OPERATOR'S MANUAL

FOR

LIGHT CURVE AND Spot FITTING PROGRAMS

for

RS CVn STARS

February 2006

Michael Rhodes

Edwin Budding

Michael Zeilik

Operator's Manual for Light Curve and Spot Fitting Programs

Table of Contents

Page

List of Tables

Page

Operator's Manual for Light Curve and Spot Fitting Programs

List of Figures

Page

Introduction

This manual provides instructions for using the group of MSDOS programs designed for analyzing the light curves of RS Canum Venaticorum binary stars and doing theoretical fits of circular dark spots to the distortion-wave curves of these stars.[1] The use of these programs, however, is not restricted to this class of stars. It can be used to fit any eclipsing, non-contact binary stellar systems and to match starspots to any photometric distortion wave.

The programs run on an IBM compatible microcomputer. The minimum suggested hardware configuration is at least a 486 system with 8 MB of RAM and a hard disk—a Pentium with 16 MB of RAM is recommended.

The following programs are used:

Fitter.exe	The curve fitting program.
Spot.exe	The spot fitting program.
AddParam.exe	Adds parameters to the raw data file for the Fitter program.
AddParSp.exe	Adds parameters to the raw data file for the Spot program.
Binner.exe	Reduces the number of data points in a raw data file to 200. Used when the input data contains more than 200 points.
Shifter.exe	Shifts the input data so the maximum value is approximately equal to zero, the format expected by the Fitter program. Also, if the eclipse is more positive in magnitude, it inverts the values so the eclipse is more negative in magnitude.
ShiftFaz.exe	Shifts the phase of the data so that the maximum delta magnitude is at phase zero.
ShiftSpot.exe	Shifts the input data so the maximum value is approximately equal to 1.0, the form needed by the Spot program.
Fold.exe	Combines two or more separate data files into a single data file.
Grapher.exe	Allows the user to make a quick screen plot of the various output data from either the Fitter or Spot program.
Pmag.exe	Used for the manual entry of light-curve data. The phase can be entered in phase units, degrees, Universal Time, or Heliocentric Julian date.
SpotGraph.exe	Allows the user to plot positions and sizes of spots on a Mercator projection of the star.
WinGraph.exe	A windows program that combines the Grapher and SpotGraph programs with a much more flexible interface that allows you to save the plot as a graphics file or print it out. Can only be run in Windows.

---

[1] These Dos programs have been combined into a single Windows program called CurveFit that is available for those who would prefer the advantages of the Windows environment.

Fitter Program

Preparation of Fitter Data Files

It is important to use high-accuracy photometric data (1% or better) if possible. Use the following procedure:

1. You need complete coverage over a short period of time. Closely spaced points over a few orbital periods is best. The more spread out in time the data is, the higher the likelihood that the starspots will move and/or change in size. Approximately 100 data points are needed to give a good fit without using excessive computer time. If more than 200 points are available, then use the data binning utility to calculate the normal points. If normal points are available in the original sources, then use them, provided they are not spread out to far in time.

2. Check to see whether the observations are in the instrumental system or standard UBV system. For old photometry done without filters, check to see if an effective wavelength is given. Watch out for "visual" photometry!

3. Write the basic information for the source of the material in a data log.

4. If you need to manually enter the phase and delta magnitude data, you can use the Pmag data entry program. This will prompt you for the proper header information for the data file and will then allow you to enter the phase and delta magnitudes of the binary system you want to analyze. You should use the following naming convention for the file produced:

starname#.org

where **#** is a number used to differentiate between different data files of the same star system, and **org** stands for the original data file. For example, if the system in question is XY Ursae Majoris, and this is the first file that has been created for this system, then the file name would be: **xyuma01.org**. Remember that in DOS filenames are limited to eight characters plus extension. The format for the data file is shown in Table 1. At the beginning and end of the file are eight lines of information about the data. At the beginning of the file there is a blank line after the eight information lines. Note also that after the last phase and delta magnitude, a phase of -99.0 and a delta magnitude of 0.0 is required to indicate the end of the data.

5. Use the Grapher program (or if you have Windows, use WinGRAPH) to plot out the points of the data set and examine them to see if the shoulders outside of the eclipse have a delta magnitude of 0.0. If not, the magnitudes will have to be shifted so this is the case. Use the Shifter program to do this. You should give the output file from the Shifter program the extension **.sft** to distinguish it from the original data file. Be sure to write down in the log book the offset (in magnitude) calculated by the shifting utility. This program will also convert the data into the format of eclipses having more negative delta magnitude if the original data has shows eclipses in more positive delta magnitude. After using the Shifter program, make another plot of the data to make sure the offsets were done properly so the shoulders of the light curve have a delta magnitude equal to 0.0.

6. If the primary minimum is far away from phase 0.0, use the ShiftFaz program to offset the phases, so that primary minimum corresponds closely to phase 0.0.

Preparation of the Input file for the Fitter Program

To prepare the data file for input to the Fitter program, use the AddParam program. This program will ask you for the name of the data file you want to use and then prompt you for the various parameters necessary for the Fitter program. It will insert these parameters with heading, phase, and

delta magnitude information into a new file using the name of the data file you entered, but will give it the extension **.dat**.

Table 2 shows the 16 parameters the Fitter program uses for optimizing the fit of a light curve of an eclipsing binary system. Typically, only a few of these parameters will be varied for any given run. Astronomical data and physics are needed to estimate the values of some of the input parameters.

Table 3 shows a sample listing of an input file for Fitter program as produced by the AddParam program. The first line of seven numbers after the heading information are control parameters and their function is as follows:

First - Tells the Fitter program whether or not to print out the light curve which was read in. (0 = no print out, 1 = print out.)

Second - Tells the Fitter program the total number of parameters (16).

Third - Tells the Fitter program whether an eccentric orbit fitting will be used (0 = circular orbit). If so, fitting parameters 9 and 10 (eccentricity and mean anomaly at orbital phase zero) will be used; otherwise they will be ignored.

Forth - Tells the Fitter program the number of iterations to use.

Fifth - Tells the Fitter program whether to calculate surface fluxes using blackbody approximations (= 1) or your own values (= 0). Usually we use the blackbody approximation. In that case it is necessary to provide the effective temperatures of the two stars.

Sixth - Tells the Fitter program whether or not a correction file will be used. This is a file generated by the Spot program that accounts (theoretically) for the distortion wave. For the first pass of the Fitter program a correction file is not used.

Seventh - Tells the Fitter program whether or not to print a final light curve (0 = No, 1 = Yes).

Next comes a listing of the fitting parameters and the initial steps in their values for the fitting search. Step sizes are normally "guesstimates" of the expected order of accuracy of each parameter value. The AddParam program prompts you for the initial value of each of these and the step size. Note that the program provides some default values. **U**, the unit of light, should be nominally 1.0 for the combined light of the two stars. **L$_1$** is the fractional luminosity of the primary (hotter) star. **K = r$_2$/r$_1$** is the ratio of the radii of the secondary and primary stars. (Here primary refers to that star eclipsed at the primary minimum.)

Next are the limb darkening coefficients, **u$_1$** and **u$_2$**, for the primary and secondary star. You can infer these from the measured (or assumed!) spectral types and they will typically be in the range from 0.6 to 0.8. (See Al-Naimiy, 1978, for a table of values, which is given as Table 4 at the end of this manual.) The phase correction, $\Delta\varphi_o$, is any offset to the primary minimum at phase 0.0; it can arise from period changes (or a poor ephemeris!).

The parameter **r$_1$** (= **r$_h$**) is the radius of the primary star in units of the semi-major axis of the orbital separation. The inclination, **i**, will normally be close to 90° for an eclipsing system. The eccentricity of the orbit, **e**, is zero for circular orbits as is the longitude of periastron, ϖ. (Actually ϖ is not used but the mean anomaly at phase zero, **M$_o$**. These two quantities are easily related for a given eccentricity--see Budding, 1974, *Astro. Sp. Sci.*, **26**, 371.) Longitude of periastron, ϖ, is what is customarily quoted for the appropriate element, but **M$_o$** is a more convenient parameter for this fitting algorithm.

The fractional luminosity of the secondary, **L$_2$** (= **L$_c$**) is normally tied to **L$_1$** so that **L$_1$ + L$_2$ = U** 1.0, but this condition can be relaxed. The mass ratio, **q**, is **m$_2$/m$_1$**.

