2

OBSERVATIONAL TECHNIQUES

2.1. Photometry

(a) Observations

$UBV(RI)_c$ observations of the programme stars were carried out at the European Southern Observatory (ESO), LaSilla, Chile, during April 1987 and May 1988 using the 50 cm ESO Cassegrain telescope. A single channel photometer equipped with a thermo-electrically cooled RCA 31034 GaAs photomultiplier tube and standard filters matching the $UBV(RI)_c$ system and operating in the photon counting mode was used for the observations. A 21 arc sec diaphragm was used throughout the observations. The integration time was set to 1 sec and the integrations were continued until either the desired standard deviation in the total photon counts registered was achieved, or the maximum number of integrations already specified was reached. The maximum number of integrations were fixed typically at 60 and 20 for the star and sky measurements and the standard deviations were set, respectively, at 0.5% and 5.0%. Typically, a standard deviation less than 0.5% was achieved within thirty integrations for a star of $V = 12$ mag in all bands except $U$ where due to the low available flux it required a larger number of integrations. About 15–20 photometric standards in the Cousin system,
available in the E - region (Vogt et al. 1981) were observed each night in order to determine the atmospheric extinction coefficients as well as the system transformation coefficients.

*BV* measurements of T Tau stars were made during March 1993 using the 75 cm telescope of Vainu Bappu Observatory (VBO), Kavalur, simultaneously with the spectroscopic and polarimetric observations of those objects. A single channel photometer equipped with a thermo-electrically cooled EMI 9658R tube and operating in the photon counting mode was used for this purpose. The integration time was set to 5 sec and the integrations were repeated for a sufficient number of times so as to reduce the error due to photon statistics.

Stromgren *uvby* photometry of the programme stars were obtained with the 50 cm ESO telescope during four seasons, June 1988, August 1989, January 1990 and July 1990. On some occasions observations were made only in *b* and *y* bands due to the intrinsic low photon flux of the programme stars in *u* and *v*. The observations during June 1988 were carried out using a thermo-electrically cooled EMI 6256 photomultiplier tube and during the other three seasons a dry ice cooled EMI 9658A tube was used. A 15 arc sec diaphragm was used throughout for the observations. About 15 to 30 standard stars taken from the list of Perry et al. (1987) were observed each night of programme star observations.

In order to study the photometric behaviour of the programme stars in detail, observations spanning over several years are required. This is a rather difficult task to perform due to several factors, like, the heavy demand for telescope time and bad weather conditions. The Long Term Photometry of Variable stars project (LTPV) of ESO (Sterken, Manfroid, Mekkaden et al. 1993) was started solely to build up data base for objects which need high quality and uninterrupted data over several seasons. The above project exploits fully the best observing conditions prevailing at LaSilla. Only two of the stars (HD 81410 and HD 127535) could be included in the project for obtaining observations spread over several seasons because of the heavy demand for the telescope time. The LTPV programme uses the Stromgren *uvby* photometric system and the observations are carried out either with
the Stromgren Automatic Telescope (SAT, the Danish 50 cm telescope), or with the ESO 50 cm telescope, both at ESO, La Silla. The SAT, which is mostly used to carry out the LTPV programme, is equipped with a six channel instrument consisting of a uvby spectrograph—photometer and a two channel Hβ photometer, all combined in one box. All the passbands are defined by interference filters placed in front of each of the six photomultiplier tubes and a six channel photon counting system is used to record the data simultaneously (Gray & Olsen 1991). However, for the LTPV programme only the uvby bands are used.

The LTPV observations were mostly carried out in blocks of one month duration. Multiple observations obtained for a star in a single night were averaged to give one single observation for that night. A sufficient number of standard stars taken from the catalogue of Olsen (1983) were also observed each night for the purpose of atmospheric extinction correction and transformation of instrumental quantities to standard quantities.

In all the above cases mentioned a typical sequence of observation in each filter consists of the observations of the comparison, variable and check star, in that order. The comparison and check stars chosen were always located close to the variable and were similar in spectral types so that the differential magnitudes were almost free from any uncertainty in the determination of the extinction and system transformation coefficients. The sky measurements were taken immediately after the observations of each star.

