# AN ANALYSIS OF THE LIGHT CHANGES OF THE ECLIPSING BINARY XY CETI IN THE FREQUENCY-DOMAIN

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**Abstract.** The photoelectric observations of the eclipsing binary XY Ceti presented by us (see Srivastava and Padalia, 1975) have been analysed by Okazaki (1978) and Ramella *et al.* (1980). They presented different sets of elements from the same set of our observations. This necessitated us to obtain the elements of XY Ceti again employing recent method of determination of elements.

The revised geometrical elements of the eclipsing binary XY Ceti have been obtained by the method of Fourier analysis of the light changes in the frequency-domain, which was developed by Kopal (1979). These have been compared with our earlier (Srivastava and Padalia, 1975) results obtained by employing Russell and Merrill's (1952) method. The revised absolute dimensions of XY Ceti have been obtained using the spectroscopic elements given by Popper (1971), and the newly derived geometrical elements. The Roche radii have been derived to discuss the evolution of the system. The secondary component lies reasonably near to the Main Sequence, while the primary component falls above it. The evolutionary discussion indicates that the system is a detached one.

## 1. Introduction

The eclipsing binary XY Ceti ( = BD + 2°460 = HD 018957 = BV 347 = SAO 110887) was discovered by Strohmeier and Knigge (1961). Strohmeier (1963) listed its light elements. Its photographic light curve was also given. Morrison and Morrison (1968) observed the star in a $V$ filter and doubled the period given by Strohmeier (1963). Popper (1971) determined the spectroscopic elements of the system and suggested that both components of the system are metallic line stars, and belong to the Main Sequence. Hilditch and Hill (1975) gave Strömgren indices of the system at five phases. Hill *et al.* (1975) presented MK classification of the system. Srivastava and Padalia (1975) secured first $U$, $B$, and $V$ observations of XY Ceti and presented its detailed analysis. Lacy (1977) estimated the radii of the system using the Barnes–Evans relation. Al-Naimiy *et al.* (1978) obtained $B$ and $V$ observations of the system and presented magnitudes at its maximum and at primary minimum, the $B - V$ value outside the eclipses, and also gave the time of primary minimum. Okazaki (1978) obtained few $U$, $B$, $V$ observations of the system and gave $V$-magnitude and colour indices. He analysed our (Srivastava and Padalia, 1975) observations alongwith the observations given by Morrison and Morrison (1968) and presented revised elements. He found that the system did not suffer significantly from reflection and ellipticity effects, but he suspected that a small amount of eccentricity might be present in the system. He also found that the colour excess $E_{B-V}$ not exceeding $0^m.1$, was present in the system, and showed that both components of XY Ceti lie below the Main Sequence. Ramella *et al.* (1980) further analysed our (Srivastava and Padalia, 1975) observations of the system XY Ceti and presented

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revised elements. The elements based on our observations given by Okazaki (1978) and Ramella *et al.* (1980) are not consistent, hence, we re-derived the elements of the system employing the latest method of determination of elements developed by Kopal (1979), and presented revised elements of the system in this paper.

## 2. Observations

Before our observations, Strohmeier and Knigge (1961), Strohmeier (1963), and Morrison and Morrison (1968) secured the observations of the eclipsing binary system XY Ceti.

Strohmeier and Knigge (1961) and Strohmeier (1963) secured only photographic observations and gave light elements. Morrison and Morrison (1968) observed XY Ceti only in the *V* filter. Even there no continuous set of observations spanning even one complete eclipse was obtained nor the light curve was adequately covered. They also presented the geometrical elements of the system.

Before our observations no photometry in all the three (*U*, *B*, and *V*) filters was available in the literature. For these reasons it was considered to put the star XY Ceti on our observational programme. A total of 22 nights of observations were secured in *U*, *B*, and *V* filters during the period November 1969 to February 1971. These observations were published earlier (see Srivastava and Padalia, 1975).