The values of the next four parameters depend on whether you are using the blackbody approximation or your own values for the calculation of surface fluxes. If using your own values, you must give **T$_1$**, the coefficient of gravity darkening for the primary; **T$_2$**, the coefficient of gravity darkening for the secondary; **E$_1$**, the luminous efficiency of the primary; and **E$_2$**, the luminous efficiency of the

3

secondary. Typical values are near unity. The formulae used to calculate the gravity and reradiation flux parameters (T_1, T_2, E_1, E_2) are given in Budding and Najim (1980).

If you are using the blackbody approximation, then parameter 13 is T_1, the effective temperature of the of the primary (hotter!) star, and parameter 14 is T_2, the effective temperature of the secondary. You can infer their values from spectral types (see Table 5), using the tables in Allen (1973), Lang (1980), or Hayes (1978). In many cases, we do not know the spectral type of the secondary, so it is necessary to make a reasonable guess for its effective temperature. Parameter 15 is the effective wavelength of the observations [note that the units are in Ångstroms (centimeters within the procedure)]. Finally, parameter 16 plays the role of an "empirical albedo", which multiplies the reflection factors E_1 and **E2**. Normally, this should be kept at unity.

The next line of sixteen numbers shows the selection of parameters to be optimized. Each digit corresponds, in order, to each of the 16 optimization parameters. A "0" indicates that the parameter will not be optimized (i.e. it will remain fixed). A "1" indicates that the corresponding parameter will be optimized by the Fitter program. At most, you will usually optimize seven parameters: **U** (#1), L_1 (#2), **K** (#3), $\Delta\varphi_o$ (#6), r_1 (#7), **i** (#8), and L_2 (#11). Note that L_1 and L_2 are coupled, so that for #11, you will normally insert a "2", which tells Fitter that the parameters #2 and #11 are coupled. These sixteen numbers can thus have the following values:

> 0 - not altered
> 1 - optimize in a direct way
> 2 - constrained to optimized parameter by some internally set constraint.

The strategy to follow involves fitting the "easiest" parameters first and then optimizing the others. For the first run, it is usually best to vary only **U**, the reference luminosity, and $\Delta\varphi_o$, the phase correction, in order to fix these values first. **U** and $\Delta\varphi_o$ are sometimes referred to as the "fiducial" parameters for the axes of the conventional Cartesian system, i.e.:

> **U** $\rightarrow$ y reference level (1)
> $\Delta\varphi_o$ $\rightarrow$ x reference level (0)

The next line gives another set of six control parameters. The first number (**D**) is the nominal error in the observations; it should be checked for each data set and hopefully is not larger than 0.01 magnitude. If in doubt, use 0.01 mag, which can be easily rescaled. The second number is the reduction of steps in progressive iterations when "homing in" on an optimum. The third number is the increase (augmentation) of step-size. The fourth number is the difference in chi-square between iterations at which the program will stop. The fifth and sixth numbers (A_2 and A_3) tell the optimizer which routines to use. They are involved in internal switches in the optimizing strategy: a search for a linear trend (to within A_2) then vector search. If the chi-squared fails to improve (to within A_3), then switch back to normal (parabolic) mode. Generally, only **D** needs to be changed in this line, but it may be of interest to experiment with some of the other quantities to see what effect they have on the results.

The final line of sixteen control integers tells the Fitter program what order to vary the parameters in its fitting process. Normally you can leave these in the natural arithmetic order: 1, 2, 3, etc., but you can change to another order if you want. It may be a good idea, sometimes, to check a solution by approaching it from a different route: i.e. by having a different sequence for parameter optimization.

For subsequent runs, you can change these various parameters with a text editor such as the Windows Notepad editor using the final values from the previous calculation. If you use another editor, such as WordPad or Word, be sure to use the plain text mode so you don't introduce any spurious control characters into the file!

Running the Fitter Program

Now you can run the Fitter program, which will prompt you for the name of the input data file (the one prepared using the ADDPARM program). If there are already output files from a previous run, it will

ask if you want to overwrite them. It will also ask you if you want to print out the error matrix (usually reply "yes"). It will produce the following output files:

> **filename.out** - main output information
> **filename.mod** - theoretical light curve
> **filename.obs** - observational points
> **filename.dif** - difference curve used as input for Spot program.

where "**filename**" is the filename of the input data file.

Once you have made an initial run of the Fitter program, plot the theoretical light curve (the **.mod** file) overlaid on the observed light curve (the **.obs** file) (using the Grapher program or WinGraph if you are using Windows) to see how well they match. Then edit the Fitter input file "**filename.dat**" and replace the initial values of **U** and $\Delta\varphi_o$ with those found in the first run. Hold $\Delta\varphi_o$ fixed for the next run, and optimize for **U** (#1), L_1 (#2), **K** (#3), r_1 (#7), **i** (#8), and L_2 (#11, you should put a 2 here to indicate that L_1 and L_2 are coupled). Note: the main fitting is an even function about the zero phase point, so $\Delta\varphi_o$ is usually fairly independent of all other parameters for a uniformly spaced data set corresponding to a genuine likeness to the underlying model (i.e. intrinsically symmetric). **U** is, however, not so independent in principle; it could correlate strongly with E_2 for example. Getting values for these six parameters are about all you should reasonably hope for from a photometric solution. The masses and temperatures of the stars should come from other lines of evidence (i.e. spectroscopy).

If the next run finds some reasonable value for **i**, you can fix it for subsequent runs. Use the output from the previous run as input for the next. It should not take more than three or so runs to get a reasonable set of fits. If it does not, that should warn you that something is amiss. Check your initial run for just **U** and $\Delta\varphi_o$ by doing a plot with **filename.mod** and **filename.obs** super-imposed. Your initial model curve should not look too bad in basic outline, though there may be significant misfits around the minima. Figure 2 shows a plot made using the WinGraph program.
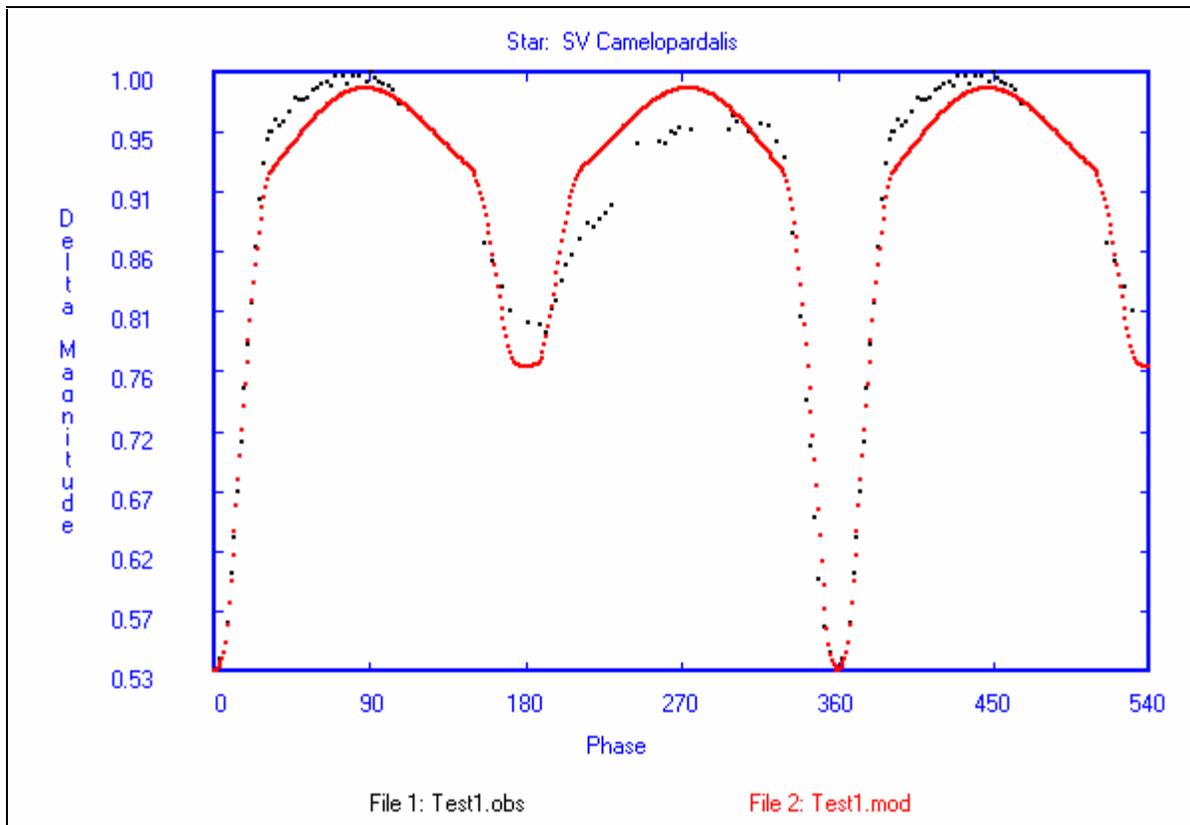

Figure 1. Plot of Theoretical Light Curve with Observed Light Curve Superimposed

When you are satisfied with the results, make a copy of the final **filename.dat** file called "**filenameC.dat**". The "C" stands for "clean", and it will be used for the CLEAN run.

