A dynamical analysis of the observed time residuals for eclipsing binary stars

John Harrington Doolittle

The University of Montana

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A DYNAMICAL ANALYSIS OF THE OBSERVED TIME RESIDUALS FOR ECLIPSING BINARY STARS

By

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B.A. Physics, University of Montana, 1973

Presented in partial fulfillment of the requirements of the degree of

Master of Arts

UNIVERSITY OF MONTANA

1976

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Date Sept 30, 1976
A Dynamical Analysis of the Observed Time Residuals for Eclipsing
Binary Stars (174 pp.)

Director: Thomas E. Margrave

This thesis presents a method of analysis for determining the
masses and dynamics of unseen companion bodies whose presence
about an eclipsing binary star may be inferred from the cyclic
variation in residuals of the observed times of eclipse. Application
to the eclipsing binary system RZ Cassiopeiae indicates that
the observed time residuals may be the result of the motion of two
unseen companions of spectral types M3-M5. Included are FORTRAN
computer codes which predict future eclipses, create and manipu­
late O-C residual data files, and fit observations with a theoret­
ical O-C residual curve generated by a three-body dynamical
interaction model. A tabulation of time residuals is given for
fourteen eclipsing binary stars.
ACKNOWLEDGEMENTS

This study has been supported in part by University of Montana Small Research Grant 841-3R, which has allowed the author to make eclipsing variable star observations at the Blue Mountain Observatory. The literature search has been greatly simplified by access to the University of Pennsylvania's Eclipsing Variable Star card catalog, provided through the courtesy of R. S. Koch. Appreciation is also extended to Mrs. E. H. Doolittle for assistance in locating reference material at Wesleyan University, and to H. G. Krogstad for clerical assistance in assembling eclipsing variable star data files.
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1. O-C RESIDUAL FILES

KO Aquilae
RY Aquarii
BF Aurigae
BF Aurigae (secondary)
44i Bootis
44i Bootis (secondary)
DO Cassiopeiae
RZ Cassiopeiae
RZ Cassiopeiae (abbreviated)
TW Cassiopeiae
XX Cephei
SW Cygni
WW Cygni
TW Draconis
TX Herculis
TX Herculis (secondary)
Z Orionis
AT Pegasi

2. FORTRAN CODE LISTINGS

Program FILCHG
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CHAPTER I

INTRODUCTION

An effect of companions on eclipsing binary stars

It has long been recognized that the presence of unseen companion bodies in motion about an eclipsing binary pair could result in the observed deviation from predicted times of occurrence for the binary eclipses. The gravitational reaction of the central pair of stars to moving companions would cause it to wander with respect to the center-of-mass (COM) of the multibody system. This wandering motion of the eclipsing binary will cause its distance from the sun to be variable. Since the speed of light is a constant, the amount of time required for light to arrive from an eclipsed binary pair is directly proportional to its distance. The variation of light travel-time with distance is exhibited in the long term variation of the residuals found by subtracting the expected time of eclipse from the observed time of eclipse. The light travel-time effect has the underlying assumption that the period of revolution of the binary pair about each other is constant. Any radial motion toward or away from the sun that the entire multibody system might have will be constant and thus adds a constant amount to the intrinsic period of the eclipsing binary pairs without affecting the amplitude of the period variation.

While the light travel-time effect has often been postulated to explain the historical behavior of certain eclipsing binary systems, no
method of analysis has yet been devised which describes the masses and time-dependent positions and velocities of the possible companions which would account for the observed residuals. A method of determining these parameters by applying a technique of fitting the residual curve using dynamical models is developed in this thesis. The method is then applied to the eclipsing binary system RZ Cassiopeiae.

Abundance of multiple-body systems

Before suggesting the existence of companions to explain the time residuals observed for the light minima of eclipsing binary systems, it is worth considering whether such systems are likely. Choosing as a representative sample of the galaxy's spiral arm population, the 253 stars found within 10 parsecs (32.62 light-years) of the sun, 42.3% are found to be single stars, while the majority (57.7%) are members of multiple star systems. It seems probable that less massive dark companions would be associated with stellar systems in even greater abundance, since the greatest gravitational interaction experienced by any one companion would most likely be due to the central pair, while the other companions would only offer secondary perturbations, and gravitational stability of the system could be expected. B. M. Oliver (1972) lists examples of several stars known to have dark companions, either through astrometric or spectroscopic studies, and concludes "that a more or less continuous spectrum of systems exists between symmetrical binaries at one extreme and single stars with a giant planet, or planets, at the other." Apparently, multiple-body systems are the rule rather than the
exception, and it is quite plausible to hypothesize low-mass companions about the central pair in eclipsing binary systems.

**Binary star classification**

Binary star systems can be classified in one or more of several categories. Stars which appear on nearly the same line of sight yet are separated by such large distances that they are not bound gravitationally, are known as optical pairs and are of little interest. Visual binary stars are also resolvable but are indeed bound. Their motion about a common barycenter, or two-body center-of-mass, is usually well described by the laws of Kepler and observations can yield a determination of their orbital elements and masses.

For many binary systems only one point of light can be seen due to its particular distance from the earth and spatial separation and the relative luminosities of the component stars. One classification of unresolved pairs is that of the astrometric binary. Although these systems often are relatively close to the earth and the apparent magnitude of one body is beyond detectability, the presence of the dark companion is seen as a wavy displacement of the visible star rather than the linear proper motion expected for a single star when sky photographs that are taken several years apart are compared. An example of an astrometric binary is Barnard's star. Explanations for the observed motions of this star have been offered which postulate the presence of one (Van de Kamp 1962, 1969a), two (Van de Kamp 1969b), or even three (Suffolk & Black 1973) unseen companions whose masses are comparable to that of Jupiter.
Spectroscopic binaries are those whose spectra show a periodic doppler effect. Much information about the projected orbit of one or both stars about the system's COM can be derived by noting the temporal manner in which the spectral lines are shifted towards the red as a star recedes and towards the blue as it approaches the point of observation. Binary stars whose motions are in a plane other than the plane of the sky (i.e. the plane whose normal is the line of sight) will have radial velocities with respect to the earth and might be expected to exhibit such a doppler effect. A maximum doppler effect for any system occurs when the system's orbital plane lies along the line of sight to earth. These systems are particularly interesting because their orientation causes each star to periodically eclipse the other and are thus referred to as eclipsing binaries. Since eclipsing binaries are also spectroscopic systems, information about the relative orbits and masses of the stars can be determined through spectroscopic analysis.

**Eclipsing binary star light curves**

The variation of the brightness of eclipsing binary stars is conveniently displayed by a graph depicting the system's apparent magnitude versus time. Usually referred to as a light curve (figure 1; Rossati, 1970), it is characterized by constant brightness except during times when eclipses cause a reduction in the amount of light reaching the observer. Since the two stars may be of different absolute magnitudes, alternate eclipses can differ in depth as measured from the near constant brightness seen during times outside of eclipse. The deeper or primary eclipse occurs when the brighter star is eclipsed by the less
Fig 1. Light curve of RZ Cassiopeiae
bright star. The secondary eclipse occurs approximately one-half period later when it is the less bright star which is being blocked from view by the brighter star. Since the light curve is repetitive, the period can be defined between any two times with the same relative phase. However, by convention the time of zero phase occurs at the midpoint of the primary eclipse.

**Predicting eclipses**

When the period (P) of an eclipsing binary is well defined, the prediction of times of occurrences of eclipses (T\text{calc}) can be made simply by extrapolating from a known time of occurrence (T\text{known}) of a past eclipse.

\[ T_{\text{calc}} = T_{\text{known}} + E \times P \]  

(1.1)

The epoch (E) is necessarily an integer indicating the number of events which have occurred since the known time.

The linear elements of this expression (i.e. P and T\text{known}) are occasionally revised for binary systems which display apparent variations in eclipse period.

The difference between the observed time of an eclipse (O) and the time calculated from the linear elements (C) is referred to as an O-C time residual. A plot of O-C residuals against time, in years (appendix 1), or against epoch number, shows a temporal history of the system's eclipse period. The sign of any particular residual indicates whether that eclipse occurred earlier (negative) or later (positive) than predicted. The slope of the O-C curve shows whether the eclipse period at
that time tends to be shorter (positive) or longer (negative) than the value of the period chosen for the calculations.

Variations of eclipse period

The period variations exhibited in the O-C residual curves of eclipsing binary stars may be classified as being either continuous or discontinuous.

Continuous variations. A possible explanation of a continuous variation which is periodic could be apsidal rotation. If the relative orbit of the eclipsing pair of stars is an ellipse of eccentricity greater than zero, then a rotation of the line of apsides is possible. The effect of the variable orbital velocities associated with elliptical orbits compounded by the rotation of the orbit is to produce a sinusoidal variation in the O-C curve (figure 2). Observational evidence for apsidal rotation is found when a graph of the time residuals for the secondary minima has the same shape as the graph of primary minima residuals but is of the opposite phase (Wood, 1950). In such cases the secondary minima will oscillate about the 0.5 phase point of the light curve with a period corresponding to the period of apsidal rotation.

It is interesting to note that a light travel-time effect also is associated with these systems. The spatial excursion of the point of eclipse, however, is relatively small. Typically this effect has an O-C amplitude of less than one minute during the cycle of apsidal rotation and therefore may be considered to be of minor importance.

In other cases in which the O-C curve shows continuous variation, the secondary minima residual plot again shows the same form as the...
Fig. 2. Evidence of apsidal rotation
primary minima residual plot, but the phases of both curves are the same. In such cases the secondary minima remain fixed halfway between the primary minima, further excluding apsidal rotation as an explanation. The continuous variation exhibited by the O-C curve may then be attributable to the presence of a third body in motion about the COM of the entire system. The displacement of the eclipsing binary stars with respect to the three-body center-of-mass is observed at earth as a light travel-time effect. Translation of the three-body COM relative to our heliocentric coordinate system will cause a difference between the observed eclipse period and the absolute period. However, since this difference is a constant, it is of little consequence in a study of period variation. If there is more than one periodicity in the O-C curve it may be necessary to postulate the presence of additional bodies to satisfactorily explain the nature of the system.

Discontinuous variations. The second category of eclipsing binary O-C curves is characterized by abrupt discontinuities attributed to sudden changes in the eclipse period. The explanation for this is mass ejection by either or both of the binary's components. According to Kepler's Third Law,

\[(m_1 + m_2)P^2 = a^3\]  \hspace{1cm} (1.2)

where \(m_1\) and \(m_2\) are the masses of the components, \(P\) is the orbital period of revolution, and \(a\) is the average linear separation between the components, a change in period can be caused by either a change in separation or in either body's mass. F. B. Wood (1950) has shown that while the ejection of mass can only provide an increase in period, the
eruptive force of this action working within the gravitational field of the other star can provide either an increase or a decrease in period as a result of a change in the separation, depending on the point on the star's surface at which the thrust acts. He concludes that the greater effect is ascribed to the explosion with less importance given to the effect of mass loss and points out that sometimes the two will reinforce each other, and at other times they will cancel. Quantitatively, he finds that a mass loss of about $10^{-6}$ solar masses ($M_\odot$) can cause a period change of one second in a typical system which has a total mass of $2M_\odot$, a period of revolution of about 2 days, and a mean separation of 0.039 A.U.

In cases where the mass loss model is applicable, the primary and secondary O-C residual curves are effected equally and maintain the same phase as they do for systems classified under the unseen companion hypothesis. Therefore, for systems whose residual periodicity is not well defined, there remains some ambiguity as to which of these latter two groups it belongs. It seems likely that perturbing forces of a multiple-body system acting to change the separation between the eclipsing binary components could also cause sudden jump discontinuities in an otherwise periodically varying O-C curve.

**Selection criteria**

The intent of this study is to investigate eclipsing binary stars whose behavior is explained by the unseen companion hypothesis. Selecting suitable stars for analysis began with a search through the Flower and Cook Observatory Finding List of Eclipsing Variable Stars (1963).
Attention was given only to those entries which are noted as having variable eclipse periods. A further selection criteria imposed was that of observability at latitude 46.8°N from early July until the middle of November, the operating season of the University of Montana Blue Mountain Observatory. This allows for continuing investigation at that site of any stars determined to be of interest. An upper limit to apparent magnitude was set at 10.5. Table 1 shows the uneclipsed apparent magnitude (m_v), the depth in magnitude of both the primary (Pri.) and secondary (Sec.) eclipses, and the orbital eccentricity (e) of several candidate stars selected.

A literature search was begun with an initial objective of finding the published values of eccentricity of the relative orbits for each candidate star. Systems with an eccentricity greater than 0.10 were considered to be susceptible to apsidal rotation and were excluded from further consideration under the multiple-body hypothesis. It should be noted, however, that a study of the secondary minima behavior and a comparison of the secondary minima 0-C residuals with those of the primary minima might reveal that apsidal rotation is, in fact, not evident. In such a case, a system would warrant further consideration for application of the three-body analysis.

**Observed times of minima**

In order to determine whether the period variation noted in the Finding List mentioned above is of a continuous or discontinuous nature, it next became necessary to assemble a list of observed times of primary minima to be used in plotting an O-C curve for each candidate star.
<table>
<thead>
<tr>
<th>Star</th>
<th>$m_v$</th>
<th>Pri.</th>
<th>Sec.</th>
<th>e</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>KO Aql</td>
<td>8.5</td>
<td>1.0</td>
<td>0.1</td>
<td>0.02</td>
<td>1, 2</td>
</tr>
<tr>
<td>RY Aqr</td>
<td>9.0</td>
<td>1.3</td>
<td>0.1</td>
<td>0.00</td>
<td>1, 3</td>
</tr>
<tr>
<td>BF Aur</td>
<td>8.5</td>
<td>0.7</td>
<td>0.7</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>44i Boo</td>
<td>6.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.00</td>
<td>1, 4</td>
</tr>
<tr>
<td>DO Cas</td>
<td>8.5</td>
<td>0.4</td>
<td>0.1</td>
<td>0.13</td>
<td>1, 5</td>
</tr>
<tr>
<td>RZ Cas</td>
<td>6.4</td>
<td>1.5</td>
<td>0.1</td>
<td>0.052</td>
<td>1, 4</td>
</tr>
<tr>
<td>TW Cas</td>
<td>8.5</td>
<td>0.6</td>
<td>0.1</td>
<td>0.071</td>
<td>1, 6</td>
</tr>
<tr>
<td>U Cep</td>
<td>7.0</td>
<td>2.8</td>
<td>0.1</td>
<td>0.47</td>
<td>1, 7</td>
</tr>
<tr>
<td>XX Cep</td>
<td>8.5</td>
<td>1.1</td>
<td>0.1</td>
<td>0.14</td>
<td>1, 8</td>
</tr>
<tr>
<td>U CrB</td>
<td>7.5</td>
<td>1.2</td>
<td>0.1</td>
<td>0.13</td>
<td>1, 4</td>
</tr>
<tr>
<td>SW Cyg</td>
<td>9.5</td>
<td>2.6</td>
<td>0.3</td>
<td>0.30</td>
<td>1, 4</td>
</tr>
<tr>
<td>WN Cyg</td>
<td>10.0</td>
<td>3.8</td>
<td>0.1</td>
<td>0.00</td>
<td>1, 4</td>
</tr>
<tr>
<td>TW Dra</td>
<td>7.5</td>
<td>2.3</td>
<td>0.1</td>
<td>0.027</td>
<td>1, 4</td>
</tr>
<tr>
<td>TX Her</td>
<td>8.0</td>
<td>0.7</td>
<td>0.4</td>
<td>0.00</td>
<td>1, 4</td>
</tr>
<tr>
<td>ζ Ori A</td>
<td>3.0</td>
<td>0.2</td>
<td>0.016</td>
<td>1, 4</td>
<td></td>
</tr>
<tr>
<td>Z Ori</td>
<td>10.0</td>
<td>0.9</td>
<td>0.1</td>
<td>0.23</td>
<td>1, 6</td>
</tr>
<tr>
<td>AT Peg</td>
<td>8.5</td>
<td>0.7</td>
<td>0.2</td>
<td>0.024</td>
<td>1, 9</td>
</tr>
<tr>
<td>RT Per</td>
<td>10.5</td>
<td>1.4</td>
<td>0.2</td>
<td>0.043</td>
<td>1, 6</td>
</tr>
<tr>
<td>U Sge</td>
<td>6.5</td>
<td>3.6</td>
<td>0.035</td>
<td>1, 4</td>
<td></td>
</tr>
<tr>
<td>λ Tau</td>
<td>4.0</td>
<td>0.5</td>
<td>0.1</td>
<td>0.055</td>
<td>1, 4</td>
</tr>
<tr>
<td>TX UMa</td>
<td>7.1</td>
<td>2.2</td>
<td>0.162</td>
<td>1, 10</td>
<td></td>
</tr>
</tbody>
</table>

References:
1. Flower and Cook Ob., Finding List of Eclipsing Variables.
7. Obs., Vol. 69, p. 203.
This task was greatly simplified through access to the University of Pennsylvania's eclipsing variable star card catalog, which is a rather complete list of literature references categorized by star name. More than 200 journal articles were reviewed in varying degrees of thoroughness and a total of about 1400 heliocentric times of minima for 14 stars were compiled chronologically (appendix 1). These lists will remain archived on magnetic tape at the University of Montana where they will be accessible for future related investigations. Included in the lists are two photoelectric minima of RZ Cassiopeiae (Margrave) and one unpublished minima of AT Pegasi from observations made at the Blue Mountain Observatory.