Subsequent to our observations, Al-Naimiy *et al.* (1978) and Okazaki (1978) reported to have secured some *B*, *V* and *U*, *B*, *V* observations of the system. Neither Al-Naimiy *et al.*'s (1978) nor Ozaki's (1978) observations ara available in the literature. Al-Naimiy *et al.*'s (1978) communication presented the magnitudes of the system at maximum and at primary minimum, the $(B-V)$ value outside the eclipse, and the time of primary minimum. However, no light curve was available, and even there, the given primary minimum was not fully observed. Okazaki's (1978) communication states that the photoelectric observations of XY Ceti have been secured, but the observations secured by him are not traceable in the literature to us. However, he gave the *V* magnitude and $B - V$ and $U - B$ colour indices of XY Ceti outside the eclipse. Also, no light curve based on Okazaki's (1978) observations is available in the literature.

In the light of the above description, we consider our observations, although presented in 1975, are still important inasmuch as none has presented the *U*, *B*, *V* observations of XY Ceti either before or after our observations. Moreover, the detailed analysis of XY Ceti was first presented by us (see Srivastava and Padalia, 1975). In addition, only our observations presented the complete light curves of the system. Moreover, our observations presented in 1975, have been analysed by Okazaki (1978) and Ramella *et al.* (1980), which fact futher goes to establish the importance of our observations.

## 3. Epoch and Period

During the course of our (Srivastava and Padalia, 1975) observations three primary and four secondary minima were observed. For a detailed discussion of the period of the

TABLE I

Minima of XY Ceti

| Sl. No. | Epoch of minima J.D. Hel. | Period | O–C based on Morrison and Morrison's (1968) epoch and period |
|---|---|---|---|
| | | Primary minima | |
| 1. | 2440906.177 ($\pm 0^{\mathrm{d}}.001$) | $2^{\mathrm{d}}.7807113$ | $-0^{\mathrm{d}}.001$ |
| 2. | 2440917.301 ($\pm 0^{\mathrm{d}}.001$) | $2^{\mathrm{d}}.7807125$ | $+0^{\mathrm{d}}.001$ |
| 3. | 2440931.204 ($\pm 0^{\mathrm{d}}.001$) | $2^{\mathrm{d}}.7807119$ | $0^{\mathrm{d}}.000$ |
| | Mean | $2^{\mathrm{d}}.7807119$ | $0^{\mathrm{d}}.000$ |
| | | Secondary minima | |
| 1. | 2440529.387 ($\pm 0^{\mathrm{d}}.001$) | $2^{\mathrm{d}}.7807070$ | $-0^{\mathrm{d}}.004$ |
| 2. | 2440532.161 ($\pm 0^{\mathrm{d}}.001$) | $2^{\mathrm{d}}.7806984$ | $-0^{\mathrm{d}}.011$* |
| 3. | 2440543.298 ($\pm 0^{\mathrm{d}}.001$) | $2^{\mathrm{d}}.7807168$ | $+0^{\mathrm{d}}.004$ |
| 4. | 2440557.194 ($\pm 0^{\mathrm{d}}.001$) | $2^{\mathrm{d}}.7807070$ | $-0^{\mathrm{d}}.004$ |
| | Mean | $2^{\mathrm{d}}.7807073$ | $-0^{\mathrm{d}}.004$ |

system XY Ceti, these minima reproduced here in Table I along with the derived values of O–C based on the ephemeris given by Morrison and Morrison (1968), viz.,

$$\text{Primary Minimum} = \text{J.D. } 2438372.949 + 2^{\mathrm{d}}.780712E\,.$$

If we ignore this value of O–C(*), the average O–C values from primary and secondary minima come out to be $0^{\mathrm{d}}.000$ and $-0^{\mathrm{d}}.0013$ ($\simeq 0^{\mathrm{d}}.001$), respectively, which suggest that the minima are not shifted from their expected positions within the error of determination of minima ($\pm\,0^{\mathrm{d}}.001$). Ignoring the above secondary minima, the mean periods from primary and secondary minima come out to be $2^{\mathrm{d}}.7807119$ ($\pm\,0^{\mathrm{d}}.0000006$) and $2^{\mathrm{d}}.7807103$ ($\pm\,0^{\mathrm{d}}.000075$). The mean O–C value obtained from primary minima only is zero, which suggests that the period of the system has not changed since Morrison and Morrison's (1968) epoch. However, considering all the secondary minima, the mean O–C value comes out to be $-0^{\mathrm{d}}.004$, which suggests that the secondary minimum is slightly earlier shifted, and the mean period from all the secondary minima comes out to be $2^{\mathrm{d}}.7807073$, which is slightly lesser than the period given by Morrison and Morrison (1968). The most interesting part was that, from our observations, Okazaki (1978) found that the epoch of the secondary minimum was shifted from phase 0.5 by an amount of $+0.0016 \pm 0.0003$, and on that basis he suspected that the eccentricity was present in the system, but he failed to detect it. We have checked-up our O–C values for the secondary minima based on Morrison and Morrison's epoch and period and found that the secondary minimum is shifted earlier by $0^{\mathrm{d}}.004$ and not later as suggested by Okazaki (1978). From our observations it is apparent that the period of XY Ceti has not changed since Morrison and Morrison's (1968) epoch.