(b) Data reduction

The data reduction involves two steps, correction for the atmospheric extinction and the transformation of the instrumental magnitudes and colours thus obtained to the magnitude and colours in a standard system. Both these steps are performed using the observations of standard stars in the natural system and the magnitudes and colours available in the standard system.

If \( m \) is the magnitude observed through an airmass \( X \), the extinction corrected magnitude \( m' \), can be written as

\[
m' = m + kX,
\]
where k is the extinction coefficient. The extinction corrected colours can also be written in a similar way. The effect of second order terms in the extinction can be neglected because of the differential approach adopted in the photometric observations. The airmass is calculated from the known $\alpha$ and $\delta$ of the object and the time of observation.

The colour transformation coefficients are defined by the following equations (Hardie 1962):

\[
V = V' + \psi_1 (B - V)',
\]

\[
B - V = \psi_2 (B - V)',
\]

\[
U - B = \psi_3 (B - V)' + \psi_4 (U - B)',
\]

\[
V - R = \psi_5 (V - R)',
\]

and

\[
V - I = \psi_6 (V - I)',
\]

where the primed indicates the extinction corrected instrumental magnitudes and colours and the unprimed the standard magnitudes and colours. The $\psi$’s are the system transformation coefficients.

The $UBV(\text{RI})_e$ observations obtained at ESO were reduced using the VAX version of SNOPY, the photometric reduction program available at ESO, La Silla. The extinction and colour transformation coefficients were computed by an iterative procedure until a stable solution was reached. Table 1 gives the mean extinction, and the magnitude and colour transformation coefficients used for the reduction of the observations obtained during 1987 and 1988. The standard deviations ($\sigma$) estimated from the observations of the standard and comparison stars during these two observing runs are also listed in Table 1

The reduction of the $BV$ observations obtained at VBO were made using photometric reduction programme developed by us. Mean extinction coefficients and system transformation coefficients derived for the entire season were used in the reduction of the data.

The Stromgren $uvby$ observations obtained at ESO were also transformed to the standard system using the ESO photometric reduction program SNOPY. The Stromgren system is basically a system of colour indices
(Manfroid & Sterken 1987). The instrumental $y$ magnitudes are usually transformed to the Johnsons’ $V$ magnitudes since no standards were initially established for the Stromgren $y$ magnitudes. For the transformation of the instrumental $y$ to $V$ magnitudes the standards were taken from the catalogue of Olson (1983).

Table 1. Broadband data: mean extinction and colour transformation coefficients, and standard deviations in the observations in magnitude.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>April 1987</th>
<th>May 1988</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_U$</td>
<td>0.476±0.011</td>
<td>0.500±0.016</td>
</tr>
<tr>
<td>$k_B$</td>
<td>0.259±0.008</td>
<td>0.247±0.008</td>
</tr>
<tr>
<td>$k_V$</td>
<td>0.138±0.011</td>
<td>0.147±0.009</td>
</tr>
<tr>
<td>$k_R$</td>
<td>0.107±0.008</td>
<td>0.106±0.009</td>
</tr>
<tr>
<td>$k_I$</td>
<td>0.064±0.012</td>
<td>0.042±0.105</td>
</tr>
<tr>
<td>$\psi_1$</td>
<td>-0.057±0.005</td>
<td>-0.074±0.003</td>
</tr>
<tr>
<td>$\psi_2$</td>
<td>1.121±0.003</td>
<td>1.165±0.003</td>
</tr>
<tr>
<td>$\psi_3$</td>
<td>-0.164±0.011</td>
<td>-0.157±0.016</td>
</tr>
<tr>
<td>$\psi_4$</td>
<td>1.091±0.010</td>
<td>1.065±0.014</td>
</tr>
<tr>
<td>$\psi_5$</td>
<td>1.028±0.007</td>
<td>1.027±0.008</td>
</tr>
<tr>
<td>$\psi_6$</td>
<td>0.914±0.005</td>
<td>0.908±0.003</td>
</tr>
<tr>
<td>$\sigma_V$</td>
<td>0.010</td>
<td>0.020</td>
</tr>
<tr>
<td>$\sigma_{B-V}$</td>
<td>0.010</td>
<td>0.020</td>
</tr>
<tr>
<td>$\sigma_{U-B}$</td>
<td>0.015</td>
<td>0.030</td>
</tr>
<tr>
<td>$\sigma_{V-R}$</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>$\sigma_{V-I}$</td>
<td>0.010</td>
<td>0.010</td>
</tr>
</tbody>
</table>