The process of compiling the data lists was accomplished through the execution of the FORTRAN computer program code FILCHG (appendix 2). The information is written onto a disk file to facilitate further data handling. Since the code has been designed with full update capability, the data files need never be considered closed. As more eclipse times become available, either through additional journal research or through observation, these can be added.

The O-C time residuals corresponding to each observed event are determined by the linear elements of eq. (1.1). The set of values for O-C, and thus the shape of the residual curve, will depend on the choice of both a known time of primary eclipse occurrence \( T_{\text{known}} \) and the assumed eclipse period. The values of the periods used to calculate the files found in appendix 1 are those recently quoted in the literature. Although these values closely fit the current observations, it is not correct to suggest that they are the genuine orbital periods of one
binary component about the other, since the fact that the periods vary implies that they may include the effects of spatial motion (i.e. apsidal rotation or perturbations caused by unseen companions).

Plots of the O-C residuals for 14 stars are given in appendix 1. Also included there are a few plots of secondary minima O-C residuals.

**Average eclipse period**

It was found to be advantageous in this study to accept as a useful value of the eclipse period one which causes the O-C residuals of the primary minima to be symmetrically distributed about the line O-C= 0.0. This step is accomplished by the FORTRAN code AVEPER (appendix 2). Admittedly, this method is susceptible to statistical biasing due to occasional inaccurate data points or intervals of few observations, yet defining an "average period" has a definite advantage in a study which is concerned with the entire recorded history of a binary since published values usually apply only to limited time spans.

**Visual Detectability**

It is important to consider whether a hypothetical companion will be visually detectable, since if it proves to be theoretically possible to observe a companion but such an observation has not been made, then the validity of the hypothesis will be in doubt. The following analysis is pursued to insure that in any subsequent postulation of unseen companions associated with stellar systems, the hypothetical companions would indeed be non-visible.
In a statistical study on the completeness of binary discovery, W. D. Heintz (1969) adopts the "measure of difficulty" of discovering a visual binary which was previously introduced by E. Opik in 1924. When the visual binaries discovered over the past decades were plotted in a diagram relating the angular separation ($\rho$) of the two component stars to the difference in their apparent visual magnitudes ($\Delta m_v$), it was found that nearly all are located in a strip bounded by the straight lines $0.22\Delta m_v - \log \rho = 0.47$ and 0.99. Heintz assumes that three ranges of the discoverability index, defined as $D = 0.22\Delta m_v - \log \rho$, are delimited by $D = 0.5$ and $D = 1.0$. Binary pairs for which $D<0.5$ have been discovered prior to the past decades and are considered to be "completely discovered", while those with $0.5<D<1.0$ are "half discovered", and those with $D>1.0$ remain "undiscovered". In the present application $D>1.0$ is considered a criteria for non-detectability.

An eclipsing binary pair appears visually as one point of light. The detectability index ($D$), as well as intuition, suggests that a dim companion would be seen more easily if the brightness of the visible point of light was reduced to a minimum. Since this occurs at the time of primary eclipse, it is the published value of apparent visual magnitude for the midpoint of the primary eclipse which is used in the calculation of the detectability index.

To determine the apparent visual magnitude of the dark companion it is first necessary to find its fractional luminosity ($L/L_\odot$) in solar units through the mass-luminosity relation,

$$L/L_\odot = (M/M_\odot)\alpha$$

(1.3)
where $\frac{M}{M_\odot}$ is the companions fractional mass, also in solar units, and the exponent $\alpha$ is found to vary with mass as seen in Table 2 (Allen).

### Table 2

<table>
<thead>
<tr>
<th>$\log \frac{M}{M_\odot}$</th>
<th>$\log \frac{L}{L_\odot}$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.0</td>
<td>-2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>-0.8</td>
<td>-2.5</td>
<td>3.125</td>
</tr>
<tr>
<td>-0.6</td>
<td>-2.0</td>
<td>3.33</td>
</tr>
<tr>
<td>-0.4</td>
<td>-1.5</td>
<td>3.75</td>
</tr>
<tr>
<td>-0.2</td>
<td>-0.8</td>
<td>4.0</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
</tr>
<tr>
<td>+0.2</td>
<td>+0.8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Assuming a value for the companion mass and choosing the appropriate value for $\alpha$, the luminosity is easily obtained. This is used in eq. (1.4) to determine the magnitude that the companion would have if it were located at a standard distance of 10 parsecs and if radiation of all wavelengths was included. This quality is usually referred to as an absolute bolometric magnitude ($M_{bol}$).

$$M_{bol} = 4.77 - 2.5 \log(L/L_\odot) \quad (1.4)$$

The absolute bolometric magnitude of the sun is +4.77.

In order to convert the absolute bolometric magnitude of the companion into an absolute visual magnitude ($M_v$), it is necessary to add (eq. 1.5) the appropriate bolometric correction (BC).

$$M_v = M_{bol} + BC \quad (1.5)$$

As explained by T. L. Swihart (1968), "the BC is a measure of the ratio
of the total energy radiated by a star to that which it radiates in the visual region of the spectrum. The apparent visual magnitude \( m_v \) of the companion is calculated according to eq. (1.6),

\[
m_v = M_v + 5 \log(r/10)
\]  

which is dependent on the distance \( r \) in parsecs of the system from earth. Finally, the difference in apparent visual magnitude between the eclipsing binary at primary minimum and the companion is found by subtraction.

Since one parsec is the distance at which one astronomical unit subtends an angle of one second of arc, a knowledge of the distance \( r \) to the system in parsecs and the spatial separation \( d \) in A.U.'s between the companion and the visible star, as measured across the line of sight, will give the angular separation in seconds of arc at that time.

\[
\theta(^\prime\prime) = \frac{d(\text{AU})}{r(\text{pc})}
\]

The magnitude difference and angular separation are then used to calculate the index of discoverability.

\[
D = 0.22 \Delta m_v - \log \theta
\]

In application, it is easy to determine detectability of a suggested companion by examining its mass and greatest separation from the visible component of the system. A study has been made using the FORTRAN code DETECT (appendix 2) which incorporates the preceding analysis. The results shown in figure 3 show the curve corresponding to \( D = 1.0 \). In the region to the right of the curve, \( D \) is less than 1.0, indicating that such stars would be visible, while stars located in the left-hand region are considered non-detectable because \( D \) there is greater than 1.0. Since
Fig. 3. Detectability of companions
the index D is dependent on distance and apparent visual magnitude, a separate study must be made for each star system considered. Figure 3 is characteristic of RZ Cassiopeiae, whose distance is about 90 pc and mid-eclipse magnitude is about $+7.88$. 
CHAPTER II

PHYSICAL ANALYSIS

General procedure

Once it is assumed that one or more unseen companions are causing the observed variation in the eclipse period of a binary, it then becomes desirable to derive the parameters describing the companion(s) and the dynamics of the multi-body system.

A method of trial curve-fitting was used wherein a set of initial parameters is assumed and applied to a physical model which describes the relationships among all the bodies involved. Incremental time steps are then taken to simulate the hypothetical motion of the masses. The displacement of the eclipsing binary pair toward or away from the earth is used to determine the light travel-time effect during the time interval covered by eclipse minima observations. This result is superimposed on the empirically-derived O-C plot and a judgement is made as to how well the theoretical curve fits the actual history of the eclipsing binary. The best-fitting trial then gives the parameters which, based on the assumptions of the model, describe the dynamics of the system.

The models evolved with the specific case of RZ Cassiopeiae in mind. It seems evident from the double periodicity seen in the O-C residual curve of RZ Cassiopeiae (appendix 1) that at least two
companions are necessary to fit the past observations. Therefore, for considerations of spatial displacement, all analysis which follows assumes three coplanar point masses; two which represent the companions, and the third which represents the total mass of the binary pair located at the common barycenter. The simplifying assumption that the binary is reduced to a point seems to be justified in a first-order calculation, since the separation of the binary pair is typically less than 1% of the distance to the closest companion. The direction of revolution of all bodies about the system's center-of-mass is arbitrarily chosen to be counterclockwise with increasing time.

Circular orbits

The simplest model which was considered to explain the behavior of RZ Cassiopeiae is one in which the orbits of the companions are circular. The orbital motion (figure 4) of the closest companion \( m_2 \) about the two-body center-of-mass \( \text{COM}_1 \) causes a simultaneous circular motion of the binary. The total binary mass \( m_1 \) is known from published spectroscopic results. Adopting the shorter periodicity exhibited in the O-C curve as the value for \( P_1 \) (in years), and deducing a value of the distance \( r_1 \) of the binary from \( \text{COM}_1 \) from the amplitude of the O-C curve (i.e. \( r_1 = \text{O-C half-amplitude in days times speed of light in A.U./day} \)), then the companion mass \( m_2 \) in solar units, and its distance \( r_2 \) from \( \text{COM}_1 \) can easily be determined through a simultaneous solution of eq. (2.1), which is the definition of the center of mass, and Kepler's Third Law (2.2).

\[
m_1 r_1 = m_2 r_2
\]
Fig. 4. Epicyclic model
Because the angular velocity is constant, the angular displacement ($\theta$) at any time ($t$) may be found by

$$\theta = 2\pi \frac{t}{P_1} + \theta_0$$  \hspace{1cm} (2.3)

where $\theta_0$ gives the initial longitude.

The motion of the outer companion is determined by a similar treatment. The masses $m_1$ and $m_2$ are combined and assumed to be located at COM$_1$. The values of $P_2$ and $r_{12}$ are again obtained from the O-C curve and are used to determine $r_3$ and $m_3$ (see figure 4).

$$\left(m_1 + m_2\right)r_{12} = m_3r_3$$  \hspace{1cm} (2.4)

$$\left(m_1 + m_2 + m_3\right)P_2^2 = \left(r_{12} + r_3\right)^3$$  \hspace{1cm} (2.5)

The epicyclic displacement of the binary produces the expected superposition of sinusoidally-varying O-C values once the factor relating distance to time delay (i.e. the speed of light) is applied.

Through a procedure of making trial fits of the O-C curve by slightly varying the input parameters, a best fit was found for the case of RZ Cassiopeiae. The inadequacy of the model was immediately apparent. Since it is based on circular geometry, this model can only generate the sum of two symmetrical sine waves. The periodic variations seen in the O-C curve of RZ Cassiopeiae (appendix 1) show a definite skewness. Therefore it was decided to pursue the problem further by introducing elliptical orbits.
Elliptical Orbits

The method used to determine the instantaneous position of a body which is constrained to an elliptical orbit is outlined in most texts on celestial mechanics (e.g. Roy, 1965). It is necessary in this analysis to specify the following set of parameters (figure 5) which define the relative orbit and the position of the body at a known time:

- \( T \) = Period of revolution
- \( a \) = Semi-major axis
- \( e \) = Eccentricity
- \( t_0 \) = Time of periapse passage
- \( \omega \) = Longitude of the periapse

where \( \omega \) is measured with respect to the line of sight and in the direction of revolution.

The calculations begin by determining the mean angular velocity

\[
n = \frac{2\pi}{T}
\]

This is used in finding the mean anomaly \( M \) which corresponds to a specific time \( t \) through the relation

\[
M = n(t-t_0)
\]

The mean anomaly is inserted into Kepler's Equation,

\[
E = M + e \sin E
\]

which must be solved through a process of converging iteration. The resulting value of the eccentric anomaly \( E \) is used to locate the body in terms of the radius vector \( r \) measured from the focal point of the ellipse and the angular displacement \( \phi \) measured from the periapse, using the standard equations

\[
r = a(1-e \cos E)
\]
Fig. 5. Elliptical Orbits
\[ f = 2 \arctan \left( \sqrt{\frac{1+e}{1-e}} \tan \frac{\theta}{2} \right) \]  

(2.10)

The longitude of the periapse is added to refer the angular displacement to the line of sight, whence

\[ \theta = \omega + f \]  

(2.11)

The focal points of both of the orbital ellipses (figure 5) are located at the two-body center-of-mass. Although the two orbits are proportionate ellipses, the longitude of each periapse differs by 180° with respect to the other.

The companion mass and orbital semi-major axis are also found from two-body mechanics. At any time, the center-of-mass expression (eq 2.1) must hold true. At the particular time when the bodies are located at apastron, their distances \((r_1 \text{ and } r_2)\) from the COM can be related to the semi-major axes of their orbits by the following expressions:

\[ r_1 = a_1 (1 + e) \quad r_2 = a_2 (1 + e) \]  

(2.12)

Inserting these into eq. (2.1), we obtain..

\[ m_1 a_1 = m_2 a_2 \]  

(2.13)

Since the semi-major axis of the relative orbit is the sum of both true orbit semi-major axes, Kepler's Third Law may be expressed here as

\[ (m_1 + m_2)p^2 = (a_1 + a_2)^3 \]  

(2.14)

Solving eq. (2.13) for \(a_2\) and substituting into eq. (2.14)

\[ (m_1 + m_2)p^2 = a_1^3 \left(1 + \frac{m_1}{m_2}\right)^3 \]  

(2.15)

This may be solved for \(m_2\) which, in turn, may be used in eq. (2.13) to find \(a_2\).

In the calculational procedure, it is easiest to write the quartic expression (eq. 2.15) as
\[ g(m_2) = (m_2^4 + m_1 m_2^3)p^2 - a_1^3(m_2 + m_1)^3 \]  \hspace{1cm} (2.16)

and then to find the value of \( m_2 \) which causes \( g(m_2) \) to be equal to zero. By Descartes' rule of signs, there is, at most, one positive value of \( m_2 \).

At this point the analysis follows the same general sequence as for the circular model. The superposition of ellipses has a greater degree of freedom which allows the skewness displayed in the O-C curve of RZ Cassiopeiae to be fitted more easily.

It was decided to choose as the fundamental plane of the three-body motion that which is defined by the binary itself. From spectroscopy the inclination of this plane (figure 6; X, Y) for RZ Cassiopeiae is known to be about 82° (82°14, Horak, 1951) with respect to the plane of the sky (Y', Z'). Observations of light travel-time effects are due strictly to the component of the eclipsing binary pair's motion which is directed toward or away from the earth, and therefore the sine of the inclination is used to project the x-value of the binary's position onto the line of sight. According to Chambliss (1976), the value of the total binary mass of RZ Cassiopeiae is 2.4 solar masses \( (m_1 = m_a + m_b, \text{ where } m_a = 1.75M_\odot \text{ and } m_b = 0.61M_\odot) \).

The best fit obtained using an elliptical orbit model is shown as a solid curve in figure 7. The rms deviation from the observations is about \( \pm 15^\circ \). The orbital parameters which lead to this result are given in table 3. Also included there are the companion masses expressed in solar units. While these masses are great enough to be luminous stars, their luminosities are faint enough such that they are not visually detectable at their greatest separation from the central pair (see figure 3).
Fig. 6. Inclination of fundamental plane
Fig. 7. O-C curve of RZ Cassiopeiae fit by elliptical model
TABLE 3

MASSES AND ORBITAL PARAMETERS OF THE HYPOTHETICAL COMPANIONS

<table>
<thead>
<tr>
<th>Companion</th>
<th>$M/M_\odot$</th>
<th>$a$ (A.U.)</th>
<th>$P$ (yr)</th>
<th>$e$</th>
<th>$t_o$</th>
<th>$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer</td>
<td>0.37</td>
<td>31.25</td>
<td>105</td>
<td>0.85</td>
<td>1973</td>
<td>155°</td>
</tr>
<tr>
<td>Inner</td>
<td>0.32</td>
<td>11.29</td>
<td>23</td>
<td>0.4</td>
<td>1920</td>
<td>210°</td>
</tr>
</tbody>
</table>

The closeness of the fit gives encouragement that the presence of faint companions can be postulated to explain the historical patterns of the O-C residuals. Upon closer inspection, however, it is found that the gravitational attraction between the two companions at some time exceeds the attractive force exerted on either by the binary. Therefore, since it is incorrect to neglect the companion interaction, the value of this model is only in suggesting plausibility. A physically realistic configuration of the multi-body system can only be simulated by a model which incorporates all of the gravitational interactions simultaneously.

**Mutual interaction model**

The solution of the three-body problem may be found by the method of special perturbations. This requires a step-by-step numerical integration of the differential equations of motion and results in position and velocity information which describes the system at any desired time based on some initial configuration.