Spot Program

Generally speaking, the Spot program operates similarly to the Fitter program--the main difference lies in the different fitting functions. Hence, the main features of the input file layout for Spot are quite similar to those of Fitter.

Spot Program Input File Format

The Fitter output file "**filename.dif**" contains the difference between the theoretically derived light curve and the actual one--that is, the so-called distortion wave (if there is one!). Graph this file to see if it contains any systematic trends or looks like a scatter diagram. If it seems that the points fall randomly about zero, then either no spots exist or they are uniformly distributed in longitude. If any trends appear, you can estimate by eye the longitude of a minimum and whether one or two minima (one or two spot groups) exist.

The file naming convention here is the same as for Fitter with the addition of an "**S**" (for "spot") at the end of the name: **xyuma01** becomes **xyuma02S**, for instance. It is a good idea to change the original **.dif** file output by the Fitter program to **filenameS.org**. You need to shift the data in intensity units so that the maximum level becomes one light unit (1 corresponding to the "immaculate" condition). Use the ShiftSpot program to do this, and name the file **filenameS.sft**. When you run it, be sure to write down the magnitude offset calculated by the program. Use the AddParSp program to enter the parameters into the shifted file, and name it **filenameS.dat**. This program will prompt you for the various parameters necessary for the Spot program.

Operation of Spot Program

Do a first run of Spot at a fixed latitude of 45 degrees (= 0.785 radians) with a guess for the spot's radius and longitude. The radius size should be approximately equal to the square root of the wave amplitude (0.10 radians). If two minima are not clearly visible, start with only one spot group.

The fitting parameters are given in Table 6; there are 11 possible. They are:

(1) longitude of spot 1, α_1, in radians.

(2) latitude of spot 1, β_1, in radians.

(3) inclination of the system, **i**, in radians (use output from   Fitter).

(4) radius of spot 1, ρ_1, in radians.

(5) unit of light, **U** (normally = 1.0, use output from Fitter).

(6) the intensity of the spot, K_λ (= 0.0 for a "black" spot). K_λ is defined as the flux in the spot divided by the flux in the photosphere at the effective wavelength, λ.

(7) the limb darkening coefficient, **u**, of the spotted star (typically 0.70).

(8) the fraction luminosity of the hotter star, L_1 (use output from the Fitter program).

(9) the longitude of spot 2, α_2, in radians.

(10) the latitude of spot 2, β_2, in radians (usually set to β_1).

(11) the radius of spot 2, ρ_2, in radians.

Once you have found some reasonable values with a first run, the strategy is to vary α_1, β_1, ρ_1, α_2, β_2, and ρ_2 for the best fit. Note that two minima in the distortion wave, or one minimum with an asymmetrical shape indicate two spots. Once these parameters are optimized, you must carefully examine the error matrix to see if a "good" solution is achieved (in a chi-square sense). Beware of indeterminate values of the latitude and spot size (which are interrelated)! Once a good fit has been achieved, plot out the observational data points and theoretical curve (Figure 3).
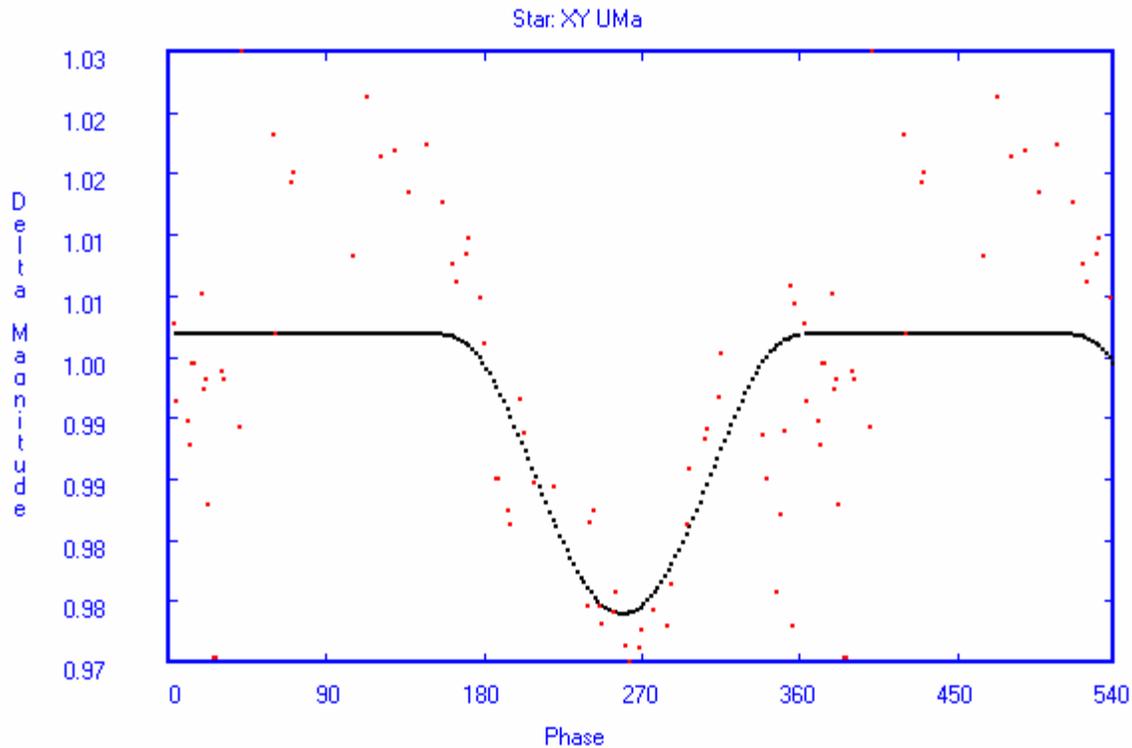
Figure 2. Plot of Theoretical Spot curve with Observed Spot Curve Superimposed

File Structure for Spot Program

The Spot program generates the following output files:

> **filenameS.out** - Main output file
> **filenameS.mod** - Theoretical fit
> **filenameS.obs** - Observational points
> **filenameS.cor** - Correction curve for curve fitting procedure

Table 7 gives a sample input file (**filenameS.dat**) for the Spot program. The first line of five numbers contains the control parameters. The first parameter tells Spot whether or not to print out the input light curve (1 = yes, 0 = no). The second parameter is the number of unknowns (= 11). The third parameter gives the system eccentricity (0 = circular): in this case a dummy variable--but it should always be set to zero. The fourth parameter gives the number of iterations (normally = 10). The fifth parameter gives the number of spots (0, 1, or 2). Following these are the eleven fitting parameters (1-11, Table 6). The line after these indicates which parameters are to be optimized (0 = no, 1 = yes). The next line contains variables that will be fixed, except for the first, **D**, which is the nominal error in the data. The next line provides the order in which the parameters will be optimized (1 to 11). Then comes the input data in phase (degrees) and intensity.

Fitter Program with Correction File

Using the best fitting parameters from the earlier runs of the Fitter program, copy them into a file called "**filenameC.dat**" ("**C**" for "clean"). Also rename the **filenameS.cor** to **filenameC.cor**. Change the correction parameter from "0" to "1" so that the correlation file output from the Spot program will be read in. Then run the Fitter program for the usual five parameters **U**, **L$_1$**, **r$_1$**, **K**, and **i**. **L$_1$ + L$_2$ = U** should be set as a constraint, unless there are some grounds for thinking there may be third light, i.e. **U** - (**L$_1$** + **L$_2$**) = **L$_3$** > 0. $\Delta\varphi_o$ will be reasonably determined independently. **E$_2$** might be a possible seventh in case of an anomalous reflection effect--but note the case of BH Vir!

