THE DETECTION OF A COMPANION STAR TO THE CEPHEID VARIABLE T MONOCEROTIS

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Received 1980 May 12; accepted 1980 June 26

ABSTRACT

We have obtained ultraviolet spectra with the International Ultraviolet Explorer (IUE) spacecraft of the classical Cepheid T Mon at several phases in the 27 day period. Significant ultraviolet emission is detected at wavelengths less than 1600 Å, where little flux is expected from classical Cepheids. Furthermore, the emission at wavelengths less than about 1900 Å does not vary with phase. Comparison with model atmosphere flux distributions shows that the emission is consistent with the flux expected from a companion star with an effective temperature of about 10,000 K (approximately A0) near the main sequence.

Subject headings: stars: binaries — stars: Cepheids — stars: individual

I. INTRODUCTION

Analysis of multicolor photometry of classical Cepheid variables suggests that a large fraction of all Cepheids are members of binary systems. Pel (1978) estimated that at least 25% of all Cepheids are in binary systems, while Madore and Fernie (1980) find the incidence of duplicity to be 35% ± 5% and suggest that the percentage may be even larger at long periods. Such a large fraction has important implications. First, to the extent that the companion stars influence visible wavelength photometry, there will be increased scatter in the period-color-luminosity relation and the distances derived from it. If the details of the nature of the companion stars are available, however, their effects can be removed. In fact, if the absolute magnitudes of the companion stars can be determined independently from the Cepheids, they can serve as checks on the period-luminosity relation. Second, if dynamical information is available on Cepheid binary systems, there is the potential for deriving Cepheid masses. Additional information on masses would help resolve the mass anomaly that exists for Cepheids with bumps in their light and velocity curves and for those with two simultaneous pulsation modes (e.g., Fricke, Stobie, and Strittmatter 1972; Petersen 1973). Of course, if the binary systems are very close, there is a possibility that the companion star may influence the evolution of the Cepheid.

In a previous paper (Mariska, Doschek, and Feldman 1980), we reported evidence that the classical Cepheid η Aql is a member of a binary system, with an A0 V companion star. For the η Aql system, emission from the companion star is detectable only at wavelengths less than about 1700 Å and is not of sufficient intensity to obtain high spectral resolution data with current experiments such as the IUE. In the present paper we report evidence that the classical Cepheid T Mon has a companion star and examine the potential of the system for determining the mass of the Cepheid.

II. OBSERVATIONS

As part of a program to search for ultraviolet emission lines in the spectra of classical Cepheid variables with IUE, we obtained spectra of T Mon on 5 days during the interval 1979 November 15–23. These observations covered five phases in the 27 day period of the star, all on the declining portion of the light curve. All of the spectra were obtained at low resolution. Exposures were made in both the long- and short-wavelength cameras and with both the large and small apertures. The spectral resolution is about 6 Å in the short-wavelength camera (1100–2000 Å) and about 8 Å in the long-wavelength camera (2000–3500 Å). Further details of the IUE instrument are given by Boggess et al. (1978a, b).

Figure 1 shows long- and short-wavelength spectra for the five phases for which we have data. Each of the short-wavelength spectra (λ < 2000 Å) represents a single exposure of about 60 minutes through the large aperture. The long-wavelength spectra (λ > 2000 Å) are in some cases combinations of data from exposures taken within a few minutes of each other through the large and small apertures. Typical long-wavelength exposures through the large aperture varied between about 1 and 18 minutes. All of the large-aperture exposures have been placed on an absolute scale using the calibration of Bohlin et al. (1980). The small-aperture...
exposures have then been placed on the same scale by first applying the Bohlin et al. (1980) calibration and then multiplying the data by a correction factor to bring it into agreement with a large-aperture exposure in the wavelength regions where both sets of data are well exposed. This correction factor adjusts for the roughly factor of 2 reduction in the flux from the star caused by the small size of the small aperture. The short gaps in the spectra are the locations of the reseau marks on the camera, where the data are unreliable. The longer gap in the top spectrum is a region where all of the spectra taken at that phase are underexposed. The phases noted on the figure were calculated using the epoch and period listed by Pel (1976).

