THE ECLIPSING BINARY WHITE DWARF BD + 16^0 516

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Abstract. From spectroscopic and photoelectric data BD +16^0 516 (V 471 Tau) is inferred to consist of a white dwarf of mass $0.72 M_{\odot}$ and radius $0.012 R_{\odot}$, with a detached K2V companion of mass $0.70 M_{\odot}$ and radius $0.78 R_{\odot}$; the separation of the two components is $3.02 R_{\odot}$. The evolutionary history of the system is discussed.

When BD + 16^0 516 (V 471 Tau) was found in 1970 to be an eclipsing binary involving the total eclipse of a white dwarf (Nelson and Young, 1970), hopes ran high for definitive results about the physical parameters of a white dwarf. Although these hopes were partially fulfilled, the analysis of this system, as is so often the case, has developed more questions than it has answered. These questions in stellar evolution are not new to students of this subject, but this system so sharply emphasizes them that the investigator is forced to re-examine all aspects, both empirical and theoretical, and to identify systematically those steps in the derivation of our understanding of this type of system which could, by reformulation, lead to a better understanding of these objects.

On the assumption that white dwarfs are indeed numerous in the Galaxy and with the knowledge that binary systems are in fact numerous, it appears reasonable to infer that BD + 16^0 516 is not unique; it is of general interest and, perhaps, quite fundamental to our understanding of the evolutionary processes in binary stars. We begin by reviewing briefly some of the observational material and the derived parameters, with particular attention to possible sources of misinterpretation which could contribute to the problems of this system.

The light curve is irregular and changes noticeably in short periods of time – on the order of months – and often changes drastically from one season to the next. The light curves in the three colors (*UBV*) show slight behavioral differences between themselves, but very marked differences during the eclipse of the white dwarf. As would be expected, the eclipse is relatively deep in ultraviolet light (0.35 mag) but almost nonexistent in yellow light. During totality, the light-curve shows considerable irregularity, obviously due to the K2 companion.

The durations of ingress and egress are so short – about 55 s – that ordinary photometric techniques are inadequate. Time resolution must be of order 1s. At Mount Laguna Observatory (Young and Nelson, 1972), we modified our charge integration system to a continuous output in connection with a high-speed strip-chart recorder. This equipment was used on a 41-cm telescope at Mount Laguna and a 1.27-m telescope at Kitt Peak. Warner *et al.* (1971) used very sophisticated high-speed photometric equipment on the 2.1-m telescope at McDonald Observatory. At times, simultaneous photoelectric observations were made at Kitt Peak and Mount Laguna in conjunction with spectroscopic observations at Kitt Peak. Therefore, this phase of the observational material is extensive and consistent.

In the wavelength interval 3400–6600 Å, the spectrum of BD + 16^0 516 displays single lines of a late-type dwarf. The lines are considerably broadened by rotation, thereby rendering classification difficult. Consequently, the adopted spectral type of K2 is based upon the $(U-B)$ and $(B-V)$ colors. The luminosity classification of V is predicated upon the Hyades membership of this system as discussed by Young and Capps (1971). The relative strengths of the singly ionized strontium lines at 4077 Å and 4215 Å are consistent with that classification. Strong emission lines of singly ionized calcium are present, as is typical for late-type components of close binary systems. No other emission lines have been found in the wavelength interval which has been examined.

The radial velocities derived from the H and K emission features were scrutinized and found in general to differ from the mean absorption-line velocity for each plate by no more than the expected probable error for a single line. Therefore, we presume that they originate in a chromosphere around the K star. However, the observations of 1971 April displayed systematic positive residuals for these emission lines on the order of 25 km s^{-1}. These observations are in the phase range 0.53–0.67. Young (1976) notes that these observations are confined to an epoch interval ($E \sim 750$) which is just prior to an abrupt and substantial increase in the orbital period recently demonstrated by Young and Lanning (1975). At the same time, the absorption line velocities showed larger than usual residuals from the velocity curve, and all were systematically negative. The evidence suggests that the external layers of the K dwarf were disturbed at that time, possibly by a mass flow within the system.