Reference is made in the following derivation of the equations of motion to figure 8, which shows the coplanar relationship among the three bodies. The origin is chosen at the system's center-of-mass.
Fig. 8. Three-body interaction forces
The total force $\dot{F}_i$ acting on each body is the vector sum of the individual gravitational forces $\dot{F}_{ij}$ due to the presence of the other bodies,

$$\dot{F}_i = \sum_{j \neq i} \dot{F}_{ij} \quad (2.17)$$

From Newton's Second Law

$$\dot{F}_i = m_i \ddot{a}_i = m_i \frac{d^2 \mathbf{r}_i}{dt^2} \quad (2.18)$$

Since the position and velocity of one of the bodies is most easily obtained through COM considerations once these quantities are known the other two, the analysis can proceed by concentrating on masses $m_2$ and $m_3$. Equating eqs. (2.17) and (2.18), and resolving into rectangular coordinates, we obtain

$$m_2 \frac{d^2 x_2}{dt^2} = F_{21} \cos \theta_1 + F_{23} \cos \theta_2 \quad (2.19a)$$

$$m_2 \frac{d^2 y_2}{dt^2} = F_{21} \sin \theta_1 + F_{23} \sin \theta_2 \quad (2.19b)$$

$$m_3 \frac{d^2 x_3}{dt^2} = F_{31} \cos \theta_3 + F_{32} \cos \theta_2 \quad (2.19c)$$

$$m_3 \frac{d^2 y_3}{dt^2} = F_{31} \sin \theta_3 + F_{32} \sin \theta_2 \quad (2.19d)$$

Now, according to Newton's third law and his law of universal gravitation,

$$\dot{F}_{ij} = \frac{G m_i m_j}{r_{ij}^3} \ddot{r}_{ij} = \ddot{F}_{ji} \quad (2.20)$$

where $r_{ij} = \sqrt{(x_j-x_i)^2 + (y_j-y_i)^2}, \quad \ddot{r}_{ij} = \ddot{x}(x_j-x_i) + \ddot{y}(y_j-y_i)$
Applying this to eqs. (2.19), we obtain

\[
\frac{d^2x_2}{dt^2} = -\frac{Gm_1}{r_{12}}\cos \theta_1 + \frac{Gm_3}{r_{23}}\cos \theta_2 \tag{2.21a}
\]

\[
\frac{d^2y_2}{dt^2} = -\frac{Gm_1}{r_{12}}\sin \theta_1 + \frac{Gm_3}{r_{23}}\sin \theta_2 \tag{2.21b}
\]

\[
\frac{d^2x_3}{dt^2} = -\frac{Gm_1}{r_{13}}\cos \theta_3 - \frac{Gm_2}{r_{23}}\cos \theta_2 \tag{2.21c}
\]

\[
\frac{d^2y_3}{dt^2} = -\frac{Gm_1}{r_{13}}\sin \theta_3 - \frac{Gm_2}{r_{23}}\sin \theta_2 \tag{2.21d}
\]

From the geometry shown in figure 8

\[
\cos \theta_1 = \frac{x_2-x_1}{r_{12}} \quad \sin \theta_1 = \frac{y_2-y_1}{r_{12}} \tag{2.22}
\]

\[
\cos \theta_2 = \frac{x_3-x_2}{r_{23}} \quad \sin \theta_2 = \frac{y_3-y_2}{r_{23}}
\]

\[
\cos \theta_3 = \frac{x_3-x_1}{r_{13}} \quad \sin \theta_3 = \frac{y_3-y_1}{r_{13}}
\]

Expressing the fractional masses as follows

\[
\gamma_2 = \frac{m_2}{m_1} \quad \gamma_3 = \frac{m_3}{m_1} \tag{2.23}
\]

and inserting into eqs. (2.21), we obtain
\[
\begin{align*}
\frac{d^2x_2}{dt^2} &= Gm_1 \left( \frac{-\left(x_2-x_1\right)}{r_{12}^3} + \frac{\gamma_3\left(x_3-x_2\right)}{r_{23}^3} \right) \\
\frac{d^2y_2}{dt^2} &= Gm_1 \left( \frac{-\left(y_2-y_1\right)}{r_{12}^3} + \frac{\gamma_3\left(y_3-y_2\right)}{r_{23}^3} \right) \\
\frac{d^2x_3}{dt^2} &= Gm_1 \left( \frac{-\left(x_3-x_1\right)}{r_{13}^3} - \frac{\gamma_2\left(x_3-x_2\right)}{r_{23}^3} \right) \\
\frac{d^2y_3}{dt^2} &= Gm_1 \left( \frac{-\left(y_3-y_1\right)}{r_{13}^3} - \frac{\gamma_2\left(y_3-y_2\right)}{r_{23}^3} \right)
\end{align*}
\]

Also,
\[
\begin{align*}
\frac{dx_2}{dt} &= v_{x_2} \\
\frac{dy_2}{dt} &= v_{y_2} \\
\frac{dx_3}{dt} &= v_{x_3} \\
\frac{dy_3}{dt} &= v_{y_3}
\end{align*}
\]

Eqs. (2.24) and (2.25) are the eight equations of motion for masses \(m_2\) and \(m_3\). Using the Runge-Kutta method of numerical integration, these are solved simultaneously for \(x_2, y_2, x_3, y_3, v_{x_2}, v_{y_2}, v_{x_3}\), and \(v_{y_3}\) at each step in time.

The values of \(x_1, y_1, v_{x_1}\), and \(v_{y_1}\) at each step are determined through the defining expression for the center-of-mass.

\[
0 = m_1 \dot{r}_1 + m_2 \dot{r}_2 + m_3 \dot{r}_3
\]

In rectangular component form
\[
0 = m_1 x_1 + m_2 x_2 + m_3 x_3 \\
0 = m_1 y_1 + m_2 y_2 + m_3 y_3
\]
or,
\[ x_1 = \frac{-m_2 x_2 - m_3 x_3}{m_1} \quad y_1 = \frac{-m_2 y_2 - m_3 y_3}{m_1} \]
or,
\[ x_1 = -\gamma_2 x_2 - \gamma_3 x_3 \quad y_1 = -\gamma_2 y_2 - \gamma_3 y_3 \] (2.27)

Differentiating eqs.(2.27) we find the velocity components of mass \( m_1 \) to be
\[ V_{x_1} = -\gamma_2 V_{x_2} - \gamma_3 V_{x_3} \quad V_{y_1} = -\gamma_2 V_{y_2} - \gamma_3 V_{y_3} \] (2.28)

To determine the light travel-time effect associated with the eclipsing pair's motion, it is necessary to project \( x_1 \) onto the line of sight using the sine of the inclination. The inclination will influence the companion masses and the sizes of the open orbits (figure 6) which are necessary to fit the residual curve. An inclination of 90° causes the plane of motion to coincide with the plane including the line of sight. This will result in the smallest companion masses and spatial excursions from the COM and therefore tend to minimize the interaction between the companions. As the inclination decreases, the spatial excursion must increase to give the same projected effect and the masses must increase to maintain the same periodicity. The result is that the companion interactions become stronger and maintaining stability becomes more difficult.

A simplification of the curve-fitting is made by defining the projection of the initial position of the eclipsing binary pair as the origin of a coordinate system (figure 9) to which the light travel-time effect is referred. This results in an initial light travel-time residual of zero for the model. As the integration continues in the
Fig. 9. Coordinate translation
center-of-mass coordinate system, the projected value of the binary pair's position is translated (by subtracting its initial COM coordinates) to determine the light travel-time effect at each step in time. If the integration is assumed to start at the ephemeris date, which is a time when the observed residual is also zero (see eq. 1.1), then the observed and model residual curves will coincide initially.

In the integration process, the time since the start of the calculations (i.e. the ephemeris date, by assumption) is found by adding the successive time steps. The clock may be caused to run into the future or into the past by selecting the time steps to be either positive or negative, respectively.

Units

The scale of physical systems being considered suggests that a convenient system of units to be used in the dynamical calculations is one in which distance is measured in astronomical units (1 A.U. is the mean distance between the earth and the sun), time is measured in years, and mass is measured in solar units (M⊙). This will cause velocity to be measured in astronomical units per year (A.U./yr) and the universal gravitational constant (G) to have units of

\[
\frac{(\text{A.U.})^3}{(\text{yr.})^2 \cdot M_\odot}
\]

The O-C residuals are most appropriately measured in units of days (although the conversion into minutes and seconds may offer a better perspective). Since distance is measured in astronomical units, the
light travel-time calculations are made most easily if the speed of light \( c \) is defined in astronomical units per day (A.U./day).
CHAPTER III

APPLICATION OF MUTUAL-INTERACTION
MODEL TO RZ CASSIOPEIAE

The eclipsing binary system RZ Cassiopeiae has a non-eclipsed apparent visual magnitude of $+6.38$ and a depth of primary eclipse of $1.5$ (Wood, 1950). Therefore a mid-eclipse visual magnitude of $+7.88$ was used as input for the determination of the detectability thresholds for hypothetical companions.

The distance in parsecs from the earth to the binary was found as follows. From the literature the spectral types of the visible components of the system are known (Chambliss, 1976). The corresponding luminosities are found from the Hertzsprung-Russell diagram (Novotny, 1973).

$$A2V \quad \log(L_a/L_\odot) = +1.2$$
$$G5IV \quad \log(L_b/L_\odot) = -0.1$$

The total luminosity of the pair is used to determine their absolute visual magnitude (eqs. 1.4, 1.5), assuming as a value for the bolometric correction that which applies to the more luminous star ($BC = -0.10$).

$$M_V = +1.62$$

The difference between the apparent and absolute visual magnitudes then yields a distance of about 90 parsecs through a solution of eq. (1.6).
A data file of about 600 Julian Dates of minima was compiled from the literature for RZ Cassiopeiae. About 128 of these were selected as being a representative set, since it is impractical to repeatedly plot the larger number of points during the curve-fitting sequence and since also a maximum number of 150 is allowed by the subroutine HISTRY.

An average eclipse period ($P_{\text{ave}}$) was determined for the unabridged file by an execution of the code AVEPER. The value obtained after 42 iterations was

$$P_{\text{ave}} = 1.19524788 \text{ days}$$

Both the original (RZCAS) and abridged (RZABR) data files are included in appendix 1. The O-C residuals of the abridged file have been calculated through an execution of the code FILCHG, using the average value of the period. Those of the original file have been calculated using a value of the period ($P = 1.19525189 \text{ days}$) common to much of the current literature. A comparison of the plots for the two files (appendix 1) shows the effect of changing the eclipse period.

The trial procedure of fitting the residual history by a dynamical model required many hours of patient execution of the code NTERAC (appendix 2). The sensitivity of the model caused many unproductive choices to be made of the initial parameters of the multiple-body system. These often resulted in close encounters among the bodies, sometimes causing one or both of the companions to escape* from the system. The

*In an isolated multiple-body system, one body can never completely escape the attraction of the others. The term "escape" is used here to suggest that the component of the velocity of a body which is directed away from the system COM will go to zero and then be directed towards the COM at a time much greater than the duration of this study.
procedure in the trial method became one of trying to maintain stability in the system while continually improving the fit of the model O-C curve to the observations by refining the input.

The orbital parameter input mode was chosen during the initial execution of the code, since approximate values of the binary orbital periods and semi-major axes could be estimated from the O-C curve. A double periodicity is exhibited by the curve and therefore two companions were assumed. The starting values of orbital periods and semi-major axes due to assumed inner and outer companions were estimated to be 25 years, 1.3 A.U., and 100 years, 3.5 A.U., respectively.

The analysis had adjusted the model O-C value to be zero at the initial time through a spatial coordinate translation and therefore the placement of the O-C curve which resulted from the model was found to be sensitive to the input values of the longitudes of periapsides chosen. The initial choice was simplified by referring to figure 10, which exhibits both the horizontal and vertical translations of the O-C curve along the epoch and residual axes, respectively, which occurred when the longitudes were varied.

First consideration in the curve-fitting procedure was given to the case where the inclination was assumed to be 90°, since this case would exhibit the least companion interaction. After 67 trials, a best fit was obtained and is shown in figure 11. The rms deviation between the observed and model residual curves is $\pm 7^m39^s$ (i.e. $\pm 0.00531$ day). The center-of-mass system rectangular coordinates of position and velocity for the three bodies at the initial time (i.e. ephemeral J.D. = 2442340) are given in table 4. Also listed are the masses of the companions.
Fig. 10. Effect of the longitude of periapse on the placement of the O-C curve.
MODEL # 67: O-C RESIDUALS

Fig. 11. O-C curve fit by interaction model 67
TABLE 4
COMpanion MASSES AND INITIAL RECTangular PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>MODEL 67</th>
<th></th>
<th>MODEL 127</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>i = 90°</td>
<td></td>
<td>i = 82°14</td>
</tr>
<tr>
<td></td>
<td>BINARY</td>
<td>INNER</td>
<td>OUTER</td>
</tr>
<tr>
<td></td>
<td>PAIR</td>
<td>COMPANION</td>
<td>COMPANION</td>
</tr>
<tr>
<td>m_y = +7.88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d = 90 pc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M/M_⊙</td>
<td>2.4</td>
<td>0.263</td>
<td>0.288</td>
</tr>
<tr>
<td>X (AU)</td>
<td>-2.83234</td>
<td>14.86341</td>
<td>-41.00514</td>
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<td>V_X (AU/YR)</td>
<td>1.30292</td>
<td>-0.35300</td>
<td>0.52601</td>
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<tr>
<td>V_Y (AU/YR)</td>
<td>2.00634</td>
<td>-1.21160</td>
<td>2.19624</td>
</tr>
</tbody>
</table>

44
in solar units. The equivalent orbital parameters are not presented because the motion of the companions relative to the binary exhibits continuous variation of the orbital parameters, and therefore the instantaneous values may not be representative of the mean orbits.

In the spatial plots of the binary and companion motions (appendix 3) the positive x-axis is directed towards earth. Model 67 has been allowed to run for 6300 years into the past and 2000 years into the future and shows no sign of becoming unstable. Although an extended investigation gives insight into the stability of a system, it should be noted that round-off error becomes significant after such a long integration period, and that the model becomes less valid with increasing time.

The second model considered was constrained to a plane of motion whose inclination was 82°14 with respect to the plane of the sky. This also is the inclination of the fundamental plane of the central binary pair's revolution about each other, and thus it has the aesthetic appeal of coplanarity which might be attributed to a common origin for all four bodies.

After an additional 60 trials (i.e. model 127), a best fit for this inclined orientation was found as is shown in figure 12. The resulting rms deviation between the curves is $\pm 9^{m}30^{s}$ (i.e. $\pm 0.0066$ day). Again the companion masses and rectangular position and velocity components corresponding to the initial time are listed in table 4. A comparison of the two models shows that a change in inclination of only $8^0$ requires the companion masses to increase by 10-15% to maintain a fit of the residual curve and therefore increases the likelihood of strong interactions between them.
Fig. 12. O-C curve fit by interaction model 127
Model 127 has been run for about 3,000 years as seen in the spatial plots in appendix 3. It appears to remain stable for at least 800 years into the future and for more than 300 years into the past. However at about year -350 a close interaction occurred, causing the outer companion to be thrown far out into space. It exceeded the detectability threshold at about year -382 and remained visible until about year -534. The system then seemed to be well-behaved until about year -1180 when another close encounter between the companions caused the two to capture each other. The newly-formed pair revolved about a common barycenter while containing to orbit the eclipsing binary. At the end of one orbit, the central pair exerted a large enough perturbation on the companion pair to again cause the outer companion to be thrown far from the COM, becoming visible again at about year -1334. This rather wild motion continued as is seen in the spatial plots.

Although model 127 gave an adequate fit to the observed O-C residual curve, it is unlikely that such a system could maintain stability for a time span approaching the age of the main sequence A2 component of the eclipsing binary (2 billion years maximum). On the other hand, the model's behavior suggests that relatively short-lived gravitational encounters between stars which are migrating through space can occur and result in the dynamical effect which is observed in the O-C residuals.

If the investigation is restricted to systems which fit the observed behavior yet remain stable over a long period of time, it then appears that the possible companion masses would be smaller than those found in model 127 and that the inclination of the companion orbital plane would be greater than 82°. Since the masses would be at least as
great as those of model 67 to account for the amplitude of the residual curve, these two models may be regarded as bracketing possible companion masses for the eclipsing binary system RZ Cassiopeiae. Apparently the companion bodies are red dwarf stars of spectral type M3-M5.
Additional credibility would be given to a hypothetical companion model if it explained the observed radial velocity residuals while fitting the photometric O-C curve. The binary orbital elements are determined through a trial procedure of fitting the spectroscopic radial velocity curves which have been observed over several consecutive revolutions. Historically these orbital elements have been the subject of continual revision. If instead of revising the elements, an investigator were to assume some average set, he might notice that the long term residuals between the observed and model radial velocity curves have a periodic behavior which could be explained by a spatial motion of the binary pair, caused through interaction with companions.

Figure 13 shows a typical radial velocity residual curve associated with an interaction model (#67) which also fits the observed light travel-time residuals of an eclipsing binary. The amplitude of this curve is about 4 km/sec, which is twice as large as that used by A. H. Batten and E. L. van Dessel (1975) to support their hypothesis of a third body orbiting about the spectroscopic binary 70 Ophiuchi.

A suggested further procedure, then, in the analysis of eclipsing binary stars with periodic O-C curves and extensive spectroscopic
MODEL # 67: RADIAL VELOCITY RESIDUAL

Fig. 13
observations, is to assemble from the literature a data file containing radial velocities and corresponding times. Assuming a set of binary orbital elements, the residuals of the observed radial velocities could be determined for each date. These values then could be read into the interaction model code NTERAC and displayed on the plot (figure 13) containing the radial velocity residuals of the model. The most probable model would be one which simultaneously gives a best fit to both the eclipse minima residuals and radial velocity residuals.

