AND USED IN THE BREAK-
C OFF CRITERION FOR RETURN
  SS=0.
  DO 3 J1=2,M
  J=J1-1
  DO 3 K=J1,M
    3 SS=SS+A(J,K)**2
C IN THE FIRST 3 PASSES ONLY ELEMENTS GREATER THAN THRESHOLD TRESH ARE
C TREATED
  TRESH=0.
  IF(L.LE.3) TRESH=0.2*SQRT(2.*SS)/XM
  DO 200 J1=2,M
  J=J1-1
  J2=J-1
  DO 200 K=J1,M
  K1=K+1
  K2=K-1
C TEST IF THE CONSIDERED ELEMENT IS ZERO OR SMALL
  IF(A(J,J)+A(J,K).EQ.A(J,J).AND.A(K,K)+A(J,K).EQ.A(K,K).OR.
  1A(J,K)**2.EQ.0.) GOTO 5
  IF(ABS(A(J,K)).LE.TRESH) GOTO 200
C THETA = COTANGENT OF TWICE THE ROTATION ANGLE
C C AND S = COSINE AND SINE OF ROTATION ANGLE
  THETA=0.5*(A(K,K)-A(J,J))/A(J,K)
  IF(0.1/THETA/THETA.EQ.0.) GOTO 4
C NORMAL CASE
  T=1./(ABS(THETA)+SQRT(1.+THETA**2))
  IF(THETA.LE.0.) T=-T
  C=1./SQRT(1.+T**2)
  S=T*C
  GOTO 100
C SMALL ROTATION ANGLE
  4 S=0.5/THETA
  C=1.
  GOTO 100
C THE CONSIDERED ELEMENT IS ALREADY ZERO
  5 A(J,K)=0.
  IF(A(J,J).GE.A(K,K)) GOTO 200
C INTERCHANGE J AND K SO THAT A(J,J) IS GREATER THAN A(K,K)

```

C=0.
S=1.

C
C EXECUTION OF JACOBI ROTATION

C
100 H=C*C*A(J,J)-2.*C*S*A(J,K)+S*S*A(K,K)
G=S*S*A(J,J)+2.*C*S*A(J,K)+C*C*A(K,K)
A(J,K)=C*S*(A(J,J)-A(K,K))+A(J,K)*(C*C-S*S)
A(J,J)=H
A(K,K)=G
IF(J2.LT.1) GOTO 102
DO 101 I=1,J2
H=C*A(I,J)-S*A(I,K)
A(I,K)=S*A(I,J)+C*A(I,K)
101 A(I,J)=H
102 IF(K2.LT.J1) GOTO 104
DO 103 I=J1,K2
H=C*A(J,I)-S*A(I,K)
A(I,K)=S*A(J,I)+C*A(I,K)
103 A(J,I)=H
104 IF(M.LT.K1) GOTO 106
DO 105 I=K1,M
H=C*A(J,I)-S*A(K,I)
A(K,I)=S*A(J,I)+C*A(K,I)
105 A(J,I)=H
106 DO 107 I=1,M
H=C*U(I,J)-S*U(I,K)
U(I,K)=S*U(I,J)+C*U(I,K)
107 U(I,J)=H
A(J,K)=0.
C
200 CONTINUE
C TEST IF ALL OFF-DIAGONAL ELEMENTS ARE ZERO
IF(SS.EQ.0.) RETURN
201 CONTINUE
RETURN
END

.FRANZ