The spectra in Figure 1 have a number of important features. At wavelengths less than 2000 Å, the magnitude of the flux and its spectral distribution are clearly incompatible with the F or G type spectrum expected for a Cepheid. Only at wavelengths greater than about 2600 Å does the continuum flux increase with increasing wavelength, as would be expected for the spectrum of an F or G type stellar atmosphere, characteristic of a Cepheid such as T Mon. The flux at wavelengths greater than about 2600 Å varies in a manner qualitatively consistent with the observed optical variations. However, unlike other Cepheids observed in the ultraviolet (e.g., Lub et al. 1979), the amplitude is largest at the longer ultraviolet wavelengths rather than the shorter, indicating that the flux variations are influenced by a companion. For example, the variation in flux at 2600 Å from phase 0.14 to phase 0.43 is only about a factor of 1.4, while the variation in flux at 3200 Å between the same phases is about a factor of 2.6. From the light curve of Pel (1976), we determine a factor of 1.6 variation in the visible flux between the same phases. Furthermore, none of the T Mon spectra
exhibits a significant Mg II absorption feature near 2800 Å. This feature is present in the other Cepheids we have studied with IUE, as well as in those studied by Parsons (1980). At wavelengths below about 2000 Å the shape of the emission as a function of wavelength and the absolute value at each wavelength are constant, independent of the phase of the Cepheid. In addition, none of the sharp continuum edges characteristic of 5500 K effective temperature stellar atmospheres (Kurucz 1979) are evident in the 1500–2000 Å data. These edges are present in several of the other Cepheids for which we have obtained IUE spectra. Between 2000 and 2600 Å the data are of poor quality. They do, however, indicate a rather flat continuum flux in this wavelength region, uncharacteristic of the spectrum expected from a Cepheid. The overall shape of the ultraviolet flux below 2000 Å is characteristic of a stellar atmosphere with an effective temperature in excess of 8500 K. Furthermore, the features discussed above are seen in all of the spectra we have obtained, including those taken with the small aperture. Thus the source of the radiation must be within 1.5 of T Mon, the radius of the small aperture. Therefore, we suggest that the features of the spectra presented in Figure 1 indicate that T Mon has a companion star with an effective temperature in excess of 8500 K.

It is not possible to completely rule out an atmospheric effect in the Cepheid because we have not observed any other Cepheids with comparable periods. However, we feel that the constancy of the flux at short wavelengths over almost one-third of the period and the fact that the short wavelength flux distribution has all the characteristics of a much hotter stellar atmosphere argue strongly for a companion star as the source of the radiation.

To determine accurately the characteristics of the companion star, we have compared the observed flux at the Earth in the wavelength range of the IUE instrument with the predicted fluxes from a series of stellar atmosphere models calculated by Kurucz (1979). We assume that the companion star is on or near the main sequence and use a log surface gravity of 4 and solar abundances. Each set of model atmosphere fluxes was reddened using the average interstellar extinction curve of Savage and Mathis (1979) and a range of color excesses from $E(B-V)=0$ to $E(B-V)=0.41$. The models were fitted to the data at phase 0.43, when the emission from the Cepheid is nearest minimum and should therefore contribute the least flux. The best fit was estimated using the data below 2000 Å, where the spectra in Figure 1 show no variation with phase. The best overall fit to the data was found for a model with an effective temperature of about 10,000 K.

Figure 2 shows the data at phase 0.43, the flux distribution predicted by the best-fit model, and flux distributions predicted by models with effective temperatures of 9500 and 10,500 K. Each set of model atmosphere flux distributions was reddened using a color excess $E(B-V)$ of 0.41 (Kraft 1961). The model fluxes have all been adjusted to fit the observations at 1600 Å, where no obvious absorption features are present. All of the model flux distributions provide an adequate representation of the data between 1600 and 1900 Å. Below 1600 Å the fit is complicated by the presence of a number of absorption features near 1300 Å. The narrow feature near 1302 Å is probably due to the O I lines at 1302, 1304, and 1306 Å. Other narrow features at wavelengths less than 1300 Å may be due to S II, Si II, or possibly Si III. The spectral resolution is
inadequate to attempt detailed identifications. In addition, a rather broad absorption feature is seen near 1400 Å, extending to about 50 Å on either side of this wavelength. These absorption features appear in all of the spectra in Figure 1 and are more pronounced in T Mon than in η Aql, where in fact the broad feature is not apparent. The 9500 K model fluxes clearly fall below the continuum adjacent to these features, and thus the model is unacceptable. The fluxes predicted by the other two models provide an adequate fit to all of the data. 

At wavelengths greater than 1900 Å the model fluxes all fall below the data. This is probably due primarily to the contribution of the Cepheid to the total flux observed at these wavelengths. However, as mentioned above, there is almost no indication of a Mg II feature near 2800 Å, contrary to our observations of other Cepheids and the observations of Parsons (1980). We believe that this is due to the Mg II feature of the Cepheid being filled in by the spectrum of the companion. Since only a very small indication of the Mg II feature is apparent in the spectrum nearest maximum, a good fit to the data is achieved when the model flux from the companion is close to the observed flux at 2800 Å. All of the models predict fluxes that are close to the observed flux at 2800 Å. Of the two acceptable models, the flux at 2800 Å predicted for the 10,000 K model is closest. The 10,000 K model atmosphere flux distribution also provides the best fit to the data for all other lower values of the color excess. We therefore feel that the 10,000 K model provides the best overall representation of the data.

An effective temperature of 10,000 K indicates that the companion is an A0 star (e.g., Allen 1973). If it is at the distance of the Cepheid, the companion star must have an absolute visual magnitude somewhat higher than that of the Cepheid. Otherwise it would dominate the visual spectrum of the Cepheid. This rules out a luminosity class I A star which is brighter in the visible than T Mon, and probably a luminosity class II A star which is only 2.7 mag fainter than the mean absolute visual magnitude of a Cepheid with the period of T Mon (Allen 1973). A white dwarf at the distance of T Mon would have negligible ultraviolet flux relative to the Cepheid. Thus we conclude that, if the companion is at the distance of the Cepheid, it must be luminosity class III, IV, or V.