A detailed description of the procedure followed for the reduction of the data collected under the LTPV programme is given in Manfroid et. al (1991) and Sterken & Manfroid (1992). The algorithm uses every measurement of
every constant and standard star. The equations for transformation of the quantities from the natural system to a standard system is written as

\[ U_s = M U_o + K, \]

where \( U \) is the vector indices

\[ U = \begin{pmatrix} b - y \\ y \\ m_1 \\ c_1 \end{pmatrix} \]

The suffixes \( s \) and \( o \) denote the standard and instrumental quantities respectively. \( K \) is the column vector of zero points in the respective quantities.

The colour transformation matrix \( M \) is written as

\[ M = \begin{pmatrix} m_{11} & 0 & 0 & 0 \\ m_{21} & 1 & 0 & 0 \\ m_{31} & 0 & m_{33} & 0 \\ m_{41} & 0 & 0 & m_{44} \end{pmatrix} \]

The instrumental setup and the final \( m_{ij} \) values for each instrumental configuration are given in Table 2. The \( m_1 \) and \( c_1 \) indices are converted back to \( u \) and \( v \) using

\[ c_1 = (u - v) - (v - b) \]

\[ m_1 = (v - b) - (b - y). \]

Table 2. Intermediate band data: colour transformation coefficients.

<table>
<thead>
<tr>
<th>PMT</th>
<th>( m_{11} )</th>
<th>( m_{33} )</th>
<th>( m_{44} )</th>
<th>( m_{21} )</th>
<th>( m_{31} )</th>
<th>( m_{41} )</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMI6256S</td>
<td>1.0706</td>
<td>1.0781</td>
<td>1.0534</td>
<td>0.0205</td>
<td>-0.1449</td>
<td>0.3028</td>
<td>1</td>
</tr>
<tr>
<td>EMI9789QA</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>EMI9789QB</td>
<td>1.0232</td>
<td>0.8935</td>
<td>1.0032</td>
<td>0.0122</td>
<td>0.0290</td>
<td>0.1632</td>
<td>2</td>
</tr>
<tr>
<td>EMI9789QB</td>
<td>1.0686</td>
<td>1.0747</td>
<td>0.9816</td>
<td>0.0431</td>
<td>-0.1412</td>
<td>-0.3040</td>
<td>1</td>
</tr>
<tr>
<td>EMI9658RA</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

References: (1) Danks 1982; (2) Florentin Nielsen 1983
2.2. Polarimetry

The state of polarization of a beam of light, particularly in scattering problems, can be described conveniently by the use of the four Stokes parameters defined as

\[ I = \langle E_{0x}^2 \rangle + \langle E_{0y}^2 \rangle, \]
\[ Q = \langle E_{0x}^2 \rangle - \langle E_{0y}^2 \rangle, \]
\[ U = \langle 2E_{0x}E_{0y} \cos \delta \rangle \]

and

\[ V = \langle 2E_{0x}E_{0y} \sin \delta \rangle, \]

where \( E_{0x} \) and \( E_{0y} \) are the amplitudes of the components of electric vector \( E_0 \) in two orthogonal planes \( XZ \) and \( YZ \) and \( \delta \) is the phase difference between the \( x \)- and \( y \)-vibrations. If \( E_0 \) makes an angle \( \theta \) (usually, called the position angle of polarization) with \( x \)-axis, then

\[ E_{0x} = E_0 \cos \theta \]

and

\[ E_{0y} = E_0 \sin \theta. \]