This run may take a little longer as the values adjust to that for a "clean" light curve. The results should have a smaller chi-square than the uncleaned run. When plotted, the regions affected by the distortion wave should have a noticeably better fit. Plot out (Figure 4) the theoretical curve (**filenameC.nod**) and the corrected data (**filenameC.obs**). As a check, also plot out the new difference curve (**filenameC.dif**). It should appear as a scatter diagram around zero, with the magnitude of the scatter on the same order as the errors in the observations. If there are still systematic trends, a second run-through may be needed.
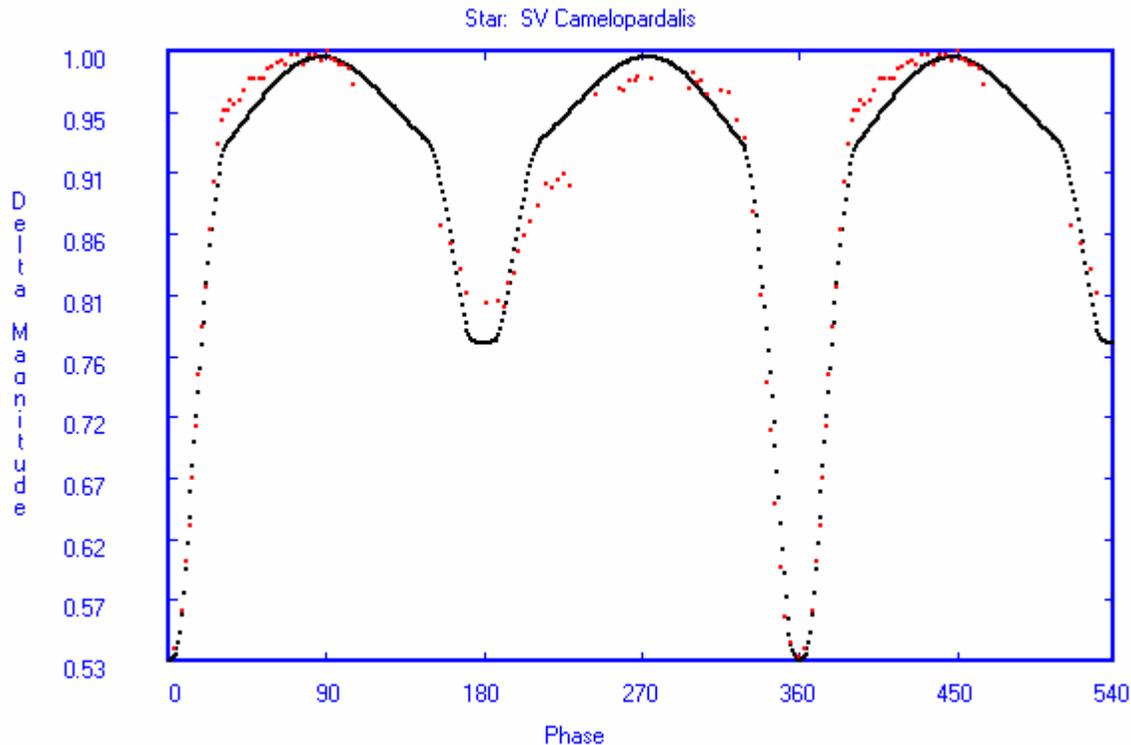
Figure 3. Plot of theoretical light curve with corrected light curve superimposed

The SpotGraph Program

You can now use the SpotGraph program (or WinGraph if you are running Windows) to plot he location of the spot(s) on a Mercator projection of the star's surface. The program asks for the latitude, longitude, and radius of the spot. It allows you to plot more than one spot, so you can enter the results from several different data sets. In this way, you can graphically display the evolution of the spot groups on a given primary star.

The WinGraph Program

Because the DOS programs GRAPH and SpotGRAPH were written in Turbo Pascal, the graphics capabilities are somewhat limited. WinGraph, written with Delphi, overcomes those limitations by utilizing the full capabilities of Windows. When you initially run WinGraph, you get a main window that looks like figure 5.
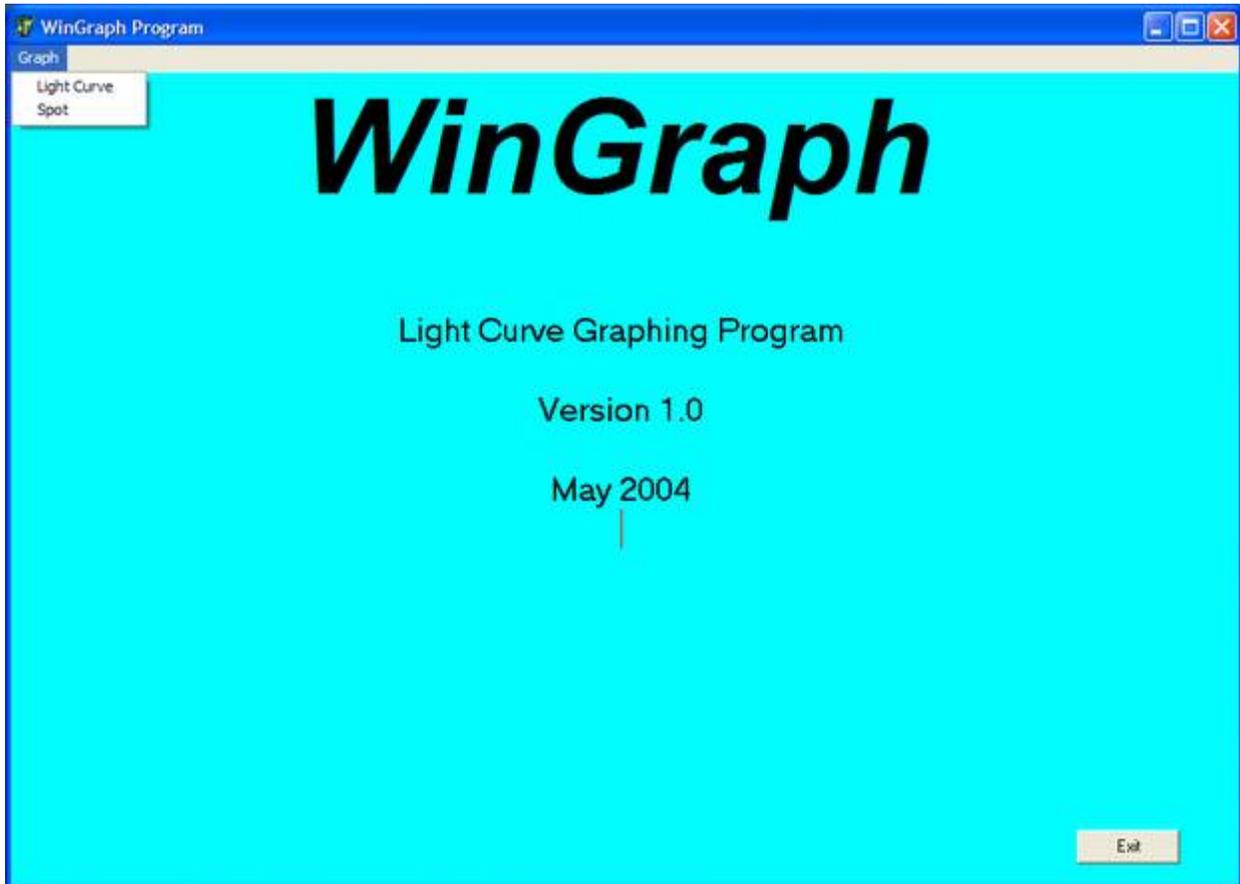
Figure 4. WinGraph Main Window