If we assume that the companion star is at the distance of T Mon, then we can use the observed ultraviolet flux to estimate the radius of the star and hence its luminosity class. The radius is given by the expression \( R / d \), where \( R \) is the radius of the star, \( d \) is the distance to the star, \( F_s \) is the surface flux at the star, and \( f_\odot \) is the flux measured at the Earth, corrected for interstellar absorption using a measured color excess. A wide range of values has been determined for the color excess for T Mon. Patterson and Neff (1979) list a range of determinations for \( E(B - V) \) from 0.13 to 0.58. Dean, Warren, and Cousins (1973) argue strongly for a value of 0.18, and van den Bergh (1977) suggests that an excess of about 0.23 is appropriate. Using the theoretical flux for the 10,000 K model at 1608 Å from Kurucz (1979), an observed flux at the Earth of 1.5 × 10^{-13} ergs cm^{-2} s^{-1} Å^{-1}, a distance to T Mon of 1090 pc from Kraft and Schmidt (1963), and the interstellar extinction law of Savage and Mathis (1979) with \( E(B - V) \) varying from 0.15 to 0.40, we find a range of radii for the companion star of 2.7–7.1 \( R_\odot \). If we use the distance estimated by Turner (1976), the radii are increased by about 30%. These results indicate that the companion could be of luminosity class III–V.

The mass of the Cepheid should be around 9 \( M_\odot \), while the companion should have a mass of about 3 \( M_\odot \) (e.g., Allen 1973). Stellar evolution theory predicts that it takes about 23 × 10^6 years for the Cepheid to reach the instability strip. For a 3 \( M_\odot \) star, however, the main-sequence lifetime is in excess of 220 × 10^6 years (Iben 1967). Thus the companion star should be on the main sequence. A luminosity class III A0 star is approximately two visual magnitudes above the main sequence. Thus, if the companion star is physical rather than just line of sight, it must be of luminosity class V. If this is the case, then using an absolute visual magnitude of +0.7 (Allen 1973) and a visual absorption of 0.5 mag, we predict a visual magnitude for the companion of about 11.4.

Although the spectra are of low resolution, it is still possible to use inferred characteristics of the two stars to set some limits on the dynamics of the system. The maximum angular separation of 1′5 at the 1090 pc distance of the system gives a maximum separation of 1635 AU. If we assume a mass of 9\( M_\odot \) for the Cepheid and 3\( M_\odot \) for the companion, then from Kepler’s third law the maximum period of the system is about 19,000 years. If we assume that the system is seen edge on and that the motion is circular, then the maximum radial velocity for this period would be 2.6 km s^{-1}. A radial velocity change of ±2.6 km s^{-1} is probably detectable; but the period is so long that no significant change would take place over the interval for which observational material is available. In addition, any inclination other than edge on would reduce the observed velocity. However, there is no observational evidence in the literature on T Mon for any anomalous behavior in either the radial velocity as a function of phase or the radial velocity of the Cepheid as a whole. Recently, however, Madore and Fernie (1980) have found photometric evidence for a companion about 2 mag fainter than the primary. We can provisionally conclude, until perhaps high-resolution spectra are obtained, that if the companion is physical rather than a line-of-sight coincidence, then the two stars are either widely separated.
or, if not widely separated, that the inclination of the orbit is considerable.

Because of the potential for determining the mass of the Cepheid, it would be of considerable interest to examine the system at high spectral resolution. An accurate measurement of the radial velocity of spectral lines of the companion in the ultraviolet may show a different velocity than that for the Cepheid as a whole. The flux from the companion near 2800 Å is large enough that such an observation could be made at high spectral resolution with IUE. The fact that the Mg II lines near 2800 Å are nearly absent suggests that the companion star contributes much of the observed flux at that wavelength. In addition, if we assume that the flux from the Cepheid is 20% of the total flux at 2800 Å, then using the fluxes from a 5500 K model atmosphere for the Cepheid and the 10,000 K model for the companion (Kurucz 1979), we find that the flux from the companion should be about a factor of 6 less than the flux from the Cepheid at the Ca II H and K lines. Thus there is a possibility of detecting the companion through its effect on the cores of these lines. Sanford (1956) noted an absorption feature in the cores of the H and K lines with a mean velocity of +16.9 km s\(^{-1}\) and little or no variation during the cycle of the Cepheid. He suggested that these lines were interstellar; however, Kraft and Schmidt (1963) list a radial velocity of +32.5 km s\(^{-1}\) for T Mon. Thus there is a possibility that these features are not interstellar. Recently, Baliunas (1980) has obtained high-resolution Ca II K line spectra of T Mon. These spectra show a number of variable features in the core of the line, but not enough spectra have been obtained to permit full understanding of the data. It is clear that further high-resolution observations of T Mon are desirable, both in the ultraviolet and visible wavelength regions.

We gratefully acknowledge many conversations with S. L. Baliunas during the course of this research. Part of this research was supported by an IUE Guest Investigator grant from NASA.

REFERENCES