```

SUBROUTINE FRANZ(X,FO,F1,P,D,N,M,W)
C PARAMETER NUMBERS: 1=CMAXA ; 2=HTA ; 3=CMAXB ; 4=HTB ; 5=BKG ; 6=HPWL
C                      7=HPWR ; 8=FPAL ; 9=FPAR ; 10=FPBL ; 11=FPBR
  DIMENSION X(N),P(M),D(M),FO(N),F1(N,M),W(N)
  DO 40 I=1,N
    FO(I)=P(5)
    F1(I,5)=1.0
    DO 10 J=6,M
10  F1(I,J)=0.
    DO 30 J=1,2
      K=2*J-1
      L=K+1
      IF(X(I)-P(K))15,15,17
15  KC=0
      GO TO 19
17  KC=1
19  Z=ABS(X(I)-P(K))
      H=Z/P(6+KC)
      IF(H.LT.0)GO TO 90
      E=Z/P(10+KC)
      S=1.0+E
      Q=P(8+KC)*S
      F=H**Q
      G=P(L)/((1.0+F)**2)
      R=G*F*P(8+KC)
      IF(H)90,21,22
21  T=-1000.0
      GO TO 23
22  T=ALOG(H)
23  IF(X(I)-P(K))25,26,27
25  F1(I,K)=-R*(T/P(10+KC)+S/(P(6+KC)*H))
      GO TO 28
26  F1(I,K)=0.
      GO TO 28
27  F1(I,K)=R*(T/P(10+KC)+S/(P(6+KC)*H))
28  F1(I,L)=1.0/(1.0+F)
      F1(I,6+KC)=F1(I,6+KC)+R*S/P(6+KC)
      F1(I,8+KC)=F1(I,8+KC)-G*F*S*T
      F1(I,10+KC)=F1(I,10+KC)+R*T*E/P(10+KC)
30  FO(I)=FO(I)+P(L)/(1.0+F)
40  W(I)=1.0/FO(I)
      D(1)=20.
      D(2)=0.1*AMAX1(P(2),P(4))
      D(3)=20.
      D(4)=0.1*AMAX1(P(2),P(4))
      D(5)=0.4*P(5)
      D(6)=0.4*P(6)
      D(7)=0.4*P(7)
      D(8)=0.4*P(8)
      D(9)=0.4*P(9)
      D(10)=0.4*P(10)
      D(11)=0.4*P(11)
      RETURN
90 WRITE(5,91)
91 FORMAT(' ERROR IN FRANZ SUBROUTINE-H IS NEGATIVE')
      RETURN
      END

```

```

GRAPH
  SUBROUTINE GRAPH(X,Y,Z,NOP,MOP,KN,KB,KKA,KKK,IRUN,ICOL,ISCAN,ITOTS
    C)
C
C  Y AND Z ARE THE Y COORDS TO BE PLOTTED
C  IF NOP.EQ.0 ONLY Y IS PLOTTED
C  IF NOP.EQ.2 Y AND Z ARE PLOTTED SIMULTANEOUSLY USING DIFFERENT SYMBOLS
C
C  IF MOP.NE.0 THE CHANNELS FROM CHANNEL KN-KB TO KN+KB ARE PLOTTED.
C  IN ADDITION,SEPARATELY ON A LARGER SCALE
C
C  IF NOP.EQ.2 THE CHANNELS KKA,KKK ARE MARKED WITH A $ NEXT TO THE
C  CHANNEL NUMBER AND A MESSAGE
C
C  IRUN,ICOL,ISCAN,ITOTSC ARE THE RUN NUMBER,COLOUR CODE,
C  SCANS/INTEGRATION AND TOTAL SCANS RESPECTIVELY
C
  DIMENSION X(120),Y(120),Z(120),LINE(101)
C
C  ASSIGN PRINTER UNIT NUMBER
C
  IW=5
  WRITE(IW,22)IRUN,ICOL,ISCAN,ITOTSC
22  FORMAT('1',,/,/,/,/,' RUN',I4,'-',I3,' SCANS/INTEGRATION=',I5,'
    *TOTAL SCANS=',I5)
  DO 25 I=1,101
25  LINE(I)=1H
  NFC=1
  NSC=2
  NLC=120
10  IF(NOP.EQ.0)GO TO 30
  IF(NOP.EQ.2)GO TO 130
  WRITE(IW,23)
23  FORMAT('0NOP NOT EQUAL TO 1 OR 2')
  RETURN
C
C  GRAPH OF Y ONLY
C
  30  WRITE(IW,1000)
1000  FORMAT('0 N X(N) Y(N)')
  YMAX=Y(NFC)
  DO 70 N=NSC,NLC
  70  YMAX=AMAX1(YMAX,Y(N))
  DO 90 N=NFC,NLC
  IY=INT(100.0*Y(N)/YMAX+0.5)+1
  LINE(IY)=1H*
  WRITE(IW,1001)N,X(N),Y(N),LINE
1001  FORMAT(' ',I3,1X,F5.1,F9.1,1X,101A1)
  LINE(IY)=1H
  90  CONTINUE
  GO TO 200
C
C  GRAPH OF Y AND Z
C
  130  WRITE(IW,1002)
1002  FORMAT('0 N X(N) Y(N) Z(N)')
  YMAX=Y(NFC)

```