## 4. Determination of Elements

Earlier, Morrison and Morrison (1968) and Srivastava and Padalia (1975) derived he elements of the system XY Ceti using Russell and Merrill's (1952) method. Subsequent to our (Srivastava and Padalia, 1975) work, Okazaki (1978) used our observations and obtained revised elements of the system employing Kitamura (1965) and Budding's (1973) method. Ramella *et al.* (1980) further analysed our observations, published in 1975, and determined revised elements applying Wood's programme. These elements are given in Table II.

TABLE II

Geometrical elements of XY Ceti given by various authors (based on Srivastava and Padalia's (1975) observations

| Elements | Srivastava and Padalia (1975) | Okazaki (1978) | Ramella *et al.* (1980) | Mean |
|---|---|---|---|---|
| $k$ | 0.75 | 0.94 | 0.83 | 0.84 |
| $i$ | 87°.5 | 88°.4 | 87°.6 | 87°.8 |
| $r_1$ | 0.171 | 0.157 | 0.168 | 0.165 |
| $r_2$ | 0.129 | 0.142 | 0.140 | 0.137 |

In the discussion we have not considered the elements of Morrison and Morrison (1968) as they were based on scanty observations. Also, Koch *et al.* (1970) assigned low weight to their analysis.

It is apparent from Table II that there is variance in the elements given by various authors, and some elements show variation from 0.1 to 10% from the mean values. The elements given by Okazaki (1978) are considerably different from the other two sets of elements given by Srivastava and Padalia (1975) and Ramella *et al.* (1980). The elements given by Ramella *et al.* (1980) are not far removed from the elements given by us (see Srivastava and Padalia, 1975). These different elements prompted us to re-analyse our observations, published in 1975, employing recent method of determination of elements, and to obtain revised elements of the system for bringing about a consencious regarding the elements of XY Ceti.

The light curves were smoothened through the normal points of secondary minimum in $U$, $B$, and $V$ filters, which is an occultation (see Srivastava and Padalia, 1975). The intensities at one degree interval having been read out from these curves and are listed in Table VII. The values of the moments $A_0$, $A_2$, $A_4$, and $A_6$, the geometrical elements of XY Ceti and their errors, have been obtained following the method of Kopal (1979) as described in our earlier paper (see Srivastava, 1984). The values of moments are listed in Table III.

The geometrical elements derived using Kopal's (1979) method have been given in Table IV along with the elements derived earlier (see Srivastava and Padalia, 1975) based on the method by Russell and Merrill (1952).

TABLE III

Moments of XY Ceti

| Moments | $U$ filter | $B$ filter | $V$ filter |
|---|---|---|---|
| $A_0$ | $0.375 \pm 0.003$ | $0.375 \pm 0.003$ | $0.375 \pm 0.003$ |
| $A_2$ | $0.0114 \pm 0.0002$ | $0.0118 \pm 0.0002$ | $0.0117 \pm 0.0001$ |
| $A_4$ | $0.00054 \pm 0.00003$ | $0.00057 \pm 0.00003$ | $0.00056 \pm 0.00004$ |
| $A_6$ | $0.000031 \pm 0.000003$ | $0.000034 \pm 0.000003$ | $0.000032 \pm 0.000003$ |

TABLE IV

Geometrical elements of XY Ceti

| Elements | Russel and Merrill's method | Kopal's method | Mean |
|---|---|---|---|
| $x$ (assumed) | 0.6 | 0.6 | 0.6 |
| $k$ | 0.75 ($\pm$0.01) | 0.89 ($\pm$0.01) | 0.82 |
| $i$ | 87°.5 ($\pm$0°.5) | 86°.2 ($\pm$0°.0) | 86°.9 |
| $r_1$ | 0.171 ($\pm$0.001) | 0.170 ($\pm$0.004) | 0.171 |
| $r_2$ | 0.129 ($\pm$0.002) | 0.152 ($\pm$0.003) | 0.141 |