The Stokes parameters can be re-written as

\[ I = \langle E_{0x}^2 \rangle + \langle E_{0y}^2 \rangle = \langle E_0^2 \rangle, \]
\[ Q = I \cos 2\theta, \]
\[ U = I \sin 2\theta \cos \delta \]

and

\[ V = I \sin 2\theta \sin \delta. \]

The most general form of polarization is partially elliptical polarization which can also be described in terms of the ellipsometric parameters, handedness, ellipticity, azimuth and intensity. The Stokes parameters are related to the ellipsometric parameters by

\[ I = a^2 + b^2 = E_0^2, \]
\[ Q = I < \cos 2\chi \cos 2\beta >, \]
\[ U = I < \sin 2\chi \cos 2\beta > \]
and
\[ V = I < \sin 2\beta >. \]

where \( a \) and \( b \) are the semi-major and minor axes and \( \tan \beta \) is the handedness, left or right. The ellipticity \( \epsilon \) is given by
\[ \epsilon = |\tan \beta| = \frac{a}{b} \]

and \( \chi \) is the angle between the major axis of the ellipse traced by the end point of electric vector and the x-axis of the coordinate system, defined as the azimuth.

From the above equations it is obvious that for any beam of light, the parameters \( Q \) and \( U \) take particular values according to the chosen reference axes, whereas the other two remain independent. In other words, the quantities \( I, (Q^2 + U^2), V \) and \( U \) are invariant under a rotation of the reference axes.

For a celestial object the equatorial coordinate system provides a convenient system of reference axes, with the x-axis in the direction of north, y- in the direction of east and z- in the direction of the line of sight. The direction of vibration of the electric vector (position angle \( \theta \)) is measured eastward from the direction of north, and the degree of polarization is given by
\[ p = \frac{(Q^2 + U^2 + V^2)^{\frac{1}{2}}}{I}. \]

The Stokes' parameters can be written in terms of the degree of linear polarization \( p \), position angle \( \theta \), and the degree of circular polarization \( q \) as
\[ I(\text{intensity}), \]
\[ Q = Ip \cos 2\theta, \]
\[ U = Ip \sin 2\theta \]
and
\[ V = Iq, \]
with \( p = (Q^2 + V^2)^{1/2}/I \) and \( q = V/I \). For partially plane polarized light, \( V = 0 \).

Linear polarization measurements of the T Tauri stars were made using the PRL- polarimeter (Deshpande et al. 1985). In astronomical polarimetry the main sources of error are of atmospheric origin, the scintillation and seeing. A Wollaston prism is used as the analyzer and so the two beams with mutually perpendicular planes of polarization can be measured simultaneously. The scintillation noise pattern is same for all planes of polarization because air is not birefringent and hence by taking the ratio of the two beams it can be essentially eliminated. This procedure also helps to reduce the errors caused by any variation in atmospheric transparency (Hiltner 1962). The simultaneous measurement of the two beams ensures that the incident radiation is fully utilized, thereby reducing the observation time required to build up the desired signal to noise ratio.

The imperfections in the telescope guiding and the nonuniform sensitivity across the surface of photocathodes tend to reduce the polarimetric accuracy. The errors caused by these two sources can be minimized by the use of Fabry lenses in front of detectors (Cox & Sinnott 1977). Young (Serkowski 1974) has shown that the errors of atmospheric origin can be reduced by a sinusoidal modulation of the light with a frequency that is larger than a critical value which depends on the telescope aperture. This principle is applied in the PRL polarimeter and the rapid modulation of the signal is achieved by the rotation of a super achromatic half-wave plate. The main disadvantage of using such a plate, made by cementing three achromatic plates of quartz and magnesium fluoride (Pancharatnam 1955), is the wavelength dependence of position angle of its effective optical axis and hence an accurate determination of position angle becomes difficult since when wide spectral bands are used corrections that depend on the spectral energy distribution of the observed object must be applied to the measured position angle. This problem can be avoided by introducing another stationary identical Pancharatnam plate between the rotating plate and analyzer (Frecker & Serkowski 1976). The intensity \((I')\) of the transmitted light by two half-wave plates followed by the analyzer depends only on the Stokes parameters \( I, Q \) and \( U \) of the
incident light and the angle ($\Psi$) between the effective optical axes of the two half wave plates, and is given by (Serkowski 1974)

