IUE ULTRAVIOLET SPECTRA OF THE INTERACTING BINARY U CEPHEI

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1. INTRODUCTION

The eclipsing binary U Cephei has proven to be of great interest in the study of stellar evolution in close binary systems. Batten (1974), Hall and Walter (1974), Rhombs and Fix (1976), Markworth (1977), and Olson (1978), among others, have recently reported on their intensive ground based studies of U Cephei. Kondo, McCluskey and Wu (1978) have investigated the ultraviolet light curves of U Cephei obtained with Astronomical Netherlands Satellite (ANS). Kondo, McCluskey and Stencel (1979) have discussed the International Ultraviolet Explorer (IUE) spectra of U Cephei. This paper discusses results incorporating additional IUE high resolution spectra of U Cephei obtained in both far-ultraviolet and mid-ultraviolet spectral regions.

According to Batten (1974), the system consists of a B7 V primary of 4.2 $M_\odot$ and 2.9 $R_\odot$ and a G8 III-IV secondary with 2.8 $M_\odot$ and 4.7 $R_\odot$. Its orbital period is about 2.5 days. The G-star is evolved and losing mass, some of which is accreted by the B-star, some leaves the system and some may return to the G-star (Figure 1).

2. OBSERVATIONS

The IUE instrumentation has been discussed in detail by Boggess et al. (1978). All of the observations were obtained in the high resolution modes: three exposures in the far-ultraviolet (1200-1900 A at $\lambda/\Delta\lambda \sim 10^4$) and sixteen exposures in the mid-ultraviolet (1900-3200 A at $\lambda/\Delta\lambda \sim 10^4$). The sixteen mid-ultraviolet spectra, taken over a period of about one year, cover most phases of interest with the exception of primary eclipse which is too deep in the ultraviolet for high resolution observations to be obtained. The three far-ultraviolet spectra were obtained at phases 0.184, 0.680 and 0.903 over a period of about ten months.

M. J. Plavec, D. M. Popper and R. K. Ulrich (eds.), Close Binary Stars: Observations and Interpretation, 237–241.

3. DISCUSSIONS AND CONCLUSIONS

The lines showing the effect of the gas streaming most distinctly are the resonance line of Fe II at 2599.395 A and the resonance doublet of Mg II at 2795.523 and 2802.698 A. The temperature and the density of the gas stream is such that it is seen primarily in terms of phase-dependent, Doppler-shifted excess absorption in those resonance lines. The signature of the gas stream is rather subtle; hence, it can be unambiguously observed only in the strong resonance lines of the ions of these abundant elements. For actual spectral profiles and their variations, the interested reader is referred to Kondo et al. (1979, 1980). The spectral variations cannot be accounted for in terms of orbital Doppler-shifting of the photospheric absorption in the B-star; the gas stream can be seen clearly as shifting excess absorption indicating the directions of the gas stream.

We note that several mid-ultraviolet spectra obtained months apart at nearly the same phase are quite similar. This indicates that U Cephei was relatively stable over this period of time. This is useful when comparing the far-ultraviolet spectra with one another since they were obtained at wide intervals and are few in number. Olson also informs us that U Cephei was in its quiescent state during the period of the IUE observations judging from his photometric data.

Lines of Si II, Si III, Si IV, C II, C IV, Fe III, Al II and Al III have been identified in the far-ultraviolet. Most of these absorption lines are shallow and broad, indicative of the rapid rotation (~300 km s^{-1}) of the B-star and hence of their at least partial association with the photosphere of the B-star. The phase variation of the radial velocities also shows this partial association with the B-star. However, significant total absorption variations, perhaps due to hot/cool spots on the B-star and gas streaming effects, are observed.

To recapitulate, the effects of mass streaming are most clearly seen in the resonance lines of Fe II and Mg II in the mid-ultraviolet spectrum of U Cephei; the far-ultraviolet absorption lines of Si II, Si III, Si IV, C II, C IV, Fe III, Al II and Al III are probably also affected.

A model consistent with these observations is shown in Figure 1. The gas stream leaves the G-star from the hemisphere facing the B-star. It circles around the B-star with some of the gas probably falling onto the forward and trailing hemispheres of this star. The rest escapes from the system after orbiting about 270° around the B-star. Some of this gas may fall back onto the trailing hemisphere of the G-star rather than escaping from the system. Observations near phase 0.15 obtained on June 2, September 7, September 12, 1978 and May 9, 1979 indicate a relatively stable stream pattern during this eleven month period.

The radial velocity of the edges of the absorption features are as high as 400-500 km s^{-1} along the projected line of sight. With the exception of locations near the B-star, which has an escape velocity of about 740 km s^{-1}, this velocity is sufficient to allow the gas to escape from the system.

It is possible that one source of the kinetic energy of the gas stream is the same mechanism that may drive stellar winds. Wolff and Kondo (1978) noted that the non-linear mode (g-mode) of oscillations in one of the components in a binary system (e.g., HZ Her = Her X-1) may lead to a surge of mass from the star. Modisette and Kondo (sumbitted for publication) indicate that this mass surge could be a continuous phenomenon if the beat periods of the harmonics involved are sufficiently close to each other. Another source of energy for the gas stream is heating by the B-star of the G-star's facing hemisphere; it could also contribute or give rise to the observed mass ejection (cf. Modisette and Kondo).

The gas in the stream is hot enough to keep most Fe, Si and Mg atoms in ionized states; it is well above 10000°K. The density of the gas is low enough so that practically all atoms are in the ground state; it must be below about 10^{15} particles cm^{-3}. Batten's estimate of 10^{13} electrons cm^{-3} is consistent with our data. The absence of emission probably indicates that the total volume occupied by the gas stream having significant densities is not much larger than the volume of the B-star.