The **Graph** menu contains two options: **Light Curve** and **Spot.** When you select **Light Curve**, a new windows is opened that looks like Figure 6.
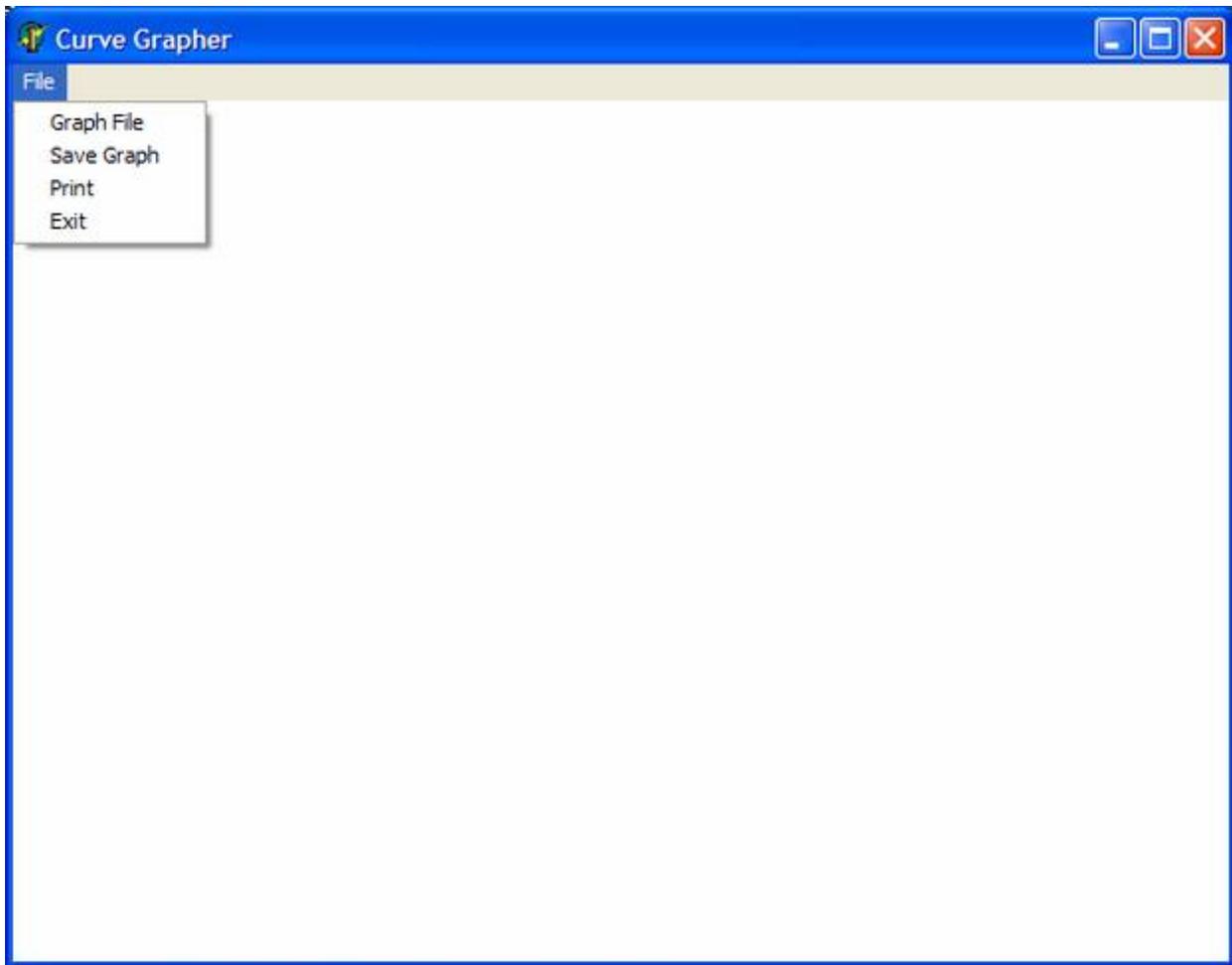
Figure 5. WinGraph Light Curve Window

The File Menu on the Light Curve window has several options:

Graph File Plots delta magnitude versus phase. Two data files can be plotted to compare for example the modal curve with the actual data. Both light curve and spot curve data can be plotted.

Save Graph Saves the plot as a Windows bitmap file for further processing or pasting into other applications.

Print Prints the graph.

Exit Returns to the main WinGraph window

When you select the **Spot** option, a new window is opened that looks like Figure 7.
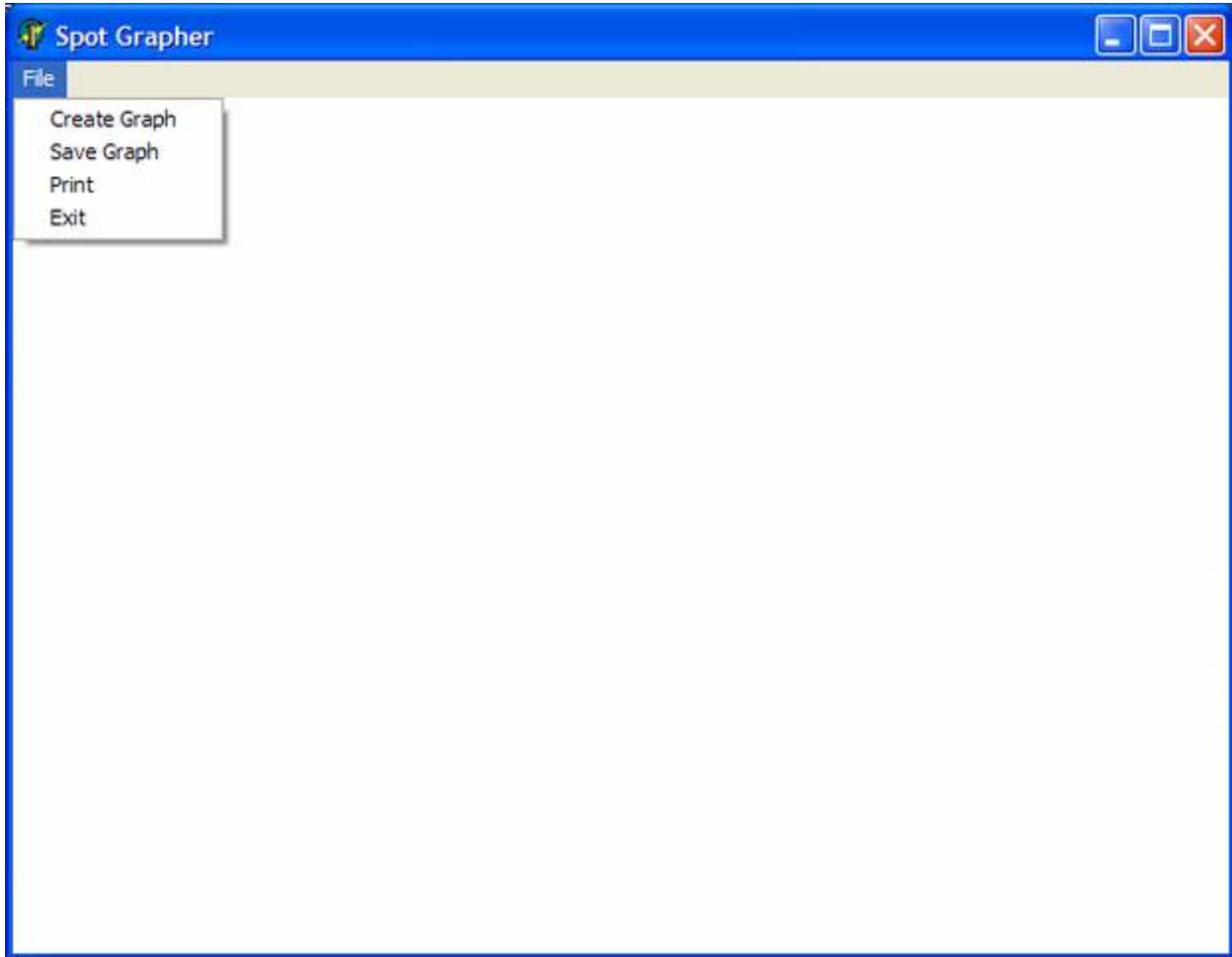
Figure 6. WinGraph Spot Graph Window

The File Menu on the Spot graph window has several options:

Create Graph   Allows you to create a Mercator projection of the star on which the positions and sizes of the spots are plotted.

Save Graph Saves the plot as a Windows bitmap file for further processing or pasting into other applications.

Print   Prints the graph.

Exit   Returns to the main WinGraph window

Epilogue

After the last iteration, some further numerical operations will appear in the main output file "**filename.out**" (both from the Fitter program and the Spot program). These are connected with the setting up of the curvature Hessian and the error matrix. Some detailed notes about this are provided in Budding and Najim (1980). A fuller, and readable background is provided in Bevington's (1969) book *Data Reduction and Error Analysis for the Physical Sciences*.