In deriving the above elements, the values of $1 - \lambda_1$, $1 - \lambda_2$, $L_1$, $L_2$, and $\alpha_0 (= 1)$ have been adopted to be the same as published earlier (see Srivastava and Padalia, 1975). The subscripts 1 and 2 refer to the primary and the secondary components, respectively. The revised elements obtained, using Kopal's method, are not very different from our earlier results based on Russell and Merrill's (1952) method; however, some difference emerges in the value of $r_2$, and consequently in the value of $k$, considering various set of elements, the error of 0°.5 in the value of $i$ has been adopted in column 2 of Table IV.

## 5. Absolute Dimensions

The revised absolute dimensions of the system XY Ceti have been obtained using the spectroscopic elements given by Popper (1971) and the geometrical elements obtained employing Kopal's (1979) method, and are listed in Table V along with the absolute dimensions derived earlier by us (see Srivastava and Padalia, 1975).

In deriving these absolute dimensions, the spectrum-luminosity classification of the components has been adopted from our earlier paper (cf. Srivastava and Padalia, 1975). The absolute visual and the bolometric magnitudes of the primary and the secondary components have been revised on the basis of the present geometrical elements, obtained employing Kopal's (1979) method, and using $T_\odot = 5730$ K, $T_1 = 8700$ K (A5V), and $T_2 = 8100$ K (A7V) (see Arp's, 1958, table).

TABLE V

Absolute dimensions of XY Ceti

| Elements | Russell and Merrill's method | Kopal's method | Mean |
|---|---|---|---|
| $A(R_\odot)$ | 12.51 | 12.51 | 12.51 |
| $M_1(\odot)$ | 1.76 | 1.76 | 1.76 |
| $M_2(\odot)$ | 1.63 | 1.64 | 1.64 |
| $R_1(\odot)$ | 2.14 | 2.13 | 2.14 |
| $R_2(\odot)$ | 1.61 | 1.76 | 1.69 |
| $\rho(\odot)$ | 0.04 | 0.04 | 0.04 |
| $\rho(\odot)$ | 0.09 | 0.07 | 0.08 |
| $M_1$(bol) | $1\overset{m}{.}25$ | $1\overset{m}{.}27$ | $1\overset{m}{.}26$ |
| $M_2$(bol) | $2\overset{m}{.}19$ | $1\overset{m}{.}99$ | $2\overset{m}{.}09$ |
| $M_1$(vis) | $1\overset{m}{.}66$ | $1\overset{m}{.}67$ | $1\overset{m}{.}67$ |
| $M_2$(vis) | $2\overset{m}{.}53$ | $2\overset{m}{.}53$ | $2\overset{m}{.}43$ |
| $\log(L_1/L_\odot)$ | 1.35 | 1.34 | 1.35 |
| $\log(L_2/L_\odot)$ | 0.98 | 1.06 | 1.02 |

## 6. Roche Constants

The revised Roche constants for the equipotential surfaces of XY Ceti have been computed, using the geometrical elements obtained from Kopal's (1979) method, and new absolute dimensions, using the relations given by Kopal (1959a) and are given in Table VI along with the Roche constants obtained earlier (see Srivastava and Padalia, 1975) based on the geometrical elements derived employing Russell and Merrill's (1952) method.

TABLE VI

Roche constants of XY Ceti

| Roche constants | From geometrical elements based on | | Mean |
|---|---|---|---|
| | Russell and Merrill's method | Kopal's method | |
| $C_0$ | 4.00 | 4.00 | 4.00 |
| $C_1$ | 7.27 | 7.31 | 7.29 |
| $C_2$ | 8.78 | 7.66 | 8.22 |
| $C_1/C_2$ | 0.83 | 0.95 | 0.89 |

The value of $C_0$ having been read out from the table given by Kopal (1959b) corresponding to a mass-ratio of 0.93. The revised values of Roche constants are not very different from our earlier results (see Srivastava and Padalia, 1975), however, the value of $C_2$ differs. Since $C_1 > C_0$ and $C_2 > C_0$, we infer that the system is a detached one.