$$I' = \frac{1}{2}(I \pm Q \cos 4\Psi \pm \sin 4\Psi).$$

The upper signs represent the case with the principal plane of analyzer at position angle $\theta^o$ and the lower signs with that at $90^o$. The rotation frequency of the first half wave plate is 10.41 Hz and because of the $4\Psi$ factor the actual modulation frequency is four times this value. The Glan-Taylor prism, which can be inserted in the beam of light, is for the purpose of checking the instrument for 100% polarization. The acquisition and on-line processing of the data are done using a PC.

The T Tauri stars were observed during 1990, 1991, 1992 and 1993 seasons with the 236 cm Vainu Bappu Telescope of VBO. During 1990, 1991 and 1992 seasons only a few sets of observations could be collected because of the limited telescope time available. Nevertheless, these observations serve the purpose of detecting the presence of any variation in the linear polarization exhibited by these stars. During March 1993 the T Tauri objects could be observed continuously on 9 nights, making it possible to carry out a detailed study of the variability of polarization with respect to the rotation period of these stars. The observations were done mostly in V band and occasionally in B and R bands.

The observing procedure with the PRL polarimeter is as follows. After selecting the desired filter, the sky background adjacent to the programme star is first measured by integrating for a pre-specified time interval (typically, 60 sec), depending on the sky conditions and the brightness of the object in the wavelength band considered. The measurements are then repeated on the required object after centering it in the diaphragm. The data reduction program is automatically activated at the end of integration and the computer calculates and prints out the time of observation, percentage of linear polarization ($P\%$), its probable error ($\epsilon_p$), position angle of polarization ($\theta^o$) and the magnitude ($m$). The sky background is subtracted before a least square solution for the Stokes parameters is made. The parameter I is essentially the brightness of the source, and hence it is converted into magnitude which is printed. The above procedure is repeated several times.
(typically 15 to 20 times) to bring down the errors due to the photon statistics to a desired level. The probable error in the computed position angle is estimated using (Treonor 1962)

\[ \epsilon_\theta = 28.5^\circ \epsilon_p P^{-1}. \]

Several zero polarization standard stars from the list of Serkowski (1975) were observed each night to determine the instrumental polarization which was found to be significant. Since the Stokes vectors linearly add at low polarization levels, we have

\[ Q_{\text{observed}} = Q_{\text{star}} + Q_{\text{instrumental}} \]

and

\[ U_{\text{observed}} = U_{\text{star}} + U_{\text{instrumental}}. \]

The intrinsic linear polarization and position angle of the object are given by

\[ P_{\text{star}} = (Q_{\text{star}}^2 + U_{\text{star}}^2)^{1/2} \]

and

\[ \theta = \frac{1}{2} \tan^{-1} \frac{Q_{\text{star}}}{U_{\text{star}}}. \]

The Stokes parameters \( Q \) and \( U \) are calculated from the observed values of \( p \) and \( \theta \). The observations of zero polarization standards directly give the instrumental \( Q \) and \( U \). Several polarization standards, were also observed to correct the the zero point error in the observed position angle. These objects were also chosen from the list of Serkowski (1975).