**Reduced O-C residuals**

Figure 14 shows the difference between the observed O-C residual values and the corresponding values which result from the hypothetical interaction of a binary with companions. The reduced residual curve offers a convenient way of estimating whether or not there may exist undetected periodicities which might be attributable to additional unseen companions. A good fit of the O-C curve should produce a reduced residual curve which shows observational scatter or noise which is equally distributed about the abscissa.

**Osculating orbital elements**

How far in time a model can be used to represent the interactions between bodies is limited by the real time required to make the necessary calculations. An interesting further project which could be undertaken would be to write a subroutine to determine the osculating orbital elements (ref. Danby, 1962) at specific intervals during the dynamic calculations of the code NTERAC. It would then be possible to
MODEL # 67: REDUCED O-C RESIDUALS

Fig. 14
execute the model for a time period long enough to show patterns of variation in the orbital elements of the companions. A variation-of-parameters technique could then be used to make the large calculational steps necessary to reconstruct the motions of the system at a time several million or even billions of years ago. This method has been applied to the orbit of Pluto by Bensen and Williams (1971), who used time steps of 500 years.

**Error control**

Round-off error is cumulative as the number of calculation steps increases. It could be reduced by using double precision for all variables used in many steps. Since this requires more core storage, however, it is preferable to reduce the step size in the integration scheme, since the error associated with a fourth-order Runga-Kutta method varies as the fifth power of the change in step size.

Although the increased number of steps would increase round-off error, the result is still a gain in accuracy. To see the effect that changing the step size has on the results, model 67 was run twice for 200 years using step sizes of 0.01 year and 0.10 year. It was found that in this relatively stable model the two trials gave differences in position vectors for each body of less than $3 \times 10^{-7}$ A.U. in each year and differences in velocity vectors of less than $1 \times 10^{-7}$ A.U./YR in each year. Since the accuracy gained by reducing the step size by a factor of ten is very small in a stable case, the larger step size may be used to expedite the trial fitting procedure. When a near fit is found, the step size may be reduced to obtain the final fit.
An additional refinement to the code NTERAC would be to introduce a subroutine which would continually adjust the integration step size to a maximum value which would still maintain an acceptable error tolerance. This could be done by making a parallel integration at each step in time using a lower-order scheme such as Simpson's method. A comparison of the results of the two methods at the end of each step would determine if the next step should be integrated with the same or an even larger step size, or whether the previous step should be repeated using a reduced step size. The computation time lost in making the additional calculations is outweighed by the gain resulting from the use of the largest allowable step size (Strack, 1963). This method would be most important in cases where close encounters require very small step sizes to maintain accuracy.

**Minimizing companion interactions**

The analysis which has been presented has considered only those cases in which the companion motions are coplanar with the same direction of revolution as the central pair. It is possible that two companions could revolve in opposite directions about a binary. During a close encounter in such a case, each body would spend less time within the other's sphere of influence, and therefore the interaction would be less severe. If the constraint of coplanarity is removed, the probability of a close encounter is decreased. These two additional degrees of freedom could be used to fit O-C residual curves in systems where otherwise the trial procedure suggests that no stable configuration fits the O-C residuals.
Predictions

A test of how well a hypothetical model describes an actual system is its ability to make predictions. Figure 11 and 12 show that the trend of both models 67 and 127 is that eclipses of RZ Cassiopeiae which occur shortly after the ephemeris Julian date will be observed to occur slightly earlier than predicted by the linear elements of eq. (1.1). Since the ephemeris Julian date (i.e. model year = 0) corresponds to late 1974, indication of whether either model correctly predicts the observed trend can be expected by 1980 or 1985.

As more observations are made for an eclipsing binary, the O-C residual curve will further reveal its behavior. Continual revision of the fitting parameters will then better define the system. Although the controversy of explaining the apparent variation in the eclipse period of RZ Cassiopeiae continues, the results given in the preceding chapter give support to the hypothesis that the binary is experiencing a perturbation caused by two red dwarf companion stars.
CHAPTER V

SUMMARY

The observed time residuals for some eclipsing binary stars may be caused by a light travel-time effect produced by unseen companion bodies. An object which has sufficient mass to cause a measurable perturbation of its central binary pair may be unseen because it is "of low luminosity, a faint dwarf, close to and lost in the image of the primary star or too faint to be recorded photographically, even at a large angular separation from the primary" (Van de Kamp, 1975). While the companion hypothesis for explaining eclipse time residuals has often been postulated, the determination of the masses and dynamics of such companions has not been rigorously pursued.

A method of deducing the masses and dynamics of unseen companions associated with eclipsing binary stars is presented in Chapter II. The general technique applied uses a physical model to generate light travel-time residuals which fit the observations by adjusting the assumed values of companion masses and their initial positions and velocities. Models employing circular or elliptical orbits of two companions about the central binary pair are considered and discarded since a substantial interaction between the two companions is not included by superimposing the simultaneous two-body analyses. Allowance for the mutual interaction among all bodies in the system results in a three-body problem.
which can only be solved numerically. The Runge-Kutta method of inte-
gration is encoded into the Fortran program NTERAC (appendix 2), which
solves the eight simultaneous equations of motion (eqs. 2.24, 2.25)
to describe the dynamics of the system at each step in time.

Application of the mutual-interaction model to the eclipsing binary
star RZ Cassiopeiae is described in Chapter III. These results indicate
that the companions, whose presence is postulated in order to explain
the observed eclipse time residuals of that system, have masses between
0.26 and 0.33 solar masses. If the companions are considered to be
main-sequence stars, they would be of spectral type M3-M5.

A hypothesis reveals its validity through its ability to make cor-
rect predictions. The fit of a model to the observed eclipse time
residuals of RZ Cassiopeiae has been extrapolated into the future
(figure 11). A discernible change in the eclipse time residuals and in
the radial velocity of the binary pair is predicted by 1985.
APPENDIX 1

O-C RESIDUAL FILES

Observations of eclipsing variable star minima are generally reported as heliocentric Julian dates. Quite often an observer will fail to include in his publication the accuracy of his results. By noting the method of observation, a typical value for its accuracy may be assigned through reference to table 5.

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In the following plots of the O-C residuals of eclipsing binaries which exhibit variable periods, year zero corresponds to January 1, 1980. Residual values are indicated by an asterisk (*) with crosses (+) located above and below to indicate the observational accuracy. The eclipse periods are given in units of days.
In the tables of eclipsing binary minima, the observational accuracies and O-C residuals are given in units of days. Julian dates are truncated to show only five digits to the left of the decimal (e.g. 2442000.1234 will be entered as 42000.1234).
KOAOI, PERIOD: 2.86395400

O-C RESIDUALS (DAYS)

YEARS

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**CHRONOLOGY OF 9 OBSERVATIONS OF KOASL**

TCALC = JD 41837.4710 + E * 2.36395400

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CHRONOLOGY OF 47 OBSERVATIONS OF 17002
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<td>POHL</td>
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<td>DOOLITTLE</td>
<td>BLUE MT. OBSERVATORY</td>
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</tbody>
</table>
APPENDIX 2

FORTRAN CODE LISTINGS

The Fortran codes listed in this section are stored on magnetic tape at the UM Department of Physics and Astronomy. Also available are detailed descriptions of the codes, which may be consulted during execution or modification attempts.
Program FILCHG

This Fortran code determines O-C residuals for the observed times of minima of eclipsing binary stars, using the linear elements of eq. (1.1). A disk file containing the information exhibited in appendix 1 is created by the initial execution. Later executions allow for the addition or deletion of observations and for the residuals to be recalculated using new values of the ephemeris date and period.
THIS PROGRAM CREATES, UPDATES, AND MODIFIES ECLIPSING BINARY
OBSERVATION FILES. PRESENT MAXIMUM NUMBER OF ENTRIES IS 700.
DOUBLE PRECISION TI, PERIOD, TNEW, TCH, TCK, TSAVE, O1UM, TT, T30, FN
1, TICALC, OFLT, SAVT
DIMENSION TI(700), DOBS(700), SAVT(700), HOLD(700), NPOECH(700)
1, O3P(7), O3NEW(7), SAVO(700), SAVOB(7, 700), I0(20),
20BINPT(I), 20BLAST(I)

BLANK='9'
ICOUNT=0
ITA=0

DO 10 I=1,700
  TI(I)=0.
  DOBS(I)=0.
  SAVT(I)=0.
  HOLD(I)=0.
  NEPOCH(I)=0
  SAVO(I)=0.
  DO 10 M=1,7
    O3(M, I)=BLANK
  10 SAVOB(M, I)=BLANK
  DO 20 I=1,7
    O3NEW(I)=BLANK
    O3INPT(I)=BLANK
  20 O3LAST(I)=BLANK

TYPE 30
30 FORMAT(' SPECIFY FILE NAME: ', $)
   ACCEPT 40, FILE

40 FORMAT($)
   TYPE 50
50 FORMAT(' CREATE NEW FILE(0)?/ ', ' UPDATE FILE(1)?/ ',
       ' 1' CHANGE LINEAR ELEMENTS(-1)?/ ' )
   ACCEPT 60, FILE

60 FORMAT($)
   IF(FILE)230,70,230

++ Enter new file ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++70
   TYPE 90
80 FORMAT(' SPECIFY NO. OF OBSERVATIONS')
   ACCEPT 60, IMAX
   TYPE 90
90 FORMAT(' ENTER FPHERIAL JD: ', $)
   ACCEPT 130, T1
   TYPE 100
100 FORMAT(' ENTER TIMES OF MINIMA IN CHRONOLOGICAL ORDER.')
   TYPE 110
110 FORMAT(' OBSERVERS NAME MAY BE 15 LETTERS MAXIMUM. ', /
       ' 1' REFERENCE NOTE MAY BE 20 LETTERS MAXIMUM. ', /
       ' 2' <CR> MAY BE USED WHEN INPUT IS SAME AS FOR PRECEDING ENTRY. ' )
   DO 210 I=1, IMAX
      TYPE 120, I
210 FORMAT(I5, ' ENTER JD: ', $)
   ACCEPT 130, TT(I)
   TYPE 130
130 FORMAT($)
   TYPE 140
140 FORMAT(' ENTER ACCURACY(DAYS): ', $)
   ACCEPT 150, DINPT
   TYPE 150
150 FORMAT(F)
   DOBS(I)=DINPT
   IF(DINPT.LT.0.00001) DOBS(I)=DOBS(I-1)
Ibu hORM AFC» fc M T E R 03Stf?VFR N Û  H  E  •  *  ,  / I ^  X  t  '  <M lift

ACCEPT 170O(ODINPT(M)M=1,3

180 CONTINUE

FORMAT(' ENTER REFERENCE','/20x,' '<')

ACCEPT 170O(ODINPT(M),M=4,7)

IF(ODINPT(1).EQ.BLANK)OD(M,I)=OB(M,I-1)

190 CONTINUE

FILE

200 CONTINUE

210 CONTINUE

220 CALL IFIlE(I FILE)

READ(I4,A30),IMAX,PERIOD,T1,
1(NEPCH(I),IT(I),D0BS(I),HOLD(I),(OB(J,I),J=1,7),I=1,IMAX)

WRITE(I6,330),IMAX,PERIOD,T1,
1(NEPCH(I),IT(I),D0BS(I),HOLD(I),(OB(J,I),J=1,7),I=1,IMAX)

230 CONTINUE

240 CALL IFIlE(I FILE)

READ(I4,A30),IMAX,PERIOD,T1,
1(NEPCH(I),IT(I),D0BS(I),HOLD(I),(OB(J,I),J=1,7),I=1,IMAX)

WRITE(I6,330),IMAX,PERIOD,T1,
1(NEPCH(I),IT(I),D0BS(I),HOLD(I),(OB(J,I),J=1,7),I=1,IMAX)

250 CONTINUE

260 CONTINUE

ACCEPT 60,NEPH

IF(NEPH.EQ.0)GO TO 260

270 CONTINUE

280 CONTINUE

290 CONTINUE

300 CONTINUE

ACCEPT 60,INDEX

IF(INDEX.EQ.0)GO TO 330

INDEX=INDEX-1COUNT

IMAX=IMAX-1

JTOP=IMAX

IF(INDEX.GT.IMAX)JTOP=INDEX

DO 320 J=INDEX,JTOP

IT(J)=IT(J+1)

D0BS(J)=D0BS(J+1)

310 CONTINUE

CONTINUE

ICOUNT=ICOUNT+1

GO TO 290

CONTINUE

CONTINUE

CONTINUE

END
MNUM = MNUM + 1
ACCEPT 130, TNEW
IF (TNEW.LT.1.) GO TO 510
C INCLUDE FOLLOWING STATEMENT IF NEW OBSERVATIONS GIVEN AS N.E.A
C TNEW = TNEW + 378860.5 - 400000.0
TYPE 140
ACCEPT 150, DINPT
DOBLIST = DOBNFW
DOBNEW = DINPT
IF (DINPT.LT.0.00001) DOBNFW = DOBLST
TYPE 160
ACCEPT 170, (OBINPT(M), M=1, 3)
DO 360 M = 1, 3
OBLAST(M) = OBNEW(M)
DOBNEW(M) = OBINPT(M)
IF (OBINPT(1).EQ.BLANK) OBNEW(M) = OBLAST(M)

CONTINUE
TYPE 190
ACCEPT 170, (OBINPT(M), M=4, 7)
DO 370 M = 4, 7
OBLAST(M) = OBNEW(M)
DOBNEW(M) = OBINPT(M)
IF (OBINPT(4).EQ.BLANK) OBNEW(M) = OBLAST(M)

CONTINUE
DO 480 K = 1, IMAX
IF (TT(K).LT.TNEW) GO TO 450
MCOUNT = 0
DO 380 M = 1, IMAX
CHECK = DOBS(TNEW - TT(M))
IF (CHECK.GT.PERIOD) GO TO 390
MCOUNT = MCOUNT + 1
ID(MCOUNTER) = K
CONTINUE
IF (MCOUNT.EQ.0) GO TO 420
TYPE 390
FORMAT (" SIMILAR MINIMA!")
TYPE 400, (ID(M), DOBS(ID(M)), (OR(J, ID(M)), J = 1, 7), M = 1, MCOUNT)
FORMAT (20 (F12.5, F10.5, 2X, 3A5, 2X, 4A6/))
TYPE 410
FORMAT (" TYPE (1) TO DISREGARD NEW ENTRY, <CR> TO PROCEED!")
ACCEPT 60, MGO
IF (MGO.EQ.1) GO TO 350
CONTINUE
SAVT(K) = TNEW
SAVD(K) = DOBNFW
DO 430 M = 1, 7
SAV03(M,K) = OBNEW(M)
LBEG = K + 1
IMAX = IMAX + 1
DO 450 L = LBEG, IMAX
SAVT(L) = TT(L - 1)
SAVD(L) = DOBS(L - 1)
DO 440 M = 1, 7
SAV0B(M,L) = OB(M,L - 1)
CONTINUE
GO TO 500
SAVT(K)=TT(K)
SAVR(K)=OBS(K)
DO 470 M=1,7
470 SAV0(M,K)=O8(M,K)
480 CONTINUE
IMAX=IMAX+1
SAVT(IMAX)=TNEW
SAV0(IMAX)=OBSNEW
DO 490 M=1,7
490 SAV0(M,IMAX)=OBSNEW(M)
500 DO 520 I=1,IMAX
   TT(I)=SAVT(I)
   OBS(I)=SAVR(I)
   DO 510 M=1,7
510 OBS(M,I)=SAV0(M,I)
520 CONTINUE
GO TO 350
530 TYPE 220,TT(I),OBS(I),(O8(J,I),J=1,7),I=1,IMAX
540 TYPE 550
550 FORMAT(' ENTER PERIOD.'),
   IF(P0UM.EQ.0.0)GO TO 560
   PERIOD=P0UM
560 CONTINUE
C ++++++LINEAR DETERMINATION OF O-C ++++++++---------
570 SM=Q.
   TEST=PERIOD/2.
   DO 600 I=1,IMAX
   T0B=TT(I)
   NBEG=OBS(T0B-T1)/PERIOD-2.
580 CONTINUE
C ++++++CALCULATE TIME OF MINI---------------
DO 580 N=NBEG,1000000
FN=N
   IF(T0J.LT.T1)FN=-FN
   NPOCH(I)=FN
   TCALC=T1+FN*PERIOD
   DELT=OBS(T0B-TCALC)
   IF(DELT.GT.TEST)GO TO 580
   OMINC=TOB-TCALC
   GO TO 590
580 CONTINUE
590 CONTINUE
   OMINC(I)=OMINC
   SUM=SUM+OMINC*OMINC
500 CONTINUE
   FMAX=IMAX-1
   DIV=SQRT(SUM/FMAX)
C ++++++++OUTPUT STAGE ++++++++---------
610 TYPE 620,PERIOD,OFV
620 FORMAT(4X,' PERIOD=',1F015.3,' GIVES MINIMUM RMS
   OF VARIATION=',1PE12.6)
   CALL OFIL(1,FILE)
   PRINT 240,FILE,IMAX,T1,PERIOD
   PRINT 240,FILE,IMAX,PERIOD,T1,
   IF(NPOCH(I),TT(I),OBS(I),HOLD(I),(O8(J,I),J=1,7),I=1,IMAX)
   WRITE(1,630),IMAX,PERIOD,T1,
   IF(NPOCH(I),TT(I),OBS(I),HOLD(I),(O8(J,I),J=1,7),I=1,IMAX)
630 FORMAT(I10,2D20.10/,700(I7,017.10,F8.5,F9.5,2X,3A5,2X,4A5/))
540 END FILE 1
END
Program AVEPER