An unsuccessful search has been made for spectroscopic features of the white dwarf in the ultraviolet, using tracings made from 18 Å mm^{-1} spectrograms which were obtained with the 5.08-m coudé by Greenstein.

Thirty-seven spectrograms, well distributed in phase, were used to determine the velocity curve. Thirty-three of them were obtained with the 2.3-m Cassegrain spectrograph at Kitt Peak with a dispersion of 39 Å mm^{-1}. The remaining four were obtained by Kraft and Anderson with the 3.05-m coudé spectrograph at Lick Observatory at a dispersion of 47 Å mm^{-1}. All of the spectrograms were measured on a Grant oscilloscope comparator, and wavelength adjustments were made based upon the statistics of line residuals. Eighteen standard stars of similar spectral type were observed to provide transformation to the Wilson system.

A solution for the orbital parameters from the velocity curve indicates a circular orbit and a γ velocity of $+40.0 \pm 2$ km s^{-1} which compares favorably with the computed radial velocity this system should have if it is a member of the Hyades, i.e. $+34.3$ km s^{-1}. The position angle should be $99°51'$ and that given by Giclas *et al.* (1962) for this system is $99°$. From the proper motion of 0.09 arc sec yr^{-1} given by Giclas *et al.*, and the standard formula for a moving cluster, the absolute visual magnitude is $+6.8$ mag. This is to be compared with $M_v = +6.5$ mag as determined by the color-color and H-R diagram given by Johnson *et al.* (1962) as well as those given by Morgan and Hiltner (1965). It would seem that the spectral classification of K2 V for one component is reliable.

The solution of the light curve proved to be very difficult due to the unusually small value (0.01) for the ratio of the radii. The reason is obvious – the white dwarf is being eclipsed by what almost amounts to a straight edge. Therefore, the shape of the top of the ingress or egress curve is almost identical to the shape at the bottom. This makes it very difficult to determine the ratio of the radii, the limb darkening, and the angle of inclination. The tables of auxiliary functions do not behave well for such small values of k so a computer program was written to optimize the parameters for the best fit of a computed curve to the observed curve. In that the limb of the K star does not present a truly straight edge, a weak solution is possible which will strengthen with improved data.

To define the results more precisely iteration was used; this involved the expression for the projected separation, assumed values for the mass and radius of the K star and the angle of inclination, which leads to the computation of the mass function and re-evaluation of R_K. From this procedure and additional data provided by Warner *et al.* (1971), Young and Lanning (1975) have recently published improved values for the two components. They assume the K dwarf to have a mass of $0.70 M_\odot$ and infer a radius of $0.78 R_\odot$ and for the white dwarf a mass of $0.72 M_\odot$ and a radius of $0.012 R_\odot$. The separation is $3.02 R_\odot$ or $3.87 R_K$. The tables for the Roche model indicate that the K star does not fill the inner-Roche lobe.

Young and Lanning (1975) discussed all available observations obtained during the past 4.7 yr (3300 cycles) and noted systematic variations in the predicted times of contact. A plot of the (O-C) curve, suggests that the period first decreased, then increased, and is now decreasing at the rate of about 2 s per century.

BD + 16^0 516 raises very interesting evolutionary questions: How can a system composed of two stars, each with a mass of about $0.7 M_\odot$, and orbital separation of $3 R_\odot$ and a period of 0.5 days produce a white dwarf? No rearrangement of the present total mass could provide one of the stars with enough mass to have evolved off the main sequence during the existence of the Hyades. On the other hand a system with sufficient mass, say 2.0 to $3.0 M_\odot$, to evolve in the available time would require rather special circumstances of mass loss to result in the mass, separation and period of this system. Were the two stars initially farther apart or closer together than they are now? Hills and Dale (1974) present a case for the two stars being initially farther apart. They propose that the progenitors consisted of a $0.18 M_\odot$ star, now the K star, and a $1.9 M_\odot$, now the white dwarf, with an initial separation of about 5 times the present value. A two-stage development is proposed, the first of which attempts to overcome the difficulty of mass transfer to a small target at relatively great distance by isotropic mass loss of $0.48 M_\odot$from the evolving primary. The second stage consists of mass transfer of $0.62 M_\odot$ to the secondary. However, true isotropic mass loss will result in an increase in the period but no change of separation – except, of course, for the very small amount of mass that is intercepted by the less massive companion. Thus it is difficult to see how the two components can get close enough for the very small mass of the secondary to contribute significantly to the development of a Roche surface that would be effective in transferring appreciable mass and thus reducing the separation to its present value.