The main point here is to test for determinacy of the sought parameters and also to provide more realistic formal errors than the interim formal errors determined with each iteration. The final list of formal errors takes into account the inter-correlations between parameters. The curvature Hessian must be positive definite for a valid optimum. Ideally, it should be dominated by its central diagonal (well-determined solution).

Guides to the character of this Hessian, and therefore the nature of the solution, are provided by the eigenvalue and eigenvector list; and also the Hessian's inverse--the error matrix. The standard deviation error assessments are determined in a direct way from the leading diagonal solution. If any such element is negative, it indicates a breakdown in determinacy. This is usually caused by "asking the light curve to tell you more than it knows"--i.e. seeking to determine too many parameter values. The presence of correlation effects between different parameter values has a highly contributory effect here.

The same effects are show in a different way by the eigenvalue list. The eigenvalues must all be positive for a valid optimal "unique" solution. (Actually, "unique" has a somewhat restricted meaning here). The eigenvalues represent the axes in a principle axis transformation of the error ellipsoid. The eigenvectors indicate the orientation of these axes with respect to the scaled parameter axes.

The main point here is to establish where the essential determinacies of the problem really lie. Usually, for example, we find that the largest eigenvalue is closely oriented towards the axis of the "unit of light" parameter. This just confirms "Murphy's Law"; the light curve tells you best the thing you are least interested in--i.e. the mean out-of-eclipse light level.

References

Allen, C. W.: 1973, *Astrophysical Quantities* (Third Edition). Athlone Press (London), p. 206.

Al-Naimiy, H. M.: 1978, *Astrophys. Sp. Sci.*, **53**, 181.

Bevington, P. R.: 1969, *Data Reduction and Error Analysis for the Physical Sciences*, McGraw Hill Book Co., NY.

Budding, E.: 1974, *Astrophys. Sp. Sci.* **26**, 371.

Budding, E.: 1977, *Astrophys. Sp. Sci.* **48**, 207.

Budding, E. and Najim, N. N.: 1980, *Astrophys. Sp. Sci.* **72**, 369.

Budding, E.: 1993, *An Introduction to Astronomical Photometry*, Cambridge University Press (Cambridge).

Hayes, D. S.: 1978, *The H-R Diagram*, edited by A. G. D. Philips and D. S. Hayes, Dordrecht, p. 70.

Lang, K. R.: 1980, *Astrophysical Formulae*, Springer Verlag, (Berlin), p. 564.

Table 1. Example of Original File

```
RT Andromedae
Date: 11, 12 Nov, 12 Dec UT 1987
Observatory: Capilla Peak 61 cm CCD camera
Wavelength: V (using Mould "V" filter 537.5 nm)
Comparison star: BD 52 3384 (SAO 35208)
Error: 0.01 mag ?
Source: Capilla archives N=96
11 Nov, 12 Dec partially cloudy

 0.2590    1.1860
 0.2670    1.1840
 0.2720    1.1890
 0.2860    1.1900
 0.3020    1.1850
 0.3120    1.1870
 0.3260    1.1830
 0.3370    1.1700
 0.3490    1.1740
 0.3590    1.1640
 0.3710    1.1590
 0.3820    1.1600
 0.3930    1.1550
 0.4030    1.1410
 0.4160    1.0900
 0.4260    1.0900
 0.4470    1.0310
 0.4670    0.9480
 0.4870    0.9160
 0.8100    1.1800
 0.8270    1.1540
 0.8360    1.1490
 0.8480    1.1410
 0.8710    1.1370
 0.8770    1.1330
 0.8900    1.1300
 0.8990    1.1160
 0.9110    1.0380
 0.9170    1.0020
 0.9240    0.9570
 0.9530    0.6480
 0.9580    0.5750
 0.0340    0.8350
 0.0410    0.9010
 0.0460    0.9550
 0.0520    1.0010
 0.0570    1.0290
 0.0640    1.0900
 0.0700    1.1010
 0.0780    1.1230
 0.0840    1.1370
 0.0920    1.1380
 0.1660    1.1910
 0.1720    1.1760
```

Table 2. Standard Eclipsing Binary Fitting Parameters

1. **U**   - the reference luminosity

2. $\mathbf{L_h = L_1}$ - the fractional luminosity of the hotter (primary) star

3. $\mathbf{K = r_2/r_1}$ - the ratio of the radii

4. $\mathbf{u_1}$ - the coefficient of linear limb-darkening for the primary star

5. $\mathbf{u_2}$ - the coefficient of linear limb-darkening for the secondary star

6. $\mathbf{\Delta\varphi_o}$ - the phase correction

7. $\mathbf{r_h = r_1}$ - the radius of the primary star (in units of the semi-major axis of the orbital separation)

8. **i**   - the orbital inclination

9. **e**   - the eccentricity of the orbit

10. $\mathbf{M_o}$ - the mean anomaly at phase zero

11. $\mathbf{L_c = L_2}$ - the fractional luminosity of the cooler (secondary) star

12. $\mathbf{q = m_2/m_1}$ - the mass ratio

13. $\mathbf{T_1}$ - the coefficient of the gravity-darkening for the primary star (or the temperature of the primary star)

14. $\mathbf{T_2}$ - the coefficient of the gravity-darkening for the secondary star (or the temperature of the secondary star)

15. $\mathbf{E_1}$ - the luminous efficiency for the primary star (or effective wavelength of the observations in Ångstroms)

16. $\mathbf{E_2}$ - the luminous efficiency for the secondary star (or the "empirical albedo", normally kept at unity)

Table 2 (continued)

Notes: The final main (publishable) output from this can be expected to be:

(1)[*]   The geometric parameters (independent of the wavelength) r_1, r_2 (= **K** x r_1), and **i**.

(2)[*]   The fraction luminosities L_1/U, L_2/U.

(3) The adopted parameters (temperatures and wavelength if blackbody approximation, otherwise limb darkening coefficients, gravity darkening coefficients and luminous efficiencies; and the mass ratio). Usually eccentricity = 0 is adopted.

(4)[*]   Any possible correction to the zero point of the phase, if significant.

(5)[*]   The actual reference out-of eclipse apparent magnitude of the system (obtained from the reference luminosity used as a correction to the initially adopted delta magnitudes).

[*] (all with error measures)

Table 3. Sample Listing of Fitter Input File

```
Star: RT And
Date: 11-12 Nov, 12 Dec 1987
Observatory: Capilla Peak (CCD camera)
Wavelength: R (Mould filter - 667.0 nm)
Comparison star:  BD 52 3384 (SAO 35208)
Error: 0.01 mag
Source: data from Capilla
N = 99

  0  16  1  10  1  0  0
  0.9800000   0.0020000
  0.8700000   0.0050000
  0.7200000   0.0050000
  0.4900000   0.0050000
  0.7300000   0.0500000
  0.0000000   0.1000000
  0.3100000   0.0050000
  1.5376345   0.0043633
  0.0220000   0.1000000
  2.9700000   0.1000000
  0.1000000   0.0050000
  0.6500000   0.0050000
6250.0000000 100.0000000
4900.0000000 100.0000000
  0.0000667   0.0000010
  1.0000000   0.0100000
 1 1 1 0 0 1 1 0 0 0 2 0 0 0 0 0
  0.0100   0.9000   1.1000   0.0200   0.1000   0.1000
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
 0.82200000  -0.08300000
 0.82900000  -0.08000000
 0.83900000  -0.09100000
 0.84900000  -0.09300000
 0.87200000  -0.10100000
 0.87800000  -0.12600000
 0.89100000  -0.13600000
 0.90000000  -0.14000000
 0.91200000  -0.18500000
 0.91900000  -0.22000000
 0.92600000  -0.26400000
 0.95400000  -0.56600000
 0.96000000  -0.62800000
 0.03700000  -0.33500000
 0.04200000  -0.29300000
 0.04700000  -0.24800000
 0.05300000  -0.20600000
 0.05800000  -0.17000000
 0.06500000  -0.13500000
 0.07200000  -0.10100000
 0.08000000  -0.09000000
 0.08600000  -0.07200000
 0.09400000  -0.07400000
 0.16800000  -0.05000000
 0.17300000  -0.03600000
 0.18100000  -0.02700000
 0.23400000  -0.03600000
 0.24100000  -0.01100000
```