This code employs a method of iteration to find a value of the eclipse period for which the sum of all positive and negative O-C residuals considered approaches zero. The average period thus obtained is determined to nine decimal places and can be used to modify the original data file through the execution of PERCHG.
C COMPUTES ECLIPSE PERIOD WHICH GIVES AVERAGE OF ALL C O-C VALUES NEARLY EQUAL TO ZERO.
IMPLICIT DOUBLE PRECISION (A-H,P-Z)
DIMENSION TT(800),OB(7)
COUNT=0
ITAB=0
TYPE 10
10 FORMAT(' SPECIFY FILE NAME:',I)
ACCEPT 20,FILE
20 FORMAT(A5)
CALL IFILE(1,FILE)
READ(1,140),IMAX,PERIOD,T1,
1(DUM,TT(I),DUM,DUM,(OB(J),J=1,7),I=1,IMAX)
TYPE 30,FILE,PERIOD,IMAX
30 FORMAT(' INPUT FILE ',A5,' WRITTEN WITH PERIOD=1815.9,
1" AND CONTAINS 10 TIMES OF MINIMA.
PERIOD=PERIOD.*1.0004
IPER=IPER
PERIOD=PERIOD.*1.0D-04
LINEAR DETERMINATION OF O-C +++++++++++++++++++++++++++++++
ISTOP=0
PERSp=1.0E-04
SM=0
TEST=PERIOD/2.
DO 70 I=1,IMAX
TOB=TT(I)
NBEG=OABS(TOB-T1)/PERIOD*2.
CALCULATE TIME OF MINIMA
DO 50 N=NBEQ,100000
FN=N
IF (TOB.LT.T1)FN=-FN
TCALC=T1+FN*PERIOD
DEL=OABS(TOB-TCALC)
IF (DEL.LT.TEST)GO TO 50
DIF=TOB-TCALC
GO TO 60
50 CONTINUE
60 CONTINUE
SUM=SUM+DIF
70 CONTINUE
ISENS=1
IF (SUM.LT.0.)ISENS=-1
IF (ISTOP.EQ.0)ISENS=ISENS
ISTOP=ISTOP+1
IF (ISTOP.LT.100)GO TO 90
TYPE 80
80 FORMAT(' STOPPED AT 100 TRIALS')
STOP
30 CONTINUE
P9=P0
P0=PERIOD
S9=SO
SO=SUM
TYPE 100,ISENS,LSENSE,PERIOD,SUM
100 FORMAT(215,2(1PD20.12))
IF (ISENSE.EQ.LSENSE)GO TO 110
PERIOD=PERIOD-1.1*PERSp
PERSp=PERSp/10.
110 PNEW=PERIOD+PFRSTP
SEND=PFRSTP
IF (SEND.LT.1.E-10) GO TO 120
PERIOD=PNEW
GO TO 40
C
OUTPUT STAGE

120 TYPE 130,P9,S9,ISTOP
130 FORMAT(// 'PERIOD=' ,1PD15.9/, ' ABSOLUTE DEVIATION=' ,
11PD15.6/,I5, ' TRIALS.' )
140 FORMAT(I10,2D20.10/,800/I7,J17.10,F8.5,F9.5,2X,3A5,2X,4A5/)STOP
END
Program DETECT

This Fortran code is used to determine the detectability of a low luminosity companion which is in the proximity of a brighter star or close binary. The input parameters which must be specified by the user are the distance in parsecs from the earth to the stellar system and the apparent visual magnitude of the visible central star(s). The output is given in a data file which may easily be plotted on the Calcomp plotter as shown in figure 3.
PROGRAM TO DETERMINE VISUAL DETECTABILITY OF COMPANIONS.

STEPS THROUGH MASSES FROM 0.01 TO 1.60 (M/MSUN) AND
FINDS SEPARATIONS (AU) AT WHICH DETECTABILITY INDEX C=1.0.

DIMENSION BOLM(30), BOLC(30), FMASS(150), SEPAU(150)
1, FLM(30), ALPH(150)

DATA BOLM/22, 0, 13.1, 12.0, 11.5, 11.0, 10.5, 9.9, 8.7, 8.7, 7.9, 7.5  
1, 7.2, 6.8, 6.6, 6.1, 6.0, 5.8, 5.5, 5.1, 4.9, 4.6, 4.4, 4.3, 5.3, 3.3, 3.0  
2, 2.4, 2.2, 2.1/

DATA BOLC/-5.8, -5.8, -4.6, -4.0, -3.4, -2.9, -2.6, -2.3, -2.0, -1.71  
1, -1.45, -1.17, -0.99, -0.62, -0.30, -0.09, -0.07, -0.05, -0.04, -0.03, -0.02, -0.01, 0.04, -0.03/  
DATA FLM/-3.0, -2.1, -0.8, -0.5, -0.2, -0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.3, 2.0, 2.4, 2.9, 3.0, 3.3, 3.75, 4.0, 4.2, 4.4, 4.5, 4.7/

DATA ALPH/2.9, 2.9, 3.1, 3.3, 3.3, 3.75, 4.0, 4.2, 4.4, 4.5, 4.7/

TYPE 10  
10 FORMAT(' ENTER DISTANCE(PG): ', 3)
ACCEPT 20, DIST
20 FORMAT(' ENTER APPARENT VISUAL MAGNITUDE AT  
1 MID-POINT OF PRIMARY ECLIPSE: ')
ACCEPT 20, APTMAG
DD 40 I=1,150
FI=I
FMSS(I)=FI*0.01
FLOGM=ALOG10(FMSS(I))

DETERMINE DIFFERENCE IN MAGNITUDE
J=7
CALL INTRP(FLM, ALPH, FLOGM, ALPHA, J)
XLUMI=FMSS(I)**ALPHA
BOLMAG=4.77-2.5*ALOG10(XLUMI)
J=30
CALL INTRP(BOLM, BOLC, BOLMAG, BC, J)
ABMAG=20L MAG+BC
APTMAG=ABMAG+5.5*ALOG10(DIST/10.)
DELMAA=ABS(APTMAG-APTMAG)
SEPLOG=0.22*DELMAA 1.0
SEPSEC=10.**SEPLOG
SEPAU(I)=SEPSEC*DIST

CONTINUE
50 FORMAT(150, (?F10.2/))
C WRITE FILE FOR CALCMP PLOTTER.....
C CALL OFILE(1,'GRAPH')
WRITE(1,60)
C WRITE(1,60)
60 FORMAT('GRAPH01',/  
1'TITLE13DETECTABILITY',/  
2'XAXIS15SEPARATION (AU)' ,/  
3'YAXIS23COMPANION MAss (M/4SUN)',/  
4'SPEC0.0 150.0 0.0 1.50 1.1 15 15 .02 3 3',/  
5'DATA 150')
WRITE(1,50), (FMSS(I), SEPAU(I), I=1,150)
WRITE(1,70)
70 FORMAT('PLOT 020107',/  
1'ST OP')
END FILE 1
STOP
END
SUBROUTINE INTRP(X, Y, X1, F1, J)
C LINIRE INTERPOLATION SUBROUTINE.

J=NUMBER OF ENTRIES IN ARRAY.
GIVEN ARRAYS X(N) AND Y(N), SUBROUTINE WILL FIND FOR EACH VALUE OF X1 THE CORRESPONDING VALUE OF Y SUCH THAT F1 = Y(X1).

DIMENSION X(30), Y(30)
ORDER = 0
IF (Y(1) .GT. X(J)) ORDER = 1
I = 1
10 IF (ORDER .GT. 0) GO TO 20
IF (X(I+1) - X(I)) 30, 40, 40
20 IF (X(I+1) - X(I)) 40, 40, 30
30 I = I + 1
40 IF (I + 1 - J) 10, 40, 40
F1 = (X(I+1) - X(I)) * Y(I) + (X1 - X(I)) * Y(I+1)
F1 = F1 / (X(I+1) - X(I))
RETURN
END
Program NTERAC

This code makes the dynamical calculations of the three-body mutual interaction model and displays the resulting light travel-time effect on a plot of the O-C residuals observed for an eclipsing binary star. As shown in figure 15, the main routine CONTRL directs the logical flow of information through several subroutines.

The initial position, velocity, and mass must be known for each body before the dynamical calculations begin. This may be accomplished through either subroutines PARAM or RECTIN. Subroutine PARAM accepts the elements which describe the orbit of a binary about the two-body center-of-mass due to a companion, since these may be inferred from the observed O-C residual curve's cyclic pattern. The companion mass and orbital semi-major axis are found by subroutine MASS where the solution of the quartic equation (eq. 2.16) is found by the subroutine ZEROS, which is provided through the courtesy of its author, R. J. Hayden. Subroutine PARAM then proceeds to calculate the companion's initial position through a converging iteration of Kepler's Equation as described previously (eqs. 2.6, 2.11). The rectangular components of the position are found in the usual manner. The expressions which yield the velocity components are obtained by differentiating the position equations as outlined in a NASA Technical Note (Strack, 1963). The analysis is repeated to account for the other companion. Finally the fractional masses are determined for each companion and are used to determine the initial rectangular position coordinates of the binary based on the three-body center-of-mass (eq. 2.27). Since the dynamical motion of the
Fig. 15. Interaction model flow chart
three-body system follows open paths rather than the constraint of orbits, the superpositioning of simultaneous two-body systems is used in subroutine PARAM only to define the initial configuration.

A more direct way of defining the initial conditions of the system is to simply enter the position, velocity, and mass of each body through subroutine RECTIN. In practice, it is difficult to choose a set of rectangular input parameters at random which will describe the initial conditions of a system which will remain stable. The subroutine RECTIN is, however, quite useful for continuing the dynamical calculations of systems whose masses, positions, and velocities are known.

The subroutine DETECT determines detectability thresholds which are the maximum separations between each companion and the binary, as measured perpendicular to the line of sight, at which the companions could be located without being detected visually. During the dynamical calculations the separation of each companion from the central binary pair is repeatedly checked against its particular threshold so that detectable cases may be recognized.

The dynamical calculations are made by subroutine DYNAMC which employs a fourth-order Runge-Kutta integration scheme. The eight functions which are called are the equations of motion (eqs. 2.24, 2.25). A plot of the motion in time of all of the bodies is made on a graphical CRT display. The displacement as a function of time of the eclipsing binary pair along the line of sight is used to generate light travel-time residual data. This is plotted on a CRT display along with the observationally-derived O-C residual file which is recalled from the disk by subroutine HISTRY. An rms deviation is calculated in order to
determine the accuracy of the fit by numerically comparing the model residual curve with the observations through the linear interpolation subroutine NTRP. An evaluation of how closely a simulated curve fits the system's past behavior guides in the selection of the input parameters for the next trial so as to achieve a better fit. The parameters which give a best fit are then considered to describe, based on the initial assumptions, a possible multiple-body system which is capable of satisfying the existing eclipsing binary star residual observations.

The code creates a permanent record of the input data for each trial as is shown in table 6. Also listed in this log are the final rectangular parameters, which are useful if further calculations are to be made. The comments are a subjective appraisal of the model.

To run the code, the source program NTERAC.F4 must be accompanied in execution by the graphical display subroutine package P40104.REL.
TABLE 6
TYPICAL MODEL LOG

<table>
<thead>
<tr>
<th>ORBIT 1</th>
<th></th>
<th>ORBIT 2</th>
<th></th>
<th>ORBIT 3</th>
</tr>
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<td>BINARY MASS</td>
<td>2.4206</td>
<td>BINARY MASS</td>
<td>2.4206</td>
<td>BINARY MASS</td>
</tr>
<tr>
<td>DISTANCE (PC)</td>
<td>75.30</td>
<td>DISTANCE (PC)</td>
<td>75.30</td>
<td>DISTANCE (PC)</td>
</tr>
<tr>
<td>APPARENT MAGNITUDE</td>
<td>7.88</td>
<td>APPARENT MAGNITUDE</td>
<td>7.88</td>
<td>APPARENT MAGNITUDE</td>
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<td>ORBITAL PERIOD</td>
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<td>ORBITAL PERIOD</td>
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</tr>
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<td>SEMI-MAJOR AXIS (AU)</td>
<td>1.1000</td>
<td>SEMI-MAJOR AXIS (AU)</td>
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<td>ECCENTRICITY</td>
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<td>PERIAPSE PASSAGE (Yr)</td>
<td>0.50000</td>
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<td>LONGITUDE OF PERIAPSE (DEG)</td>
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COMPANION ORBIT 1
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<td>BINARY MASS</td>
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<td>ORBITAL PERIOD</td>
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</tr>
<tr>
<td>PERIAPSE PASSAGE (Yr)</td>
<td>0.63255</td>
<td>PERIAPSE PASSAGE (Yr)</td>
<td>0.63255</td>
</tr>
<tr>
<td>LONGITUDE OF PERIAPSE (DEG)</td>
<td>235.50000</td>
<td>LONGITUDE OF PERIAPSE (DEG)</td>
<td>235.50000</td>
</tr>
</tbody>
</table>

NO. OF YEARS | 300 | STEP SIZE (Yr) | 0.150 |
| NTH POINT PLOTTED | 20 |

STARTING RECTANGULAR PARAMETERS

1 | GAMA | 0.11967 | X | 5.27219 | Y | -7.52947 |
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<tr>
<td>VXX</td>
<td>2.78315</td>
<td>VYY</td>
<td>1.94971</td>
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2 | GAMA | 0.13743 | X | 14.65245 | Y | 23.44932 |
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<tbody>
<tr>
<td>VXX</td>
<td>-1.67434</td>
<td>VYY</td>
<td>1.04687</td>
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<td></td>
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</tbody>
</table>

BINARY TO COMPANION A MAXIMUM SEPARATION (AU) | 17.124 |
BINARY TO COMPANION B MAXIMUM SEPARATION (AU) | 43.941 |
MAXIMUM RADIAL VELOCITY (KM/SEC) | 4.776 |
XTANG (AU) | -2.64466 |
YTRANS (AU) | 2.12152 |

FINAL RECTANGULAR PARAMETERS

1 | X | -3.39428 | Y | 11.77717 | VX | -1.19644 |
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<tbody>
<tr>
<td>VYY</td>
<td>-3.975956</td>
<td></td>
<td></td>
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</tbody>
</table>

2 | X | -34.72274 | Y | 9.69989 | VX | -3.79637 |
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</thead>
<tbody>
<tr>
<td>VYY</td>
<td>-1.34930</td>
<td></td>
<td></td>
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</table>

COMMENTS:
FROM 3 TO ~331 YR........PLOT ON CALCONEF..............
MASTER CONTROL FOR N-BODY PROBLEM SUBROUTINES.
COMMON/CONTROL/ITRIAL,G,PI,X(3),Y(3),VX(3),VY(3),FMASS(3)
 1,XTRANS,YTRANS
COMMON/STAR/DIST,APTMAG,FINC
DIMENSION WORD(35)
PI=3.14159265
G=6.6732E-08*3.1558E07*3.1559F07/1.49597893E13/
11.49597893E13*1.983E33/1.49597893E13
ISTRT=0
WRITE(5,10)
10 FORMAT('* INPUT: ORBITAL ELEMENTS(0)? OR RECTANGULAR COORDINATE
  IS(1)?',%) READ(5,20),ISWITCH
20 FORMAT(I)
WRITE(5,30)
30 FORMAT('* ENTER BINARY MASS:)',$)
READ(5,40),FMASS(1)
40 FORMAT(E)
WRITE(5,50)
50 FORMAT('* ENTER DISTANCE(PC):',$)
READ(5,40),DIST
WRITE(5,60)
60 FORMAT('* ENTER APPARENT VISUAL MAGNITUDE AT
  mid-point of primary eclipse:*)
READ(5,40),APTMAG
WRITE(5,70)
70 FORMAT('* ENTER INCLINATION OF BINARY ORBIT(DEG):',$)
READ(5,40),FINC
WRITE(5,80)
80 FORMAT('LAST TRIAL NO.=',$)
READ(5,20),ITRIAL
90 PAUSE
ITRIAL=ITRIAL+1
WRITE(8,100),ITRIAL,FMASS(1),DIST,APTMAG,FINC
WRITE(9,100),ITRIAL,FMASS(1),DIST,APTMAG,FINC
100 FORMAT('ITRIAL NO.=',I4,' BINARY MASS=',F10.5/,
  DISTANCE(PC)=',F9.2/, 'APPARENT MAGNITUDE=',F8.2/,
  INCLINATION(DEG)=',F8.2)
IF(ISWITCH.EQ.0)GO TO 110
CALL RECIN
GO TO 120
CALL PARAM
120 CALL DETECT(FMASS(2),VIS1)
CALL DETECT(FMASS(3),VIS2)
CALL DYNAMC(VIS1,VIS2,ISTRT,TIME)
130 WRITE(9,140),XTRANS,YTRANS
140 FORMAT('XTRANS(AU)=',F10.5,/ 'YTRANS(AU)=',F10.5)
WRITE(9,150),TIME
150 FORMAT('FINAL RECTANGULAR PARAMETERS:
  XAR=',F9.2)
J2=1
J3=2
WRITE(9,160),(J2,X(2),Y(2),VX(2),VY(2),
  J3,X(3),Y(3),VX(3),VY(3))
160 FORMAT(1/2,X,'X=',F10.5,/7X,'Y=',F10.5,
  1/6X,'VX=',F10.5,/6X,'VY=',F10.5)
WRITE(5,170)
WRITE(8,170)
WRITE(9,170)
170 FORMAT('COMMENTS:')
READ(5,180), (WORD(J), J=1, 36)
FORMAT(36A4)
WRITE(6,180), (WORD(J), J=1, 36)
WRITE(9,190), (WORD(J), J=1, 35)
FORMAT(2(1X,18A4)/*
ISTRT=1
GO TO 90
END
SUBROUTINE PAR1AM