TABLE VII

Observations of XY Ceti

| Phase in degrees | Intensity (in terms of the intensity outside eclipse as unity) | | |
|---|---|---|---|
| | *U* filter | *B* filter | *V* filter |
| 0 | 0.625 | 0.625 | 0.625 |
| 1 | 0.625 | 0.625 | 0.625 |
| 2 | 0.628 | 0.630 | 0.630 |
| 3 | 0.638 | 0.633 | 0.635 |
| 4 | 0.660 | 0.658 | 0.655 |
| 5 | 0.688 | 0.688 | 0.688 |
| 6 | 0.720 | 0.713 | 0.715 |
| 7 | 0.746 | 0.740 | 0.745 |
| 8 | 0.778 | 0.770 | 0.775 |
| 9 | 0.803 | 0.803 | 0.803 |
| 10 | 0.838 | 0.833 | 0.838 |
| 11 | 0.865 | 0.860 | 0.863 |
| 12 | 0.893 | 0.885 | 0.890 |
| 13 | 0.920 | 0.913 | 0.915 |
| 14 | 0.948 | 0.943 | 0.943 |
| 15 | 0.975 | 0.968 | 0.968 |
| 16 | 0.980 | 0.985 | 0.988 |
| 17 | 0.998 | 0.995 | 0.998 |
| 18 | 1.000 | 1.000 | 1.000 |
| 19 | 1.000 | 1.000 | 1.000 |
| 20 | 1.000 | 1.000 | 1.000 |

## 7. Roche Radii

The Roche radii ($r^*_{1,2}$) of the individual components of XY Ceti have been computed for the first time using the relations given by Paczyński (1971):

$$\left.\begin{aligned} \frac{r_1}{a} &= 0.38 + 0.2 \log \frac{1}{q}\,, \\ \frac{r_2}{a} &= 0.38 + 0.2 \log q\,; \end{aligned}\right\} \quad \left(q = \frac{m_2}{m_1}\right),$$

which are valid for the systems satisfying the conditions $0.3 < q < 20$. Here $r_1$ and $r_2$ are the radii of components (in terms of separation of their centres), $m_1$ and $m_2$ are their masses, $a$ is the separation between them. The values of radii ($r_1$, $r_2$) and the Roche radii ($r_1^*$, $r_2^*$) of the components of XY Ceti are given as:

| Component | Radius ($r$) | Roche radius ($r^*$) |
|---|---|---|
| Primary | 0.17 | 0.39 |
| Secondary | 0.15 | 0.37 |

These radii and Roche radii are schematically shown in Figure 3. It is apparent from Figure 3 that neither of the components has filled its Roche lobe.

## 8. Evolutionary Discussion

The concerned values are plotted on the [$\log(M/M_{\odot})$, $\log(R/R_{\odot})$] relation (Figure 1) and on the [spectral type, $M_{\text{bol}}$] relation (Figure 2) valid for the systems belonging to the Main Sequence (Kopal, 1955; Arp, 1958). The continuous line in Figures 1 and 2 represent the average trend of the Main Sequence. In Figure 3, lined circles represent the radii of the components, and the other (heavily lined) circles represent the Roche radii.