2.3. Spectroscopy

Spectroscopic observations of the T Tauri stars were made with the Universal Astronomical Grating Spectrograph (UAGS) attached to the 102 cm telescope of the VBO. A grating of 651 lines mm\(^{-1}\) blazed at 5000 Å was used in the first order, and a 384x576 Thomson–CSF TH 7882 CCD chip mounted in a liquid nitrogen cooled dewar as the detector. The data acquisition was done through the CCD System supplied by Photometrics Ltd.,
USA. The UAGS setup with a 250 mm Schmidt camera gives a resolution around 1.38 Å per pixel in the red region. The wavelength calibrations were done using a Fe-Ne hollow cathode. The $H\alpha$ and the $Li \, I \, 6708$ Å lines were obtained in a single exposure. The spectroscopic data were analyzed with a Sun Work Station using the Image Reduction and Analysis Facility (IRAF). The extraction of the spectrum from the two dimensional raw image involves the correction for the electronic bias, dark current, sky background subtraction, and flat fielding. Several bias and dark frames were obtained each night and the mean bias and dark values of each night were subtracted out from the raw image data. Though CCD has a good linearity, there still exists pixel to pixel variations in sensitivity. To correct for this variations a few flat field images were taken each night using a specially made white screen fixed in the dome and illuminated by a tungsten lamp. The dark and bias-corrected images were divided with the flat field images. The extracted stellar spectrum was then wavelength calibrated. The standard deviation of the polynomial fit to the wavelength position in the comparison spectra was found to be around 0.02Å. The spectra were normalized to the continuum and the equivalent width of $H\alpha$ and $Li \, I$ lines were measured. The resolution employed in the present observations is not adequate for a detailed profile analysis, and hence only the equivalent width of the lines were measured.

2.4. Period determination

In the literature, for some of the programme stars photometric periods are not available. To derive the same, a computer program, developed by us, based on an algorithm similar to the one described by Bopp et al. (1970), has been used. The period finding algorithm is based on the principle that the observations when folded with the correct period show a minimum scatter in the magnitude-phase diagram.

For each trial period the photometric phases are computed from the time of observations using an arbitrary initial epoch, and all the observations are ordered in phase. Then the quantity $Q$, taken as the measure of scatter in
the magnitude-phase diagram, is calculated from

\[ Q = \sum_{i=1}^{N-1} |(m_i - m_{i+1})| + |m_N - m_1| \]

where \(m_i\) is the \(i^{th}\) magnitude after the ordering in phase. If there are no observational errors and the light curve shows a single maximum the value of \(Q\) will be exactly twice the total range in the observed magnitudes. Because of the observational errors in a real case, however, the value of \(Q\) will be several times the total range, especially when the amplitude of light variation is small.

If \(T_1\) and \(T_N\) are the times corresponding to the first and last observations, and \(P\) is the trial period the number of cycles covered during the interval \(T_N - T_1\) is given by

\[ \phi = \frac{T_N - T_1}{P} \]

A change \(dP\) in \(P\) will cause a change \(d\phi\) in \(\phi\) given by

\[ d\phi = \frac{T_N - T_1}{P^2} dP. \]

Apart from the minimum and maximum periods to be tried, the input to the program includes a value for \(d\phi\) also. The incremental period is calculated from

\[ dP = \frac{P^2}{T_N - T_1} dP. \]

A typical value for \(d\phi\) is 0.02. If the observations span over a large time interval and a large range in period has to be tried a higher value of \(d\phi\) can be used initially to derive a preliminary period, and then the program is re-run around this period with a smaller value for \(d\phi\).

The final print out includes printer plots of (i) the light curve folded with the period which gives the minimum value for \(Q\) and (ii) the values of \(Q\) against the trial period. All the trial periods and the corresponding \(Q\) are not stored in the computer memory, only a limited number, usually 300 pairs, is stored. Once the number of trial periods exceeds this limit, each time the highest value of \(Q\) stored and the corresponding period \(P\) are replaced by
the current values if the current value of \( Q \) is smaller, otherwise the stored quantities are left as they are.

The program displays the total number of periods to be tried and the number of periods already tried which is continuously updated. If sufficient observations are available, there will be no difficulty in identifying the real period because there will be only a single deep minimum. A typical plot of \( Q \), the measure of scatter in the magnitude-phase diagram, against the trial period, which was obtained in the present analysis, is shown in Figure 18 of § 4.2.3.