ACCPTS INITIAL OSCULATING ORBITAL PARAMETERS AND
CONVITS THEM TO RECTANGULAR COORDINATE PARAMETERS.
COMMON/C0NTR1AL,ITRIAL,G,P1,X(3),Y(3),VX(71),VY(3),FM1SS(3)
1,TRANS,TRANS
COMMON/STAR/DIST,APT1MAG,FNC;
DIMENSION PERIOD(2),A(3),ECC(3),T0(2),W(2),FN(2),GAMA(2)
N=3
N=N-1
FM12=FM1SS(1)
DO 90 J=1,N
INPUT PARAMETERS ARE OF BINARY BARYCENTER ORBIT.
WRITE(5,10)
10 FORMAT(' PERIOD(YR)? SEMI-MAJOR AXIS(AU)? ECCENICITY?',
1/ PERIAPSE PASSAGE(YR)? LONGITUDE OF PERIAPSE(0RG)?'
READ(5,20),TFMP1,TEMP2,TEMP3,TEMP4,TEMP5
20 FORMAT(5F
WRITE(8,30),TEMP1,TEMP2,TEMP3,TEMP4,TEMP5
30 FORMAT(5F5,2)
WRITE(' CR> IF INPUT DATA IS THE SAME AS LAST TRIAL.....
IF (TEMP1,LT.0.01) GO TO 90
PERIOD(J)=TM1P1
ECC(J)=SQRT(1.–(1.–TEMP3*TEMP3)*SIND(FINC)*SIND(FINC))
T0(J)=TEMP4
W(J)=TEMP5*118.
IF (W(J),GT.360.) W(J)=W(J)-360.
WRITE(9,40),J,TEMP1,TEMP2,TEMP3,TEMP4,TEMP5
40 FORMAT(' BINARY ORBIT?',I2, '/ ORBITAL PERIOD=',’15X,F1.5,
1/ SEMI-MAJOR AXIS(AU)=,’10X,F10.5,
2/ ECCENTRICITY=,’17X,F10.5,
3/ PERIAPSE PASSAGE(YR)=,’9X,F10.5,
4/ LONGITUDE OF PERIAPSE(0FG)=,’3X,F10.5)
T-MP2=TFMP2/SIND(FINC)
CALL MASS(FM12,TEMP2,PERIOD(J),FM3,A(J))
FM1SS(J+1)=FM3
WRITE(9,50),J,FM1SS(J+1),PERIOD(J),A(J),ECC(J),T0(J),W(J)
50 FORMAT(' COMPANION ORBIT?',I2, '/ COMPANION MASS=',’15X,F10.5,
1/ ORBITAL PERIOD(YR)=,’11X,F10.5,
2/ SEMI-MAJOR AXIS(AU)=,’10X,F10.5,
3/ ECCENTRICITY=,’17X,F10.5,
4/ PERIAPSE PASSAGE(YR)=,’9X,F10.5,
5/ LONGITUDE OF PERIAPSE(0FG)=,’3X,F10.5)
W(J)=W(J)*PI/180.

ELIPTICAL ORBITAL ELEMENTS ARE CONVERTED TO RECTANGULAR
COORDINATES OF POSITION AND VELOCITY.
FN(J)=2.*PI/PERIOD(J)
Q=-T0(J)
ANMEAN=FN(J)*Q
E1=ANMEAN+0.5*CC(J)*ECC(J)*SIN(2.*ANMEAN)
E0L0=0.
DO 60 L=1,1000
DE=(ANMEAN-(E1-ECC(J)*SIN(E1)))/(1.–ECC(J)*COS(E1))
E1=E1+DE
DELT=ABS(E0L0-DE)
IF (DELT.LE.1.E-6) GO TO 70
E0L0=DE
60 CONTINUE
70 CONTINUE
R=A(J)*(1.–ECC(J)*COS(E1))
SJB=COS(E1/2.)
ASUB = ABS(SU3)

IF (ASUB .LT. 1.0E-30) ASUB = 1.0E-30
IF (SUB .LT. 0.0) SUB = -ASUB
IF (SUB .GT. 0.0) SUB = ASUB

TEST = SQRT((1. + ECC(J)) / (1. - ECC(J))) * SIN(F1/2.) / SU3
F = ATAN(TEST)
F = 2. * F

WF = F + W(J)

THE FOLLOWING DETERMINES X, Y, VX, VY.

X(J+1) = R * COS(WF)
Y(J+1) = R * SIN(WF)

FMU = G (FMASS(1) + FMASS(J+1))
P = R * (1. + ECC(J) * COS(F))
Q1 = ECC(J) * COS(W(J)) + COS(WF)
Q2 = ECC(J) * SIN(W(J)) + SIN(4F)
VX(J+1) = -SQRT(FMU/P) * Q1
VY(J+1) = SQRT(FMU/P) * Q2

CONTINUE

GAMA(1) = FMASS(2) / FMASS(1)
GAMA(2) = FMASS(3) / FMASS(1)

DETERMINE COORDINATE TRANSFORMATIONS: ORIGIN AT INITIAL (X1, Y1)

X(1) = -GAMA(1) * X(2) - GAMA(2) * X(3)
Y(1) = -GAMA(1) * Y(2) - GAMA(2) * Y(3)

XTRANS = X(1)
YTRANS = Y(1)

RETURN
END
SUBROUTINE MASS(IMASS, AINPUT, PINPUT, FM3, A3)
SUBROUTINE TO DETERMINE PLANET MASS AND SEMI-MAJOR AXIS.
DIMENSION XF3M(100)
COMMON/ZERO/XF3M, JM, LMAX, P, A12
COMMON/C/FM12, P, A12
JMAX=100
LMAX=6
BOT=0.0001
TOP=10.0
FINC=90.
P=INPUT
FM12=IMASS
10 FORMAT(F)
A12=INPUT/SIN0(FINC)
call ZEROS
IF(M.EQ.0)GO TO 30
IF(M.GT.1)WRITE(5,20), M
20 FORMAT('MULTIPLE SOLUTIONS TO MASS. M=',I4)
FM3=XF3M(1)
A3=A12*FM12/FM3
RETURN
30 WRITE(9,40)
WRITE(5,40)
40 FORMAT('NO MASS FOUND')
STOP
END
SUBROUTINE ZEROS

G(X) = FUNCTION WHOSE ZEROS ARE DESIRED. MUST BE WRITTEN IN
FUNCTION SUBRO.

BOT = LOWER LIMIT OF X INVESTIGATION RANGE
TOP = UPPER LIMIT OF X INVESTIGATION RANGE
JMAX = NUMBER OF INVESTIGATION INTERVALS
LMAX = NUMBER OF SQUEEZES BY FACTOR OF 10
M IS THE NUMBER OF ROOTS LOCATED IN THE INTERVAL.
RT(1), RT(2), ..., RT(M) ARE THE ROOTS FOUND.
DIMENSION RT(100)
COMMON /ZERO/ RT, JMAX, LMAX, M, BOT, TOP
A = BOT
B = TOP
FJMAX = JMAX

M = 0
DO 150 J = 1, JMAX
FJ = J
X = A + (FJ - 1) * (B - A) / FJMAX
Y = A + FJ * (B - A) / FJMAX
IF (G(X)) 10, 120, 10
10 IF (G(X) * G(Y)) 20, 150, 150
20 DO 40 K = 1, 10
FK = K
U = X + (FK - 1) * (Y - X) / 10.
V = X + FK * (Y - X) / 10.
IF (G(U)) 30, 130, 30
30 IF (G(U) * G(V)) 50, 40, 40
40 CONTINUE
50 X = U
Y = V
60 CONTINUE
S = (X + Y) / 2.
TEST TO THROW OUT INFINITIES
IF (G(S) * G(X)) 70, 100, 80
70 IF (G(S) * G(Y)) 150, 110, 90
80 IF ((G(S) - G(X)) / G(X)) 100, 100, 150
90 IF ((G(Y) - G(S)) / G(Y)) 150, 100, 100
100 R = S
GO TO 140
110 R = Y
GO TO 140
120 R = X
GO TO 140
130 R = U
GO TO 140
140 M = M + 1
RT(M) = R
150 CONTINUE
IF (G(B)) 170, 160, 170
160 M = M + 1
RT(M) = B
170 RETURN
END

FUNCTION G(X)
COMMON /C/ FM12, P, A12
G = (X * X * X * X + FM12 * X * X * X) * P * P - (FM12 + X) * A12)**3
RETURN
END
SUBROUTINE RECTI

C  COMMON/CTRL/ITRIAL,G,PI,X(3),Y(3),VX(3),VY(3),FMASS(3)
C  XTRANS,YTRANS
C  DIMENSION GAM(2)
C
C++++++INPUT MASSES & POSITIONS ++++++++++++++++++++++++++++++++++++++++++++++++++++
C
C
C
N=3
DO 30 I=2,N
IC=I-1
WRITE(5,10), IC
FORMAT(I2,' : ENTER GAMMA, X, Y : ',3)
READ(5,20), GAMMA(I-1), X(I), Y(I)
20 FORMAT(3E)
30 CONTINUE
C++++++Determine Critical Velocities ++++++++++++++++++++++++++++++++++++++++++++++++ 
DO 60 I=2,N
IC=I-1
FMASS(I)=GAMMA(I-1)*FMASS(1)
TOTMAS=FMASS(I)+FMASS(1)
X(I)=-GAMMA(I-1)*X(1)
Y(I)=-GAMMA(I-1)*Y(1)
R=SQRD((X(I)-X(1)**2+(Y(I)-Y(1))**2)
VCIPE=SRTD(G*TOTMAS/R)
VCIRX=-VCIPE*(Y(I)-Y(1))/R
VCIERY=-VCIPE*(X(I)-X(1))/R
VESCX=1.4142*VCIRX
VESCY=1.4142*VCERY
WRITE(5,40), IC, VCIRX, VCIRY, VESCX, VESCY
40 FORMAT(I2,' : CIRCULAR VELOCITY: VX=',F10.5,5X,' VY=',F10.5,1/ ' ESCAPE VELOCITY: VX=',F10.5,5X,' VY=',F10.5)
WRITE(5,50)
50 FORMAT(' ENTER VELOCITY COMPONENTS VX AND VY : ',3)
READ(5,20), VX(I), VY(I)
60 CONTINUE
X(1)=-GAMMA(1)*X(2)-GAMMA(2)*X(3)
Y(1)=-GAMMA(1)*Y(2)-GAMMA(2)*Y(3)
WRITE(5,70)
70 FORMAT(' ENTER XTRANS,YTRANS : ',5)
READ(5,20), XTRANS, YTRANS
RETURN
END
SUBROUTINE DETECT(FMASS,SEPMAU)

PROGRAM TO DETERMINE VISUAL DETECTABILITY OF COMPANIONS.
FINDS SEPARATIONS (AU) AT WHICH DETECTABILITY INDEX C=1.0.
COMMON/STAR/DIST,APTMAG,FINC

DIMENSION BOLM(30),BOLC(30),FLM(30),ALPH(30)
DATA BOLM/22.0,13.1,12.0,11.5,11.0,10.5,9.7,8.7,8.7,8.4,7.9,7.5
1,7,2,6.8,6.6,6.3,6.1,6.0,5.8,5.5,5.1,4.9,4.6,4.4,4.3,5.3,3.3,0
2,2.4,2.2,2.1/
DATA BOLC/-5.8,-5.8,-4.6,-4.0,-3.4,-2.9,-2.6,-2.3,-2.0,-1.71
1,-1.45,-1.17,-0.89,-0.62,-0.50,-0.40,-0.30,-0.24,-0.19,-0.13
2,-0.09,-0.07,-0.06,-0.05,-0.04,-0.03,-0.01,-0.01,-0.02,-0.03/
DATA FLM/-3.0,-1.0,-0.8,-0.5,-0.4,-0.2,-0.1,0.0,0,23,0,0/
DATA ALPH/2.9,2.9,3.3,3.3,3.3,3.75,4.0,4.0,23*4.0/
FLOGM=ALOG10(FMASS)

DETERMINE DIFFERENCE IN MAGNITUDE
J=7
CALL INTRP(FLM,ALPH,FLOGM,ALPHA,J)
XLU=MASS*ALPHA
BOLMA=4.77-2.5*LOG10(XLU)
J=30
CALL INTRP(BOLM,BOLC,BOLMA,BC,J)
AMAGI=BOLMA+BC
APMAI=AMAGI+5.*ALOG10(DIST/10.)
DELMA=ABS(APMAI-APTMAG)
SEPLOG=0.22*DELMA-1.0
SEPFC=10.**SEPLOG
SEPMAU=SEPFC*DIST
RETURN
END

SUBROUTINE INTRP(X,Y,X1,F1,J)

LINEAR INTERPOLATION SUBROUTINE.
J=NUMBER OF ENTRIES IN ARRAY.
GIVEN ARRAYS X(N) AND Y(N), SUBROUTINE WILL FIND
FOR EACH VALUE OF X1 THE CORRESPONDING VALUE OF Y SUCH
THAT F1=Y(X1).

DIMENSION X(30),Y(30)
IORDER=0
IF (X(I),GT.X(J)) IORDER=I
I=1
10 IF (IORDER.GT.0) GO TO 20
20 IF (X(I+1)-X1) 30,40,40
30 I=I+1
40 IF (I+1-J) 10,40,40
F1=(X(I+1)-X1)*Y(I)+((X1-X(I))*Y(I+1)
F1=F1/(X(I+1)-X(I))
RETURN
END
SUBROUTINE DYN1((VIS1, VIS2, ISTRT, TIMF)

PROGRAM TO SOLV. 3-BODY PROBLEM USING RUNGE-KUTTA INTEGRATION.

UNIT 1

T          YR
G          AU/DA
X# & Y#    AU
VX# & VY#  AU/YR
FMASS#     SOLAR MASSES
H          YR
F1 - F4    AU/YR**2
F5 - F8    AU/YR
C#1 - C#4  AU/YR
C#5 - C#8  AU