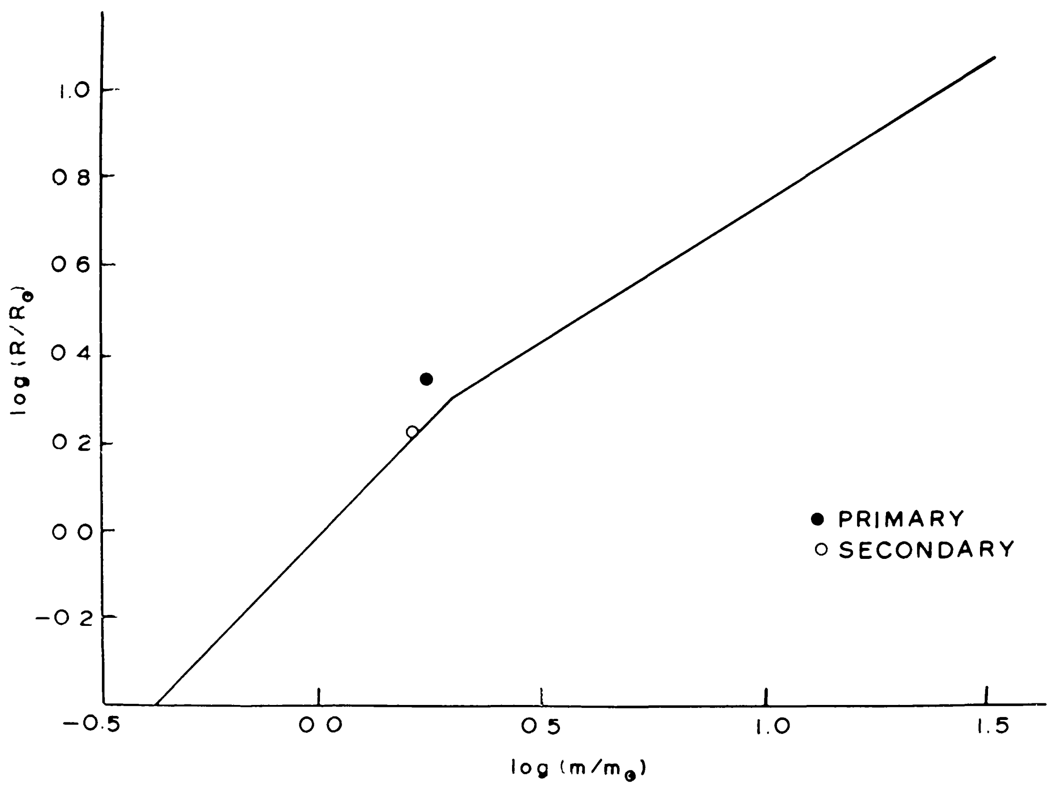


Fig. 1. Position of the components of XY Ceti on mass-radius relation for the close binary systems with detached components. The unbroken line represents the average trend of the Main Sequence (Kopal, 1955).

(i) Looking at Figures 1 and 2, it is evident that both the components of XY Ceti lie fairly on the Main Sequence.

(ii) From Figures 1 and 2, it is also evident that the primary component is slightly more evolved than the secondary as it shows the tendency to drift away from the Main Sequence.

(iii) As already stated: $C_1 > C_0$ and $C_2 > C_0$, the system XY Ceti is a detached one.