```

DO 170 N=NSC,NLC
170 YMAX=AMAX1(YMAX,Y(N))
ZMAX=Z(NFC)
DO 172 N=NSC,NLC
172 ZMAX=AMAX1(ZMAX,Z(N))
GMAX=AMAX1(YMAX,ZMAX)
DO 190 N=NFC,NLC
IY=INT(100.0*Y(N)/GMAX+0.5)+1
IZ=INT(100.0*Z(N)/GMAX+0.5)+1
IF(IY.EQ.IZ)GO TO 173
LINE(IY)=IH*
LINE(IZ)=IH+
GO TO 174
173 LINE(IY)=IH$
174 WRITE(IW*1003)N,X(N),Y(N),Z(N),LINE
1003 FORMAT(' ',I3.1X,F5.1,2F9.1,1X,101A1)
LINE(IY)=IH
LINE(IZ)=IH
IF(KKA-N)188,187,188
187 WRITE(IW*1004)
1004 FORMAT('+'',3X,'S',T80,'FIRST CHANNEL USED')
188 IF(KKK-N)190,189,190
189 WRITE(IW*1006)
1006 FORMAT('+'',3X,'S',T80,'LAST CHANNEL USED')
190 CONTINUE
200 IF(MOP.EQ.0)GO TO 400
C
C RETURN IF MOP.EQ.0 OTHERWISE RESET NFC*NSC*NLC AND GO TO 10
C FOR PRINTING OF RELEVANT SECTION OF GRAPH
C
MOP=0
NFC=KN-KB
NSC=NFC+1
NLC=KN+KB
IOUT=2*KB+1
WRITE(IW*22)IRUN,ICOL,ISCAN,ITOTSC
WRITE(IW*1005)IOUT
1005 FORMAT(' GRAPH OF ',I2,' CHANNELS CENTRED ON POSITION OF SECONDARY
* AT LARGER SCALE')
GO TO 10
400 RETURN
END

```

.GREER

```

SUBROUTINE GREER(A,B,KKA,KKK,IRUN,ICOL,ISCAN,ITOTSC)
  DIMENSION A(120),B(120),LINER(100),SCAR(12)
  DATA SCAR/5.0,10.0,25.0,50.0,75.0,100.0,250.0,500.0,750.0,1000.0,2
  *500.0,5000.0/

```

C

C ASSIGN PRINTER UNIT NUMBER

C

```

  IW=5
  WRITE(IW,22)IRUN,ICOL,ISCAN,ITOTSC
22 FORMAT('1'///' RUN',I4,'-',I3,' SCANS/INTEGRATION=',I5,'
  *TOTAL SCANS=',I5)
  WRITE(IW,21)
21 FORMAT(' ERROR GRAPHS'//)
  DO 30 I=1,100
30 LINER(I)=1H
  SCALE=A(1)
  DO 32 N=2,120
32 SCALE=AMAX1(SCALE,ABS(A(N)))
  SCALE=SCALE/25.0
  I=0
34 I=I+1
  IF(SCAR(I)-SCALE)34
  SCALE=SCAR(I)
  ISC=IFIX(SCALE)
  WRITE(IW,23)ISC
23 FORMAT(' N DIFFE- NORM',22X,' DIFFERENCE = Y(I)-FO(I)',29X,' NORM
  *ALISED DIFFERENCE'/' RENCE DIFF',21X,' SCALE:',I4,' COUNTS PE
  *R COLUMN',17X,' SCALE: 0.5 NORMALISED ERRORS PER COLUMN'/T37,' MINUS
  *,T60,' PLUS',T89,' MINUS',T109,' PLUS')
  DO 50 N=1,120
  COR=SIGN(0.5,A(N))
  IA=INT(A(N)/SCALE+COR)+26
  LINER(IA)=1H*
  IB=INT(B(N)/0.5+COR)+76
  IF(IB.GT.100)IB=100
  IF(IB.LT.30)IB=30
  LINER(IB)=1H*
  WRITE(IW,24)N,A(N),B(N),LINER
24 FORMAT(' ',I3,F8.1,F5.1,T26,100A1)
  WRITE(IW,25)
25 FORMAT('+',T51,' I',T77,' AA',T101,' I')
  IF(N.EQ.KKA)GO TO 38
  IF(N.EQ.KKK)GO TO 39
  GO TO 40
38 WRITE(IW,26)
26 FORMAT('+',T20,' FIRST')
  GO TO 40
39 WRITE(IW,27)
27 FORMAT('+',T20,' LAST')
40 LINER(IA)=1H
  LINER(IB)=1H
50 CONTINUE
  RETURN
  END

```

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