DIMENSION XSAVE(3,301), YSAVE(3,301), VSAVE(301), TSAVE(301)
COMMON/HIST/T(2,301), OMING(2,301), DOBS(150), I3AR, TMAX, ISTART
1, OIF(301)
COMMON/FACT/FACTOR, GAMA(2)
COMMON/CONT/ITRIAL, G, PI, X(3), Y(3), VX(3), VY(3), FMASS(3)
1, XTRANS, YTRANS
COMMON/STAR/DIST, APMAG, FIN;
ISTART=TSTRT
ITRIP=0
NYR=0
ISEF1=0
ISEF2=0
C=2.99792458*8.64000E04/1.49598E11
50 CONTINUE
20 FACTOR=FMASS(1)*G
GAMA(1)=FMASS(2)/FMASS(1)
GAMA(2)=FMASS(3)/FMASS(1)
C++ DYNAMICAL CALCULATIONS +++++++++++++++++++++++++++++++++++++++++++++++++++++++
WRITE(5,30)
30 FORMAT(' ENTER NUMBER OF YEARS, STEP LENGTH, AND
1 NTH POINT PLOTTED. ')
READ(5,40),(NYEAR,H,NTHPT)
40 FORMAT(I,F,1)
WRITE(9,50),(NYEAR,H,NTHPT)
50 FORMAT(' NO. OF YEARS=',I,' STEP SIZE (YR)=',F5.3,
1 '/ NTH POINT PLOTTED=',I5)
NPERYR=1./ABS(H)
NTOP=NYEAR*NPERYR
IF (H.LT.0.)NYEAR=-NYEAR
TIME=0.
60 NUM=1
NCOUNT=0
DO 70 J=1,3
XSAVE(J,NUM)=(X(J)-XTRANS)*SIND(FINC)
70 YSAVE(J,NUM)=Y(J)-YTRANS
VX(1)=-GAMA(1)*VX(2)-GAMA(2)*VX(3)
VSAVE(NUM)=VX(1)*SIND(FINC)/0.2104
TSAVE(NUM)=TIME
VMAX=0.
SEP1=0.
SEP2=0.
XMIN=0.
XMAX=0.
YMIN=0.
YMAX=0.
WRITE(9,80),TIME
FORMAT(// STARTING RECTANGULAR PARAMETERS: YEAR='",F9.2)
J2=1
J3=2
WRITE (9,90), (J2,GAMA(1),X(2),Y(2),VX(2),VY(2),
1 J3,GAMA(2),X(3),Y(3),VX(3),VY(3))
FORMAT(// /12,2X,' Y=",F10.5,/'16X,' Y=",F10.5,
1/6X,' Y=",F10.5)/6X,' Y=",F10.5))
DO 200 N=1,NTOP
TIME=TIME+H
C11=H*F1(X(2),Y(2),X(3),Y(3))
C12=H*F2(X(2),Y(2),X(3),Y(3))
C13=H*F3(X(2),Y(2),X(3),Y(3))
C14=H*F4(X(2),Y(2),X(3),Y(3))
C15=H*F5(VX(2))
C16=H*F6(VY(2))
C17=H*F7(VX(3))
C18=H*F8(VY(3))
C21=H*F1(X(2),5*C15,Y(2),5*C16,X(3),5*C17,Y(3))
C22=H*F2(X(2),5*C15,Y(2),5*C16,X(3),5*C17,Y(3))
C23=H*F3(X(2),5*C15,Y(2),5*C16,X(3),5*C17,Y(3))
C24=H*F4(X(2),5*C15,Y(2),5*C16,X(3),5*C17,Y(3))
C25=H*F5(VX(2),5*C11)
C26=H*F6(VY(2),5*C12)
C27=H*F7(VX(3),5*C13)
C28=H*F8(VY(3),5*C14)
C31=H*F1(X(2),5*C25,Y(2),5*C26,X(3),5*C27,Y(3))
C32=H*F2(X(2),5*C25,Y(2),5*C26,X(3),5*C27,Y(3))
C33=H*F3(X(2),5*C25,Y(2),5*C26,X(3),5*C27,Y(3))
C34=H*F4(X(2),5*C25,Y(2),5*C26,X(3),5*C27,Y(3))
C35=H*F5(VX(2),5*C21)
C36=H*F6(VY(2),5*C22)
C37=H*F7(VX(3),5*C23)
C38=H*F8(VY(3),5*C24)
C41=H*F1(X(2),5*C35,Y(2),5*C36,X(3),5*C37,Y(3))
C42=H*F2(X(2),5*C35,Y(2),5*C36,X(3),5*C37,Y(3))
C43=H*F3(X(2),5*C35,Y(2),5*C36,X(3),5*C37,Y(3))
C44=H*F4(X(2),5*C35,Y(2),5*C36,X(3),5*C37,Y(3))
C45=H*F5(VX(2),5*C31)
C46=H*F6(VY(2),5*C32)
C47=H*F7(VX(3),5*C33)
C48=H*F8(VY(3),5*C34)
X(2)=X(2)+C15+C25+C35+C45/6.
Y(2)=Y(2)+C16+C26+C36+C46/6.
X(3)=X(3)+C17+C27+C37+C47/6.
Y(3)=Y(3)+C18+C28+C38+C48/6.
VX(2)=VX(2)+(C11+C21+C31+C41)/6.
VY(2)=VY(2)+(C12+C22+C32+C42)/6.
VX(3)=VX(3)+(C13+C23+C33+C43)/6.
VY(3)=VY(3)+(C14+C24+C34+C44)/6.
X(1)=-GAMA(1)*X(2)-GAMA(2)*X(3)
Y(1)=-GAMA(1)*Y(2)-GAMA(2)*Y(3)
VX(1)=-GAMA(1)*VX(2)-GAMA(2)*VX(3)
VY(1)=-GAMA(1)*VY(2)-GAMA(2)*VY(3)
VTMAX=AST(VX(1)*SIND(FIND)/0.1204)
IF (VTMAX.GT.VMAX) VMAX=VTMAX
NCOUNT=NCOUNT+1
IF (NCOUNT.NE.NTHPT) GO TO 200
C++++++SAVE SPATIAL COORDS, RADIAL VELOCITY, & CHECK DETECTABILITY++++
NCOUNT=0
NUM=NUM+1
TSAVE(NUM)=TIME
DO 100 J=1,3
YSAVE(J,NUM)=(X(J)-XTRAN)*SIND(FINC)
YSAVE(J,NUM)=Y(J)-YTRAN;
IF(XSAVE(J,NUM).GT.XMAX)XMAX=XSAVE(J,NUM)
IF(YSAVE(J,NUM).GT.YMAX)YMAX=YSAVE(J,NUM)
IF(XSAVE(J,NUM).LT.XMIN)XMIN=XSAVE(J,NUM)
IF(YSAVE(J,NUM).LT.YMIN)YMIN=YSAVE(J,NUM)
CONTINUE
VSAVE(NUM)=VX(1)*SIND(FINC)/9.2104
SEP1=ABS(YSAVE(1,NUM)-YSAVE(2,NUM))
SEP2=ABS(YSAVE(1,NUM)-YSAVE(3,NUM))
IF(SEP1.GT.SEMPX1)SEMPX1=SEP1
IF(SEP2.GT.SEMPX2)SEMPX2=SEP2
IF(SEP1.LT.VIS1.OR.ISEE1.NE.0)GO TO 120
ISEE1=1
WRITE(5,110),TIME
WRITE(9,110),TIME
WRITE(9,110),TIME

110 FORMAT(' COMPANION A VISIBLE AT TIME=',F8.2)
GO TO 140

120 IF(SEP1.GT.VIS1.OR.ISEE1.NE.0)GO TO 140
ISEE1=0
WRITE(5,130),TIME
WRITE(9,130),TIME
WRITE(9,130),TIME

130 FORMAT(' COMPANION A NON-VISIBLE AT TIME=',F8.2)

140 IF(SEP2.LT.VIS2.OR.ISEE2.NE.0)GO TO 160
ISEE2=1
WRITE(5,150),TIME
WRITE(9,150),TIME
WRITE(9,150),TIME

150 FORMAT(' COMPANION B VISIBLE AT TIME=',F8.2)
GO TO 180

160 IF(SEP2.GT.VIS2.OR.ISEE2.NE.0)GO TO 180
ISEE2=0
WRITE(5,170),TIME
WRITE(9,170),TIME
WRITE(9,170),TIME

170 FORMAT(' COMPANION B NON-VISIBLE AT TIME=',F8.2)

180 IF(XMIN.GT.-200..AND.YMIN.GT.-200..AND.XMAX.LT.200..
1AND.YMAX.LT.200.)GO TO 200
IF(ITRIP.GT.0)GO TO 200
ITRIP=1
WRITE(5,190),TIME
WRITE(9,190),TIME
WRITE(9,190),TIME

190 FORMAT(' SPATIAL EXCURSION GREATER THAN 200 AU AT TIME=',F8.2)
CONTINUE
WRITE(9,210),SEMPX1,SEMPX2,VMAX

210 FORMAT(' BINARY TO COMPANION A MAXIMUM SEPARATION(AU)=',F8.3,/ 
1' BINARY TO COMPANION B MAXIMUM SEPARATION(AU)=',F8.3,/ 
2' MAXIMUM RADIAL VELOCITY (KM/SEC)=',F8.3)
C++SPATIAL CONFIGURATION PLOTTING ++++++++++++++++++++++++++++++++
C PROJECTED ON PLANE INCLUDING LINE OF SIGHT.

220 AYMIN=ABS(YMIN)
IF(YMAX.GT.AYMIN)GO TO 230
YMAX=AYMIN

230 YMIN=-YMAX
AXMIN=AES(XMIN)
IF (XMAX > AXMIN) GO TO 240
XMAX = AXMIN

YMAX = AXMIN

IF (XMAX > AXMIN) XMAX = YMAX

YMAX = XMAX

YMIN = XMIN

XMIN = XMIN * 1.34

XMAX = XMAX * 1.34

DINCX = 1.

IF (XMAX > 10.) DINCX = 10.

IF (XMAX > 100.) DINCX = 100.

DINCY = DINCX

MODE1 = 0

MODE2 = 1

ORIGIN = 0.

PAUSE

CALL ERASE

CALL SETUP(XMIN, YMIN, XMAX, YMAX, MODE1, MODE2)

CALL AXIS(ORIGIN, ORIGIN, DINCX, DINCY)

CALL HOME

NYR = NYR + NYEAR

WRITE (5, 250) ITRIAL, DINCX, NTIP, NYR

FORMAT (/ 'TRIAL NO.', 'I4, / 'SCALE (AU) = ', 'F5.0,
1/ 'NO. OF TIME STEPS = ', 'I6,
1/ 'TIME (YR) = ', 'F6)

MODE = -1

DO 250 I = 1, NUM

DO 260 J = 1, 3

CALL TIPLOT(XSAVE(J, I), YSAVE(J, I), MODE)

250 CONTINUE

CALL HOME

C+++++++Determine residuals from dynamical model ++++++++ 

DO 270 I = 1, NUM

OMINC(2, I) = -XSAVE(1, I) / C

270 CONTINUE

CALL WAIT(NWORD)

IF (NWORD.NE. 'G') GO TO 60

WRITE (5, 280)

280 FORMAT ('SAVE SPATIAL COORDS ON DISK<1> or NOT<CR> ?', 'S)

READ(5, 40), ISPACF

IF (ISPACF.NE. 0.) GO TO 340

WRITE (5, 290)

290 FORMAT ('ENTER BEGINING AND ENDING TIMES(YR) !', 'T)

READ(5, 300), TBEG, TEND

FORMAT (2F)

JTBEF = TBEG

JTED = TEND

QPLTX = 50.

IF (YMAX.GT.50.) QPLTX = 100.

IF (YMAX.GT.100.) QPLTX = 150.

IF (YMAX.GT.150.) QPLTX = 200.

IF (YMAX.GT.200.) QPLTX = YMAX

QPLTY = QPLTX * 7./ 5.

PLTX = -QPLTX

PLTY = -QPLTY

LINES = NUM/2 + 1

LINFLT = LINES - 1

CALL OFILE(1, 'SPACE')

WRITE (1, 310), ITRIAL, JTBE, JTEN, PLTX, QPLTX, PLTY, QPLTY, LINES
410 FORMAT('VERSNO3',/
1'GRAPH01',/
2'TITLF2MODEL #',I3,'::',I6,' TO',I6,' YR',/
3'XAXIS32PROJECTED ON PLANE INCLUDING LOS',/
4'YAXISO4(AU)',/
5'SPFC5',4F6.0, ' 2 2 2 .05 2 ',/
6'DATA',I4)
WRITE(1,320)((XSAVE(I,J),YSAVE(I,J),I=1,3),J=1,NUM-1)
320 FORMAT(150(12F6.1/
330 FORMAT('PLOT 01220',I5,/
1'PLOT 030420',I5,/
2'PLOT 030409',I5,/
3'PLOT 050620',I5,/
4'PLOT 050609',I5,/
5'PLOT 070820',I5,/
6'PLOT 091020',I5,/
7'PLOT 091009',I5,/
8'PLOT 111220',I5,/
9'PLOT 111209',I5,'/STOP')
END FILE 1
340 IF(NWORH.EQ. 'B')RETURN
CALL ERASE
CALL HOME
C+++++++++++++PLOT O-G CURVE ++++++++++++++++++++++++++++++++++++++++}
350 IF(ISPACE.GT.0)GO TO 380
360 WRITE(5,370)
370 FORMAT(' ENTER BEGINING TIME(#): ',F)
READ(5,370),TBEG
380 IF(TIME)390,390,400
390 TMAX=TBEG
TMIN=TBEG+TIME
GO TO 410
400 TMIN=TBEG
TMAX=TBEG+TIME
410 CONTINUE
TMAX=TMAX
IF(TMAX.LT.10.,TMAX=10.
IF(TMIN.GT.-100.,TMIN=-100.
DO 420 I=1,NUM
420 T(2,I)=TSAVE(I)+TBEG
CALL HISTORY(NUM)
RMIN=-0.1
RMAX=0.1
DINCR=10.
DINCR=0.01
CALL SETUP(TMIN,RMIN,TMAX,RMAX,MODE1,MODE2)
CALL AXITS(ORIGIN,ORIGIN,DINT,DINCR)
CALL HOME
WRITE(5,430),ITRIAL
430 FORMAT(/' TRIAL NO.' , I4)
DO 460 I=1,IMAX
IF(IBAR)440,440,450
440 MODE=-1
CALL TPL0T(T(1,I),OMINC(1,I),MODE)
GO TO 460
450 MODE=0
OCTOP=OMINC(1,I)+DINCR(I)
OCTOP=OMINC(1,I)-DINCR(I)
CALL TPL0T(T(1,I),OCTOP,MODE)
*NUM
  IF (I MODE = 1 CALL TPLOT (I (2, I), OMINC (2, I), MODE)
  CONTINUE.
  CALL HOME.
  CALL WAIT (NWORD).
  IF (NWORD EQ. 'G') GO TO 60
  IF (NWORD EQ. 'R') RETURN
  IF (NWORD EQ. 'Q') GO TO 360
C+++++++RADIAL VELOCITY RESIDUAL CURVE ++++++++000000000000000000000
  VTOP = 5,
  VBOT = -VTOP
  DINC = 1.
  CALL ERASE.
  CALL SETUP (TMIN, VBOT, TMAX, VTOP, MODE1, MODE2).
  CALL AXIS (ORIGIN, VBOT, TMAX, DINC, DINC).
  CALL HOME.
  WRITE (5, 430), ITrial, NUM.
  J = 2.
  DO 480 I = 1, NUM
  CALL TPLOT (I (J, I), VS AVE (I), MODE)
  480 CONTINUE.
  CALL HOME.
  CALL WAIT (NWORD).
  IF (NWORD EQ. 'G') GO TO 60
  IF (NWORD EQ. 'R') GO TO 360
C+++++++WRITE RESIDUAL DATA FILE FOR CALCOMP PLOT ++++++++000000000000000000000
  WRITE (5, 490)
  490 FORMAT ('SAVE RESIDUALS ON DISK (1) OR NOT<CR>/?', I)
  READ (5, 490), IRES.
  IF (IRES EQ. 0) GO TO 530
  LINES = IMAX + 1
  IF (NUM GT. IMAX) LINES = NUM + 1
  LINES = LINES - 1
  CALL OFILE (1, 'RESID')
  WRITE (1, 500), ITrial, TMIN, TMAX, LINES.
  500 FORMAT ('VERSNO', 'GRAPH01', 'TITLE25MODEL #', I3, ' O-C RESIDUALS', 'XAXIS05YEARS', 'YAXIS36EARLY', 'O-C (DAYS)', 'LATE', 'SPECS', '2F7.0', '-10.0', '0.1 2 2 2 2 0.08 2 2', 'DATA', 'I4)
  WRITE (1, 510) (IT (J, I), OMINC (J, I), J = 1, 2), VS AVE (I), DM (I),
  11 = 1, LINES)
  510 FORMAT (301 (6 F10.4/))
  WRITE (1, 520), TMAX, NUM, ITrial, TMIN, TMAX, NUM, ITrial, NUM
  520 FORMAT ('PLOT 010207', 'I5', 'PLOT 030420', 'I5', 'GRAPH01', 'TITLE39MODEL #', 'I3', 'O-C RADIAL VELOCITY RESIDUALS', 'XAXIS05YEARS', 'YAXIS12VRAD(KM/SEC)', 'SPECS', '2F7.0', '-10. 10. 2 2 2 2 0.08 2 2', 'PLOT 030520', 'I5', 'GRAPH01', 'TITLE39MODEL #', 'I3', 'REDUCED O-C RESIDUALS', 'XAXIS05YEARS', 'YAXIS36EARLY', 'O-C (DAYS)', 'LATE', 'SPECS -100. 0. -0.01 0.01 2 2 2 2 80.08 2 2', 'PLOT 010620', 'I5', 'STOP')
  END FILE 1
  530 RETURN
FUNCTION F1(X2, Y2, X3, Y3)
COMMON/FUNCT/FACTOR, GAMMA(2)
X1 = -GAMA(1) * X2 - GAMMA(2) * X3
Y1 = -GAMA(1) * Y2 - GAMMA(2) * Y3
R23 = SQRT((X3 - X2)**2 + (Y3 - Y2)**2)
R12 = SQRT((X2 - X1)**2 + (Y2 - Y1)**2)
F1 = FACTOR*((X1 - X2)/R12**3 + GAMMA(2)*Y1 - Y3)/R23**3 + GAMMA(2)*Y3)
RETURN
END

FUNCTION F2(X2, Y2, X3, Y3)
COMMON/FUNCT/FACTOR, GAMMA(2)
X1 = -GAMA(1) * X2 - GAMMA(2) * X3
Y1 = -GAMA(1) * Y2 - GAMMA(2) * Y3
R23 = SQRT((X3 - X2)**2 + (Y3 - Y2)**2)
R12 = SQRT((X2 - X1)**2 + (Y2 - Y1)**2)
F2 = FACTOR*((Y1 - Y2)/R12**3 + GAMMA(2)*(Y3 - Y2)/R23**3)
RETURN
END

FUNCTION F3(X2, Y2, X3, Y3)
COMMON/FUNCT/FACTOR, GAMMA(2)
X1 = -GAMA(1) * X2 - GAMMA(2) * X3
Y1 = -GAMA(1) * Y2 - GAMMA(2) * Y3
R23 = SQRT((X3 - X2)**2 + (Y3 - Y2)**2)
R13 = SQRT((X3 - X1)**2 + (Y3 - Y1)**2)
F3 = FACTOR*((X1 - X3)/R13**3 + GAMMA(1)*(Y2 - X3)/R23**3)
RETURN
END