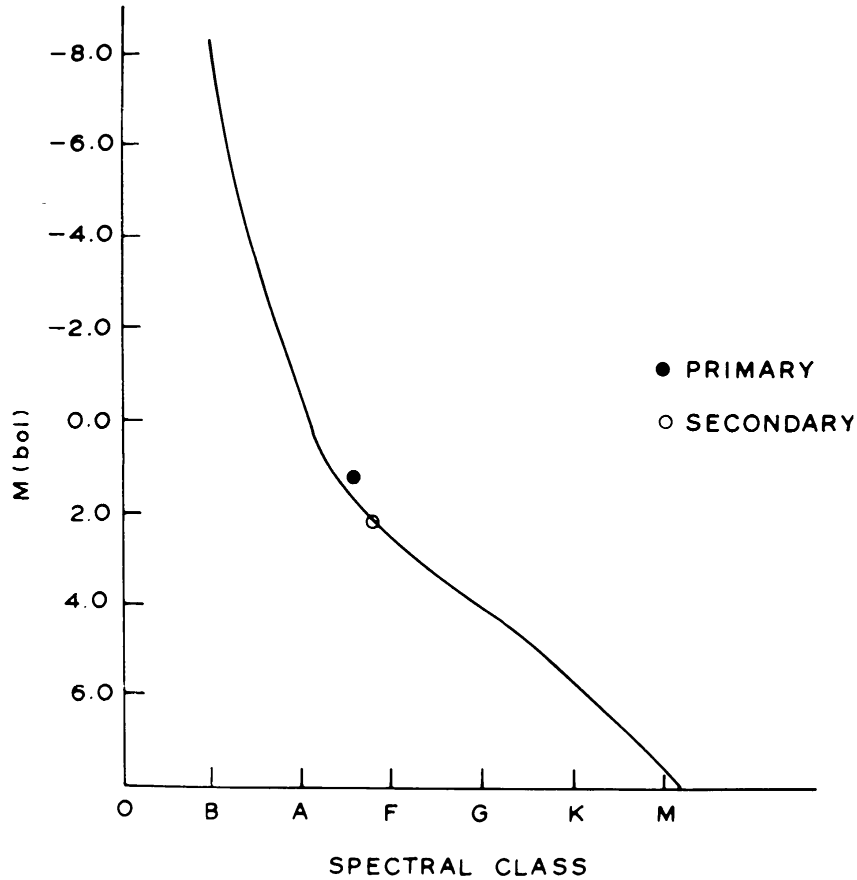


Fig. 2. Position of the components of XY Ceti on spectral class-luminosity relation for the Main-Sequence stars. The continuous line schematizes the average trend of the Main Sequence (Arp, 1958).

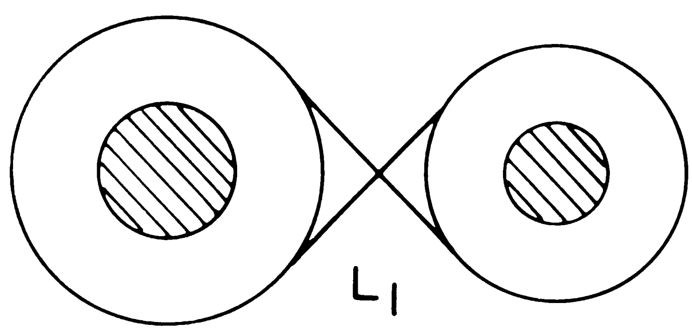


Fig. 3. Roche diagram of XY Ceti in terms of separation of the components as unit. The primary component is shown on the left.

Also, the fact (from revised Roche constants) that $C_1/C_2 = 0.95$ ($\simeq 1.0$), lends support that the system may be classified as a detached system (see Kopal, 1959c).

(iv) An examination of the values of radii and Roche radii of the components of XY Ceti, and Figure 3, reveals that the radii of the primary and the secondary components of XY Ceti are far from approaching their Roche radii, and consequently these components are far from filling their respective Roche lobes. This fact lends further support to the fact that the system is a detached one.

(v) Okazaki (1978) deduced the spectral types of the components of XY Ceti as A4 and A7, respectively, which are near to our spectral types (A5 and A7). However, he stated that both the components of XY Ceti lie below the Main Sequence, which fact is in contradiction to our results (cf. Srivastava and Padalia, 1975).

(vi) Ramella *et al.* (1980) have also classified the system as a detached one. They find that, in mass-radius and mass-luminosity diagrams, both the stars of XY Ceti have radii and luminosities, which are slightly higher than expected for the stars unevolved from the theoretical ZAMS. They have also indicated that the hotter star, which is likely to be more evolved, deviates more than the cooler one from the empirical mass-radius and mass-luminosity (Main-Sequence) relations.

## 9. Conclusions

The period of the eclipsing binary system has not significantly changed since Morrison and Morrison's (1968) epoch. The geometrical elements and, consequently the absolute dimensions derived on the basis of Russell and Merrill's (1952) and Kopal's (1982) methods do not show considerable difference in the values of $i$ and $r_1$; however, some difference emerges in the value of $r_2$. The elements show 0.1 to 10% variation from the mean of the two sets of elements mentioned above. Morrison and Morrison's (1968) elements are based on poor observations and are already given low weight (see Koch *et al.*, 1970). Okazaki's (1978) elements based on our observations are neither consistent with ours (1975 and the present) elements nor with the elements given by Ramella *et al.* (1980). However, Ramella *et al.*'s (1980) elements are closer to our elements. The importance of our elements lies in the fact that the absolute dimensions based on Russell and Merrill's method are in agreement to those given by Lacy (1977), and our absolute elements based on Kopal's (1979) method are in agreement of Ramella *et al.*'s (1980) absolute elements. Thus, our elements can be given higher weight in comparison to others. Both the components of XY Ceti are the Main-Sequence stars, primary being slightly more evolved than the secondary component. The system is detached one.

For bringing out the consistency in the elements or for adopting the most plausible set of elements of XY Ceti, it is desirable that the geometrical elements and absolute dimensions are derived using our (Srivastava and Padalia, 1975) observations employing Wilson and Devinney's method, which is also the modern method for derving the elements of eclipsing binary systems.

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