		Linearized Limb-darkening Coefficients (*u*) (Al-Naimiy, 1978)													
λ(Å)															
T$_{eff}$	**log g**	**2000**	**3000**	**3600**	**4000**	**4500**	**5000**	**5500**	**6000**	**7000**	**8000**	**10 000**	**12 000**	**16 000**	**22 000**
50 000	5.0	0.29	0.21	0.18	0.19	0.17	0.15	0.14	0.13	0.11	0.10	0.08	0.07	0.05	0.04
40 000	5.0	0.33	0.24	0.21	0.22	0.20	0.18	0.17	0.15	0.13	0.12	0.10	0.09	0.07	0.05
30 000	4.0	0.51	0.38	0.32	0.34	0.32	0.29	0.27	0.25	0.22	0.20	0.18	0.16	0.13	0.10
25 000	4.0	0.58	0.40	0.33	0.37	0.34	0.31	0.28	0.26	0.22	0.20	0.18	0.15	0.12	0.10
20 000	4.0	0.65	0.43	0.34	0.39	0.36	0.32	0.30	0.27	0.23	0.20	0.18	0.15	0.12	0.09
20 000	3.0	0.66	0.46	0.38	0.43	0.40	0.37	0.34	0.31	0.27	0.24	0.22	0.19	0.15	0.11
18 000	4.0	0.68	0.44	0.34	0.41	0.38	0.34	0.31	0.28	0.24	0.20	0.19	0.16	0.13	0.09
18 000	3.0	0.68	0.46	0.37	0.44	0.41	0.37	0.34	0.31	0.27	0.23	0.22	0.18	0.15	0.11
16 000	4.0	0.73	0.46	0.35	0.43	0.40	0.35	0.32	0.30	0.25	0.21	0.20	0.17	0.13	0.09
16 000	3.0	0.72	0.48	0.37	0.45	0.42	0.38	0.35	0.32	0.27	0.23	0.22	0.19	0.15	0.11
14 000	4.0	0.79	0.49	0.36	0.45	0.42	0.38	0.34	0.31	0.27	0.23	0.21	0.18	0.14	0.10
14 000	3.0	0.78	0.50	0.38	0.47	0.44	0.39	0.36	0.33	0.28	0.24	0.23	0.20	0.16	0.11
12 000	4.0	0.87	0.53	0.38	0.49	0.47	0.41	0.38	0.35	0.29	0.25	0.24	0.20	0.16	0.11
12 000	3.0	0.86	0.54	0.39	0.50	0.48	0.42	0.39	0.36	0.30	0.26	0.25	0.21	0.17	0.09
12 000	2.0	0.83	0.56	0.42	0.53	0.50	0.46	0.42	0.39	0.34	0.30	0.29	0.25	0.21	0.15
11 000	4.0	0.93	0.56	0.40	0.52	0.48	0.44	0.40	0.37	0.31	0.26	0.25	0.21	0.17	0.12
11 000	3.0	0.92	0.56	0.40	0.53	0.49	0.44	0.41	0.38	0.32	0.27	0.26	0.22	0.18	0.13
11 000	2.0	0.89	0.58	0.43	0.55	0.52	0.47	0.44	0.41	0.35	0.30	0.30	0.25	0.22	0.16
10 000	4.5	0.98	0.57	0.40	0.56	0.51	0.47	0.43	0.39	0.33	0.28	0.26	0.22	0.18	0.13
10 000	4.0	0.98	0.57	0.39	0.55	0.51	0.47	0.43	0.39	0.33	0.28	0.26	0.22	0.18	0.13
10 000	4.0	0.96	0.55	0.39	0.54	0.50	0.45	0.41	0.38	0.32	0.27	0.26	0.21	0.17	0.12
(10 x Metals)															
10 000	4.0	0.99	0.58	0.40	0.56	0.51	0.47	0.43	0.39	0.33	0.28	0.27	0.22	0.18	0.13
(1/10 x Metals)															
10 000	3.5	0.99	0.57	0.39	0.55	0.51	0.47	0.42	0.39	0.33	0.28	0.27	0.22	0.18	0.13
10 000	3.0	0.99	0.57	0.40	0.56	0.51	0.47	0.43	0.40	0.37	0.29	0.27	0.23	0.19	0.13
10 000	2.0	0.97	0.59	0.43	0.56	0.52	0.49	0.45	0.42	0.36	0.31	0.30	0.26	0.22	0.16
9500	4.0	1.0	0.59	0.40	0.59	0.54	0.49	0.45	0.41	0.34	0.29	0.28	0.23	0.19	0.13
9500	3.0	1.0	0.59	0.41	0.58	0.53	0.49	0.45	0.41	0.35	0.30	0.28	0.24	0.20	0.14
9000	4.0	1.0	0.60	0.42	0.63	0.57	0.52	0.47	0.43	0.36	0.30	0.29	0.24	0.20	0.14
9000	3.0	1.0	.060	0.41	0.61	0.56	0.52	0.47	0.43	0.36	0.31	0.30	0.24	0.20	0.15
9000	2.0	1.0	0.61	0.42	0.60	0.56	0.52	0.48	0.44	0.38	0.33	0.32	0.27	0.22	0.16
8500	4.0		0.64	0.47	0.69	0.62	0.56	0.51	0.46	0.38	0.33	0.31	0.26	0.21	0.16
8500	3.0		0.62	0.64	0.65	0.60	0.55	0.50	0.45	0.38	0.32	0.31	0.26	0.21	0.16
8000	4.5	1.0	0.72	0.55	0.70	0.64	0.59	0.54	0.50	0.42	0.28	0.34	0.29	0.24	0.18
8000	4.0		0.70	0.53	0.72	0.66	0.60	0.55	0.50	0.42	0.36	0.34	0.28	0.23	0.17
8000	4.0		0.70	0.53	0.72	0.66	0.60	0.55	0.50	0.42	0.36	0.34	0.28	0.23	0.17
8000	4.0		0.69	0.52	0.76	0.69	0.62	0.55	0.50	0.42	0.35	0.34	0.28	0.23	0.17
(No Conv.)															
8000	3.5		0.68	0.51	0.74	0.67	0.61	0.55	0.50	0.41	0.35	0.34	0.28	0.23	0.17
8000	3.0		0.66	0.49	0.73	0.66	0.60	0.54	0.49	0.41	0.35	0.34	0.28	0.22	0.17