FUNCTION F4(X2, Y2, X3, Y3)
COMMON/FUNCT/FACTOR, GAMMA(2)
X1 = -GAMA(1) * X2 - GAMMA(2) * X3
Y1 = -GAMA(1) * Y2 - GAMMA(2) * Y3
R23 = SQRT((X3 - X2)**2 + (Y3 - Y2)**2)
R13 = SQRT((X3 - X1)**2 + (Y3 - Y1)**2)
F4 = FACTOR*((Y1 - Y3)/R13**3 + GAMMA(1)*(Y2 - Y3)/R23**3)
RETURN
END

FUNCTION F5(VX2)
F5 = VX2
RETURN
END

FUNCTION F6(VY2)
F5 = VY2
RETURN
END

FUNCTION F7(VX3)
F7 = VX3
RETURN
END

FUNCTION F8(VY3)
F8 = VY3
RETURN
END
SUBROUTINE HIST(NUM)
C PROGRAM TO CORELATE OBServed DATA TO MODEL DATA.
C NOTE: MAXIMUM NUMBER OF TRIES IN O-C FILE IS 150.
C double PRECISION QT,QY,GT
C DIMENSION QT(150),QY(150),QNUMO(7)
COMMON/HIST/T(2,301),QMINC(2,301),QOBS(150),JTAP,IMAX,ISTART
1,DIF(301)
IF(ISTART.GT.0)GO TO 100
10 DO 20 I=1,300
T(I,1)=0.
OMINC(I,1)=0.
20 CONTINUE
ISTART=1
WRITE(5,30)
30 FORMAT(' SPECIFY INPUT FILE NAME:',5)
READ(5,40),FILE
40 FORMAT(A5)
CALL IFILE(L,FILE)
READ(1,50),IMAX,ECLPER,OT1,
1(NOMO,QT(I),DOBS(I),QY(I),(QNUMO(J),J=1,7),I=1,IMAX)
50 FORMAT(10,2020.10,150(I7,I7.10,F8.5,F9.5,2X,3A5,2X,4A5/))
WRITE(9,60),FILE,ECLPER
60 FORMAT(‘ INPUT FILE ’,A5,’ WRITTEN WITH PERIOD=’,1PD15.9)
WRITE(5,70)
70 FORMAT(‘ ERROR BARS(1) OR NOT<CR>’,3)
READ(5,80),IBAR
80 FORMAT(I)
DO 90 I=1,IMAX
T(I,1)=(QT(I)-QT1)/365.25
OMINC(I,1)=2Y(I)
90 CONTINUE
CALL ERASE
C FILLING ACCURACY CALCULATION. ++++++++
100 SUMDIF=0.
COUNT=0.
IF (T(2,NUM).LT.T(2,1))GO TO 110
KTP=1
K3T=NUM
GO TO 120
110 KTP=NUM
K3T=1
120 CONTINUE
DO 130 I=1,IMAX
IF (T(I,1).LT.T(2,KTP).OR.T(I,1).GT.T(2,KRT))GO TO 130
CALL NTRP(T(I,1),F1,NUM)
COUNT=COUNT+1.
DIF(I)=OMINC(I,1)-F1
SUMDIF=SUMDIF+DIF(I)*DIF(I)
130 CONTINUE
IF (COUNT.EQ.1.)GO TO 150
RMSFIT=SQRT(SUMDIF/(COUNT-1.))
WRITE(8,140),COUNT,RMSFIT
WRITE(9,140),COUNT,RMSFIT
140 FORMAT(’ RMS FITTING ACCURACY OF’,F5.0,’ OBSERVATIONS=’,F10.6)
C ++++++++ 
150 RETURN
END
SUBROUTINE NTRP(X1, I, J)
C LINEAR INTERPOLATION SUBROUTINE.
C J=NUMBER OF ENTRIES IN ARRAY.
C GIVEN ARRAYS X(N) AND Y(N), SUBROUTINE WILL FIND
C FOR EACH VALUE OF XI THE CORRESPONDING VALUE OF Y SUCH
C THAT Y1=Y(X).
DIMENSION X(301), Y(301)
COMMON/HIST/T(2,301), OMINC(2,301), OBS(150), IBAR, IMAX, ISTART
10 DO 10 I=1,301
X(I)=T(2, I)
Y(I)=OMINC(2, I)
10 CONTINUE
IORDER=0
IF (X(1).GT.X(J)) IORDER=1
I=1
20 IF (IORDER.GT.0) GO TO 30
IF (X(I+1)-X(I)) 40,50,50
30 IF (X(I+1)-X(I)) 50,50,40
40 I=I+1
IF (I+1-J) 20,50,50
50 F1=(X(I+1)-X(I))*Y(I)+(X-I)*Y(I+1)
F1=F1/(X(I+1)-X(I))
RETURN
END
Program BINOBS

When planning an observational program for eclipsing binary stars, it is advantageous to know well in advance the time when an eclipse is expected to occur. The Fortran code BINOBS produces a day-by-day chronological listing of times of occurrence for as many as 20 systems. It is useful to execute the code prior to the observational season each year.

A sample of the output from this code is given in table 7. The format is such that the schedules of minima for any one night are confined to a single page. This allows the observer to carry with him to the observatory only information which is relevant to that night's viewing.
### TABLE 7
ECLIPSING VARIABLE SCHEDULE OF MINIMA
FOR NIGHT BEGINNING ON 7/17
JULIAN DATE: 42977.0000

<table>
<thead>
<tr>
<th>STAR</th>
<th>JD OF MINIMA</th>
<th>UNIVERSAL TIME</th>
<th>STANDARD TIME</th>
<th>DAYLIGHT TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATPEG</td>
<td>0.0183</td>
<td>12:26</td>
<td>5:26</td>
<td>6:26</td>
</tr>
<tr>
<td>DOCAS</td>
<td>0.0565</td>
<td>13:21</td>
<td>6:21</td>
<td>7:21</td>
</tr>
<tr>
<td>XXCEP</td>
<td>0.0599</td>
<td>13:26</td>
<td>6:26</td>
<td>7:26</td>
</tr>
<tr>
<td>TWDRA</td>
<td>0.0971</td>
<td>14:19</td>
<td>7:19</td>
<td>8:19</td>
</tr>
<tr>
<td>I BOO</td>
<td>0.1858</td>
<td>16:27</td>
<td>9:27</td>
<td>10:27</td>
</tr>
<tr>
<td>I BOO</td>
<td>0.4537</td>
<td>22:53</td>
<td>15:53</td>
<td>16:53</td>
</tr>
<tr>
<td>I BOO</td>
<td>0.7215</td>
<td>5:18</td>
<td>22:18</td>
<td>23:18</td>
</tr>
<tr>
<td>DOCAS</td>
<td>0.7412</td>
<td>5:47</td>
<td>22:47</td>
<td>23:47</td>
</tr>
<tr>
<td>BFAUR</td>
<td>0.8443</td>
<td>8:15</td>
<td>1:15</td>
<td>2:15</td>
</tr>
<tr>
<td>RYAQR</td>
<td>0.9609</td>
<td>11:03</td>
<td>4:03</td>
<td>5:03</td>
</tr>
<tr>
<td>I BOO</td>
<td>0.9893</td>
<td>11:44</td>
<td>4:44</td>
<td>5:44</td>
</tr>
<tr>
<td>RZCAS</td>
<td>0.9910</td>
<td>11:47</td>
<td>4:47</td>
<td>5:47</td>
</tr>
</tbody>
</table>
PROGRAM TO CALCULATE ECLIPSING VARIABLE OBSERVATION SCHEDULE.

IMPLICIT DOUBLE PRECISION (A-H,O-Y)
DIMENSION ZSTAR(20), TKNOWN(NSTAR), PERIOD(NSTAR), OMAXAY(12)
DIMENSION HOLD(50), ZSHOLD(50), TSAVE(50), ZSSAVE(50)
NOTE: ITZONE IS STD. TIME DIFF. BETWEEN OBSERVATORY AND GMT.
ITZONE=7
DATA (MAXDAY(J),J=1,12)/31,28,31,30,31,30,31,30,31,30,31,30/
TYPE 20
20 FORMAT('1HOW MANY BINARIES BEING CONSIDERED?''.,$)
ACCEPT 30,NSTAR
30 FORMAT(I)
IF (NSTAR.GT.20 OR NSTAR.LT.1) GO TO 10
DO 80 N=1,NSTAR
TYPE 40
40 FORMAT('ENTER STAR NAME',S)
NOTE: MAXIMUM FIELD WIDTH IS 5.
ACCEPT 50,ZSTAR(N)
TYPE 60
60 FORMAT('ENTER EPHEMERAL JD, AND PERIOD',S)
ACCEPT 70,TKNOW(N),PERIOD(N)
70 FORMAT(2D)
80 CONTINUE
DO 100 N=1,NSTAR
TYPE 90,ZSTAR(N), TKNOWN(N), PERIOD(N)
PRINT 90,ZSTAR(N),TKNOW(N),PERIOD(N)
90 FORMAT(A10,2F15.8)
100 CONTINUE
TYPE 110
110 FORMAT('AT WHAT JD DOES THIS FORECAST BEGIN',S)
ACCEPT 30,IBEG
TBEG=IBEG
TYPE 120
120 FORMAT('FOR HOW MANY DAYS?',S)
ACCEPT 30,LTOP
TYPE 130
130 FORMAT('BEGINNING JD IS WHAT MONTH, DAY, YEAR(12,31,75)?',S)
ACCEPT 140,MON,I_DATE,I_YR
140 FORMAT(3I)
I_DATE=I_DATE-1
I_YR=I_YR-72
LEAP=MON(I_YR,4)
IF (LEAP.EQ.0) OMAXAY(2)=29
FOLLOWING UPDATES EPHMERAL JD TO BGGINNING OF FORECAST ++++++++ +
DO 170 N=1,NSTAR
DO 150 I=1,100000
E=I
START=TKNOW(N)+E*PERIOD(N)
IF (START.GE. TBEG) GO TO 160
150 CONTINUE
160 TKNOWN(N)=START
170 CONTINUE
C DAY LOOP ++++++++++++++++++++++++++++++++ + +
DO 310 L=1,LTOP
FL=L-1
ICOUNT=0
I_DATE=I_DATE+1
IF (I_DATE.LE. OMAXAY(MON)) GO TO 180
MON=MON+1
310 FORMAT(I)
IF (MON.GT.12) MON=1
10 A T F = 1 I
rp
180 PRINT 190,MON,INATE
190 FORMAT('1',12('/',33X,'SLEEPING VARIABLE SCHEDULE OF MINIMA',
1/37X,' FOR NIGHT BEGINNING ON',I3,'/',I3)
200 FORMAT(40X,' JULIAN DATE: ',F15.4//)
210 FORMAT(23X,' STAR',4X,' JD OF MINIMA',4X,'UNIVERSAL TIME',
13X,'STANDARD TIME',3X,'DAYLIGHT TIME',/)
220 CONTINUE
230 ZT=ZT+1
240 CONTINUE
250 FORMAT(20X,' NO ECLIPSES FOR ANY OF THESE PROGRAM STARS TODAY."
260 CONTINUE
270 CONTINUE
280 CONTINUE
290 CONTINUE
300 CONTINUE
310 CONTINUE
320 FORMAT(///' PICK UP LINE PRINTER OUTPUT')
END
Program OCPLLOT

To obtain a Calcomp plot of an O-C residual file, execute the Fortran code OCPLLOT. The only input required is the name of the file which is to be accessed. Plotting specifications and titles are determined automatically and a disk file named GRAPH.DAT is written. To complete the plotting, simply run the library code SPLLOT which reads this file.

.RUN SPLLOT (2302,11)

Examples of these plots are given in appendix 2. The residual values are represented by asterisks (*). Located above and below each residual is a cross (+) which indicates the observational accuracy of that value. The maximum number of O-C entries which may be plotted by this code is 800. Year zero corresponds to January 1, 1980 and therefore all eclipses observed prior to this date will be plotted as negative dates.
CREATE DATA FILE FOR O-C PLOT ON CALCOMP PLOTTER... IS JANUARY 1, 198...
VISION PERIOD, T1, TT
NPOCH(A0), TT(A0), DOB(S(A0), HOLD(A0), OS(7, A0))

TYPE 10

FORMAT(' ENTER FILENAME:', ?)
ACCEPT 20, FILE

FORMAT(A5)
CALL IFILE(1, FILF)
READ(1, 30), IMAX, PERIOD, T1,
1(NPOCH(I), TT(I), DOB(S(I), HOLD(I)), (O3(J, I), J=1, 7), I=1, IMAX)
FORMAT(T1, 2020, 10, B00(17, 17, 10, F8.5, F9.5, 2X, 3A5, 2X, 4A5))
YMIX=0.
DOBMAX=0.
XMIX=0.
DO 40 I=1, IMAX
  IF (DOB(S(I)) GT, DOBMAX) DOBMAX=DOB(S(I))
  IF (ABS(HOLD(I)) GT, YMIX) YMIX=ABS(HOLD(I))
  TT(I)=(TT(I) - 44298.) / 369.25
  IF (TT(I) LT, XMIX) XMIX=TT(I)
  CONTINUE

YMIX=YMX+DOBMAX
YMAX=0.05
IF (YMIX GT, 0.05) YMAX=0.10
IF (YMIX GT, 0.10) YMAX=0.15
IF (YMIX GT, 0.15) YMAX=0.20
IF (YMIX GT, 0.20) YMAX=0.25
IF (YMIX GT, 0.25) YMAX=YMIX
YMIX=-YMIX
XMIX=-10.
K=1
IF (XMIX GT, -10.) GO TO 50
XMIX=-20.
K=2
IF (XMIX GT, -20.) GO TO 50
XMIX=-30.
K=3
IF (XMIX GT, -30.) GO TO 50
XMIX=-40.
K=4
IF (XMIX GT, -40.) GO TO 50
XMIX=-50.
K=5
IF (XMIX GT, -50.) GO TO 50
XMIX=-60.
K=6
IF (XMIX GT, -60.) GO TO 50
XMIX=-70.
K=7
IF (XMIX GT, -70.) GO TO 50
XMIX=-80.
K=8
IF (XMIX GT, -80.) GO TO 50
XMIX=-90.
K=9
IF (XMIX GT, -90.) GO TO 50
XMIX=-100.
K=5
CALL OFILE (1, 'GRAPH')
M A X I = I M A X / 2 + 1
WRITE (1, 60) FILE, PERIOD, XMIN, YMIN, YMAX, KK, KK, IMAX
60 FORMAT ('VERSNO3', 'GRAPH1', 'TITLE26', A5, 'PERIOD=',
'1F12.8', 'XAXIS05YFARS', 'YAXIS199CRESIDUALS(YAYS)', /
'SPECS', F6.0, '0.', 'F5.2', '1?', 'I1', '2.08', 'I1', '?', /
'DATA', 'I3)
WRITE (1, 70) (TT(I), HOLD(I), DQ8S(I), T=1, IMAX)
70 FORMAT (400(6F10.5/))
IMAX=IMAX/2
WRITE (1, 80), IMAX, IMAX, IMAX, IMAX, IMAX, IMAX
80 FORMAT ('PLOT 01O207', I5, 'PLOT 040507', I5, 'ALTER02034107', /
'PLOT 010705', I5, 'ALTER05064107', 'PLOT 040705', I5, /
'ALTER02034207', 'PLOT 010705', I5, /
'STOP')
END FILE 1
END
APPENDIX 3

SPATIAL CONFIGURATION PLOTS

In the following plots, the direction to the earth is that of the positive abscissa.
MODEL #: 67: 100 TO 1600 YR

PROJECTED ON PLANE INCLUDING LOS
MODEL  67:  -100 TO  100 YR

PROJECTED ON PLANE INCLUDING LOS
PROJECTED ON PLANE INCLUDING LOS

MODEL # 67: 100 TO 1600 YR
MODEL 127
RZ CASSIOPEIAE: +500 TO +800 YR

PROJECTED ON PLANE INCLUDING LOG
RZ CASSIOPEIAE: +300 TO +500 YR

PROTECTED ON PLANE INCLUDING LOS
RZ CASSIOPEIIAE: 0 TO +300 yr

Projected on plane including LOS
RZ Cassiopeiae: 0 to 300 yr

Projected on plane including LOS
RZ CASSIOPEIAE: -300 TO -500 YR

PROJECTED ON PLANE INCLUDING LOS
RZ CASSIOPEIAE: -500 TO -800 YR
RZ CASSIOPEIAE: -800 TO 1100 YR

PROJECTED ON PLANE INCLUDING LOS
RZ CASSIOPEIAE: -1100 TO -1500 YR

PROJECTED ON PLANE INCLUDING LOS
RZ CASSIOPEIAE: 1400 TO 1700 YR

PROJECTED ON PLANE INCLUDING LOS
RZ CASSIOPEIAE: 1700 TO -2000 YR

PROJECTED ON PLANE INCLUDING LOS

(AU)
RZ CASSIOPEIAE: -2000 TO 2300 YR

PROTECTED ON PLANE INCLUDING LOS


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Winkler, L. 1966. Blue and yellow photoelectric photometry of the
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Wood, Frank Bradshaw. 1950. On the change of period of eclipsing