Other investigators such as Refsdal and Weigert (1969), for example, using a computer program described by Kippenhahn and Weigert (1967) computed the evolution for systems having total masses of $2.5 M_\odot$ but with various initial mass ratios and separations. This approach to the problem is very intriguing but, unfortunately, the numbers do not fit the case of BD + 16^0 516. Their method is conservative so far as mass is concerned. The starting mass of $2.5 M_\odot$, total, is a reasonable minimum initial mass for BD + 16^0 516 but at least $1 M_\odot$ must be lost to fit this system. Further, the separations and periods increase markedly throughout the process. In the cases considered, the final separations and periods are much too large to fit BD + 16^0 516. It would be of great interest to compute an evolutionary track with a very small initial separation and with sufficient mass loss to end up with parameters that fit BD + 16^0 516.

This is not to say that the above mentioned approaches are not capable of accounting for the existence of a system like BD$+16^0$516 but clearly there are important problems that must be attended to before the question can be considered resolved. At Mount Laguna Observatory we are pursuing two ideas. One involves a star of sufficient mass to evolve in the time available and a very small companion at a separation somewhat greater than present. The evolutionary process with mass transfer and decrease of separation takes place first, followed by an isotropic mass loss similar to the planetary nebula process, thus achieving the required mass loss and final separation. The other idea involves a single large-mass fast-rotating star, the collapsing core of which undergoes fission. Ostriker and Tassoul (1969) and Ostriker (1970) has pointed out that this process of white dwarf formulation is unlikely but possible. The idea has strong appeal because of certain simplifications to the problem. Is our understanding of these processes developed to the level where we can rule out the possibility of fission followed by slow outward spiraling? If the collapsing core increases its rate of rotation to the point of fission, will not some of the inner envelope also increase its rate of rotation and thus be able to transfer angular momentum to the outward spiraling pair? It is difficult to dismiss the idea of a rapidly rotating core undergoing fission into two small fragments of roughly the right mass and composition to result in a red and white dwarf close binary with surplus mass being dissipated isotropically.

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DISCUSSION

Ostriker: In answer to your two final questions:

(1) The separation envisaged prior to the hypothetical cannibalization of the K dwarf by the expanding giant (in the prior evolution) must have occurred at a separation of ~1 AU.

(2) Fission is unlikely to result in two stars of such different mean density.

Smak: From my *UBV* data, collected at KPNO last year, it appears that the K star might have a UV excess of about 0.1 Mag. Do your latest data confirm this?

Nelson: Early data shows a small amount of UV excess. Later data has not been examined for this.

Hall: The photometry of Smak and Oliver, discussed at the Gainesville AAS meeting, shows that the wave migrates towards decreasing orbital phase with a period of something like 9 months or 1 year. This explains the apparent scatter in your first light curve. Also this explains why your second light curve, obtained only one year later, appeared to show a migration towards increasing orbital phase. Does this migrating wave account for the variable depth of primary minimum in such a way as to leave the actual depth of eclipse (in light units from external contact to internal contact) the same?

Nelson: This is the interpretation that we have placed on these observations. Our own extensive observations of RS CVn lead us to this conclusion.

Hall: Since V471 Tau is so similar to the RS CVn binaries (although I do not think it actually is an RS CVn binary), you might understand the ultraviolet excess, which Smak mentioned, in the same way. It probably is related to the strong chromospheric activity on the K star, and not to a shell of circumstellar matter detached from the star.

Nelson: We are convinced that we are seeing chromospheric activity rather than a circumstellar shell.