T_{eff}	log g	λ(Å) 2000	3000	3600	4000	4500	5000	5500	6000	7000	8000	10 000	12 000	16 000	22 000
8000	2.0		0.64	0.47	0.69	0.63	0.58	0.53	0.49	0.41	0.35	0.34	0.28	0.23	0.17
7500	4.0		0.74	0.58	0.74	0.68	0.63	0.57	0.52	0.44	0.38	0.36	0.31	0.25	0.19
(L/H = 1.5)															
7500	4.0	1.0	0.77	0.60	0.70	0.65	0.61	0.56	0.52	0.45	0.39	0.36	0.31	0.26	0.20
(L/H = 2.5)															
7500	4.0		0.73	0.57	0.83	0.74	0.66	0.59	0.53	0.44	0.38	0.36	0.30	0.24	0.19
(No Conv.)															
7500	3.0		0.70	0.53	0.78	0.71	0.64	0.58	0.53	0.44	0.37	0.36	0.30	0.24	0.18
7000	4.0		0.78	0.63	0.78	0.71	0.65	0.59	0.54	0.46	0.40	0.37	0.32	0.26	0.20
7000	4.0		0.77	0.62	0.88	0.77	0.68	0.61	0.55	0.50	0.40	0.37	0.32	0.26	0.20
(No. Conv.)															
7000	3.0		0.73	0.57	0.79	0.72	0.67	0.60	0.54	0.46	0.39	0.37	0.31	0.25	0.19
7000	2.0		0.69	0.53	0.83	0.74	0.67	0.60	0.54	0.44	0.38	0.36	0.31	0.25	0.19
6500	4.0		0.82	0.68	0.80	0.72	0.66	0.60	.0.55	0.47	0.41	0.37	0.33	0.28	0.22
6500	3.0		0.77	0.62	0.82	0.74	0.67	0.61	0.55	0.47	0.41	0.38	0.33	0.27	0.21
6000	4.5		0.90	0.77	0.81	0.73	0.67	0.61	0.56	0.49	0.43	0.37	0.34	0.29	0.23
6000	4.0		0.90	0.76	0.83	0.75	0.68	0.62	0.57	0.49	0.43	0.38	0.35	0.29	0.23
6000	4.0		0.94	0.81	0.86	0.78	0.71	0.64	0.59	0.51	0.45	0.39	0.36	0.31	0.25
(No Blkt.)															
6000	4.0		0.90	0.75	0.88	0.77	0.69	0.63	0.57	0.48	0.43	0.38	0.35	0.29	0.23
(No Conv.)															
6000	4.0		0.96	0.81	0.90	0.80	0.71	0.65	0.59	0.51	0.45	0.39	0.36	0.31	0.25
(10 x Metals)															
6000	4.0	0.28	0.98	0.82	0.93	0.81	0.73	0.66	0.60	0.52	0.46	0.40	0.36	0.31	0.24
(1/10 x Metals)															
6000	4.0		0.95	0.81	0.91	0.80	0.72	0.65	0.59	0.51	0.45	0.39	0.36	0.31	0.24
(No Conv. or Blkt.)															
6000	3.5		0.87	0.73	0.84	0.76	0.69	0.63	0.58	0.50	0.44	0.39	0.35	0.29	0.23
6000	3.0		0.85	0.71	0.86	0.77	0.70	0.64	0.58	0.50	0.44	0.39	0.35	0.29	0.23
6000	2.0		0.80	0.65	0.87	0.78	0.71	0.64	0.58	0.49	0.43	0.39	0.34	0.28	0.22
5500	4.0		0.97	0.84	0.87	0.78	0.71	0.65	0.60	0.52	0.49	0.40	0.36	0.31	0.25
5500	3.0		0.94	0.80	0.90	0.81	0.73	0.66	0.61	0.52	0.46	0.40	0.37	0.31	0.25
5000	4.0	0.52	1.0	0.95	0.94	0.85	0.77	0.71	0.65	0.56	0.50	0.43	0.40	0.33	0.27
5000	3.0	0.56	1.0	0.92	0.96	0.86	0.78	0.71	0.65	0.56	0.50	0.43	0.40	0.34	0.27
5000	2.0	0.60	0.99	0.87	0.97	0.87	0.78	0.71	0.65	0.56	0.50	0.43	0.40	0.33	0.27
4500	4.0	0.18				0.99	0.90	0.83	0.76	0.65	0.58	0.49	0.46	0.38	0.31
4500	3.0	0.20				1.00	0.91	0.83	0.76	0.66	0.59	0.50	0.46	0.38	0.31
4000	4.0	0.06					0.97	0.88	0.81	0.69	0.61	0.52	0.48	0.40	0.33
4000	3.0	0.0					0.97	0.88	0.81	0.69	0.61	0.51	0.48	0.42	0.33
4000	2.0	0.0					0.97	0.88	0.81	0.70	0.61	0.52	0.49	0.42	0.33

Table 5. Main Sequence Stars
(Taken from Hayes, 1978)

TYPE	(U-V)	(B-V)	T_{eff}	B.C
O5	-1^m.48	-0^m.319	47000K	-4^m.3
O6	-1.46	-0.315	42000	-3.9
O7	-1.44	-0.311	38500	-3.6
O8	-1.41	-0.305	35600	-3.4
O9	-1.38	-0.298	33200	-3.2
O9.5	-1.35	-0.294	31900	-3.1
B0	-1.32	-0.286	30300	-2.96
B0.5	-1.28	-0.277	28600	-2.83
B1	-1.19	-0.26	25700	-2.59
B2	-1.10	-0.24	23100	-2.36
B3	-0.91	-0.20	18900	-1.94
B5	-0.72	-0.16	15300	-1.44
B6	-0.63	-0.14	14000	-1.17
B7	-0.54	-0.12	13000	-0.94
B8	-0.39	-0.09	11500	-0.61
B9	-0.25	-0.06	10180	-0.31
A0	0.00	0.00	9410	-0.15
	(B-V)	(V-R)		
B9	-0.06	0.00	10180	-0.31
A0	0.00	+0.02	9410	-0.15
A2	+0.06	+0.08	8900	-0.08
A5	+0.14	+0.16	8210	-0.02
A7	+0.19	+0.19	7920	-0.01
F0	+0.31	+0.30	7160	-0.01
F2	+0.36	+0.35	6880	-0.02
F5	+0.43	+0.40	6560	-0.03
F8	+0.54	+0.47	6190	-0.08
G0	+0.59	+0.50	6010	-0.10
G2	+0.63	+0.53	5860	-0.13
G5	+0.66	+0.54	5780	-0.14
G8	+0.74	+0.58	5580	-0.18
K0	+0.82	+0.64	5260	-0.24
K2	+0.92	+0.74	4850	-0.35
K5	+1.15	+0.99	4270	-0.66
K7	+1.30	+1.15	4030	-0.93
M0	+1.41	+1.28	3880	-1.21
M1	+1.48	+1.40	3720	-1.49
M2	+1.52	+1.50	3600	-1.75
M3	+1.55	+1.60	3480	-1.96
M4	+1.56	+1.70	3370	-2.28
M5	+1.61	+1.80	(3260)	-2.59
M6	+1.72	+1.93	(3140)	-2.93
M7	+1.84	+2.20	(2880)	-3.46
M8	(+2.00	(+2.50)	(2620)	-4.0

Table 6. Spot Fitting Parameters

Parameter	Typical Value
1. Longitude of spot 1, α_1	1.570 radians
2. Latitude of spot 1, β_1	0.785 radians
3. Inclination of system, **i**	1.50 radians (from Fitter)
4. Radius of spot 1, ρ_1	0.10 radians
5. Unit of light, **U**	1.00
6. $K_\lambda = \dfrac{\text{flux of spot}}{\text{flux in photosphere (at wavelength } \lambda \text{)}}$	
7. Limb darkening coefficient **u**	0.7
8. L_1, fractional luminosity of primary (hotter) star	0.6 (from Fitter)
9. Longitude of spot 2, α_2	5.14 radians
10. Latitude of spot 2, β_2	0.785 radians
11. Radius of spot 2, ρ_2	0.10 radians

Notes: Again, some little organization may be required to list results in a way which will draw out the data of interest, e.g.

(1) Number of adopted spots: 0, 1, or 2.

(2) Longitudes and radii of spots and their error assessments.

(3) Number of adopted parameters (L_1, L_2, K, u_1, u_2, β_1, β_2).

(4) Any further correction to the reference *apparent magnitude*, **U**.

Table 7. Sample Input File for Spot Program

```
Star: XY UMa
Date: 17, 18, & 20 Feb 89 UT
Observatory: KPNO, 50 "
Wavelength: V-band
Comparison Star: SAO 27151
Error: +/- 0.01 mag
Source: Observations at KPNO 50" by M. Zeilik and M. Rhodes


   0  11   0   10  1
  4.5300000   0.0349066
  0.7853982   0.0349066
  1.5710000   0.0500000
  0.2030000   0.0087266
  1.0020000   0.0050000
  0.0000000   0.0050000
  0.7000000   0.0050000
  0.8570000   0.0050000
  0.0000000   0.0000000
  0.0000000   0.0000000
  0.0000000   0.0000000
 1 0 0 1 1 0 0 0 0 0 0
   0.0140   0.9000   1.1000   0.0200   0.1000   0.1000
  1  2  3  4  5  6  7  8  9 10 11
  3.96000004  1.00300002
  5.03999996  0.99599999
 11.15999985  0.99419999
 12.60000038  0.99199998
 13.35599995  0.99930000
 14.76000023  0.99940002
 19.07999992  1.00559998
 20.52000046  0.99699998
 21.09600067  0.99790001
 22.50000000  0.98659998
 26.63999939  0.97280002
 27.71999931  0.97280002
 30.92399979  0.99860001
 32.32799911  0.99800003
 40.78799820  0.99370003
 42.19200134  1.02750003
 59.75999832  1.01989996
 61.88399887  1.00209999
 70.30799866  1.01559997
 71.71199799  1.01650000
270.35998535   0.97539997
277.55999756   0.97719997
285.48001099   0.97570002
286.92001343   0.97950000
296.64001465   0.98490000
298.07998657   0.98989999
306.35998535   0.99260002
307.79998779   0.99349999
314.64001465   0.99629998
316.07998657   1.00020003
340.20001221   0.99290001
341.64001465   0.98900002
```