With the advent of high capacity computers, it has become possible to treat the gas flow problem hydrodynamically. Some pioneering efforts are already being made in this direction. However, in order to construct a viable model, knowledge of the physical parameters involved (e.g., the direction of the gas flow, temperatures and densities of the gas, and boundary conditions) is essential. At the temperatures and densities of the plasma involved, the signature of the gas stream of the plasma can be investigated effectively by analyzing the resonance lines of ionized abundant elements in the ultraviolet. Extensive ultraviolet observations of selected binary systems portend to yield this much needed information.

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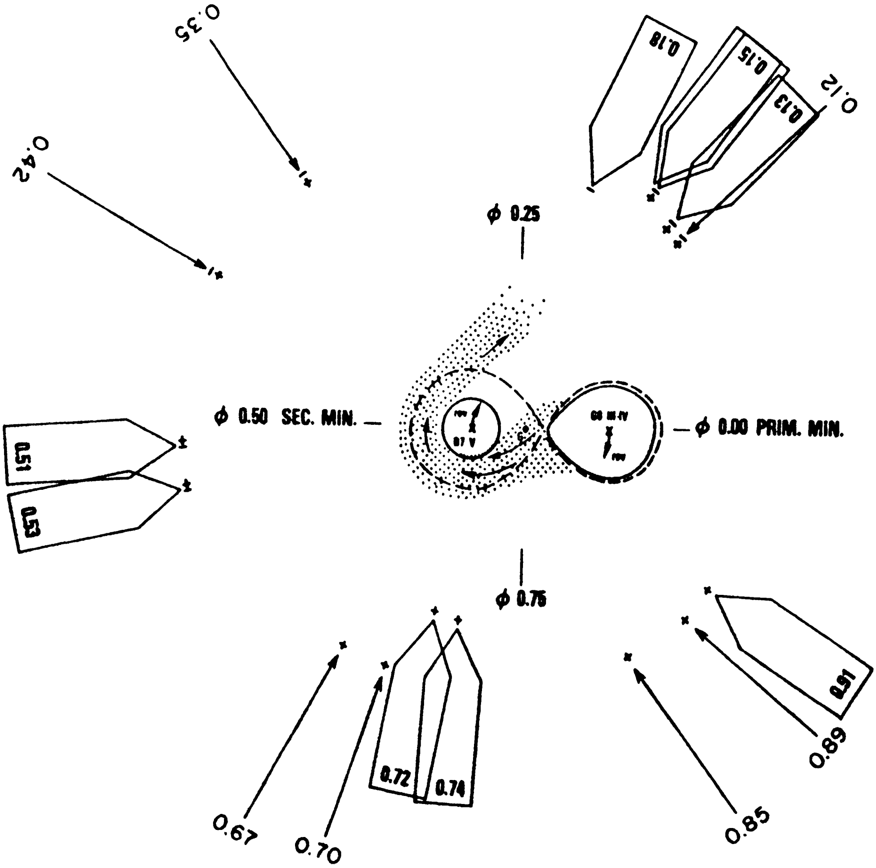

Figure 1. Schematic representation of the gas stream as observed in the Fe II and Mg II resonance lines. The broad arrows are the data from 1978 June and September and the thin arrows are the data from 1979 March and June: the phases of observation are also given. The + sign indicates that the radial velocity of the gas stream projected against the B-star is away from the observer, the - sign that the radial velocity is toward the observer, the ± sign both away and toward the observer, and the ∓ sign mostly toward, but with a minor component away from, the observer. The + sign at phases between 0.67 and 0.91 is probably due to the combination of the gas streaming around the B-star and the gas falling onto that star creating a hot spot which faces the observer shortly after phase 0.75. The ∓ sign at phases between 0.12 and 0.15 is probably due to the partial occultation of the B-star by the matter leaving the G-star.

COMMENTS FOLLOWING KONDO, MC CLUSKEY AND STENCEL

Stencel: These data do not rule out the possibility of a disk around the B star. Lines of singly ionized Fe and Mg are lower ionization. We do not yet have sufficient phase coverage in the farther UV where higher ionization lines might reveal the 12000°-13000°K disk discussed here by Olson.

Peters: Have you attempted to obtain an estimate of the column density in the stream from the observed strengths of the Fe II absorption?

Kondo: We have attempted to do so using various approaches but have thus far been unable to separate the photospheric components in the observed absorption feature. The problem is also complicated by the possible presence of hot (or cool) spots on the B star; this might give rise to varying photospheric component.

Smak: Do you exclude the possibility of contamination by emission components?

Kondo: We have been unable to detect evidence of any emission lines. The possibility of contamination by emission components could not be ruled out simply from the current data.

Nariai: I wonder if you can accelerate the flow by the gravitational accelerator.

Kondo: Simple conversion of gravitational potential energy to kinetic energy would not give rise to the observed gas stream which is leaving the binary system. We do need an additional source of energy. However, we do not claim that the local heating due possibly to the convergence of the non-linear (g-mode) oscillations is the only conceivable mechanism causing the mass ejection.

Shu: I wish to disagree somewhat with Nariai's comment. In the case of Roche lobe overflow, with matter leaving L_1 at $\sim$ sonic speeds, the matter is effectively trapped inside the Roche surface of the detached component (unless there are non-gravitational forces which intervene).

Kondo: (Please see my reply to Dr. Nariai's query.)