Exotic Stars as Challenges to Evolution
ASP Conference Series, Vol. 279, 2002
C. A. Tout and W. Van Hamme, eds.

Binaries with Invisible Massive Components

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Abstract. V505 Mon is an early type eclipsing binary (usually classified as B5 Ib), in which only spectral lines of the primary component are visible. The radial velocity curve provides $f(m) = 4.6\,M_{\odot}$, suggesting that the secondary, invisible component is more massive. We have found evidence that this star is hidden from view by the disk detected during the primary eclipse. The structure of the disk can be characterized by a central ionization zone surrounded by the neutral outer parts. The profiles of the CII 1335/6 doublet lines were used to derive the rotational velocity of the disk as well as the velocity of the stream from the primary component to the disk. The masses of the components, deduced from the fractional size of the disk, are $M_1 = 1\,M_{\odot}$ and $M_2 = 6.1\,M_{\odot}$. Due to the low mass of the primary component its supergiant nature can be ruled out. Additional matter of a cloudy nature is present in the system and both components are embedded in an extended atmosphere. V505 Mon seems to be a prototype of the whole group of similar early-type binaries, in which the more massive component is hidden by a circumstellar medium, most likely a disk. Probable members are V742 Cas, V1362 Cyg, V2174 Cyg, V447 Sct and FY Vel with orbital periods between 33 and 225 days. Emission in Hα is always present, but there are no emissions in IUE spectra, so these binaries are distinct from the W Ser type. The evolutionary state of the members of this group is not yet understood.

1. Introduction

In the comprehensive photometric and spectroscopic study of the early-type eclipsing binary V505 Mon Mayer et al. (2001, Paper I) challenged its supergiant nature and found the detailed structure of the circumstellar matter in the system consists of a disk surrounding and masking the more massive secondary component. The system is embedded in an extended circumbinary atmosphere. In our paper, we would like to support this view by detailed analysis of eclipses in the system and to show that V505 Mon is a prototype of the whole group of early-type binaries with invisible massive component.

2. V505 Mon - an early type binary with a disk

V505 Mon was first reported as a photometric variable by Wachmann (1966). Chochol & Kučera (1981) detected the eclipses and found the orbital period 53.78 days confirmed by Stagni et al. (1982) from low-dispersion spectroscopy. In Paper I, we determined the spectroscopic orbit of the primary component and brought photometric and spectroscopic evidence for the presence of a disk surrounding the secondary component.

2.1. Photometry

The UBV, $ubvy$ and HIPPARCOS photometry of V505 Mon was gathered in Paper I. The y and u light curves obtained during the Long-Term Photometry of Variables program are shown in Fig. 1. The orbital phases were calculated using the ephemeris

$$\text{Min I} = \text{JD2 445 253.71} + 53^{\text{d}}.7745 \times \text{E}. \qquad (1)$$

according to Vogt & Sterken (1993). The b, v and B,V light curves do not differ from the y curve. The primary minimum corresponds to the eclipse of the primary component. The secondary minimum is centered at phase 0.5, so a circular orbit, supported also by symmetric shape of the radial velocity curve, can be assumed. The light curve is affected by a considerable scatter. The timescale of the variability is much shorter than the orbital period. Considerable brightness drops occasionally observed outside eclipses are most probably caused by clouds of circumstellar matter.

The primary minimum in the y passband is a superposition of a shallow trough with wings extending about 0.094 phase units to both sides and of a central dip with a total width of 0.03 phase units (note the small differences in the extend of wings as compared with Paper I). The secondary minimum is very sharp with a width equal to that of the primary minimum central dip. In the u passband the trough is double peaked. It reaches its maximum depth at phases 0.96 and 0.04. The shape of the wide primary minimum suggests the existence of the disk surrounding the secondary component. Fig. 1 illustrates an attempt to fit the y and u light curves with disk profiles. The neutral absorption (electron scattering) is modelled by a disk concentrated to the secondary component with a density linearly decreasing to its outer edge. The total absorption at the phase 0.0 is 0.19 mag. The Balmer absorption (visible only in u) is modelled by a disk with outer radius R identical to the neutral disk and with inner radius $r = 0.4R$. The density again decreases linearly from the inner to the outer radius, at the outer radius being in both cases zero. The absorption at the phase 0.0 is 0.22 mag. Since the $B - V$ and $b - y$ indices are nearly identical in both eclipses the effective temperatures of components are nearly the same. The secondary might be a main-sequence star.

2.2. Spectroscopy

Spectroscopic study is based on the optical photographic and electronic spectra taken at various observatories in the years 1977-94 and the UV IUE spectra obtained in the years 1983-96. For the list of the spectra see Paper I. The star eclipsed during the primary minimum exhibits He I, Mg II, Si II, Si III, O II,

https://doi.org/10.1017/S0252921100001329 Published online by Cambridge University Press

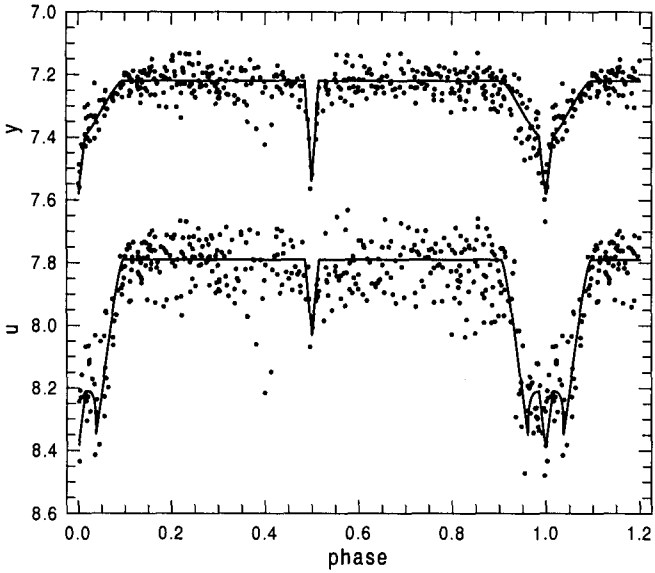

Figure 1. The LPTV y and u light curves of V505 Mon fitted with disk profiles.

N II and S II absorptions. They follow a sinusoidal radial velocity curve with semiamplitude $K_1 = 93.4$ km s^{-1} and systemic velocity $V_0 = +28.3$ km s^{-1}. It provides the semimajor axis of the orbit $a_1 \sin i = 99$ R$_\odot$ and the mass function $f(m_2) = 4.55$ M$_\odot$. Possible combinations of the primary and secondary masses are given in Table 4 of our Paper I. Neither component is filling its Roche lobe. Using the extent of the disk from photometry and the fact that in Algols they occupy 90 to 95 % of the Roche lobe (Peters, 1989) one can find the corresponding mass ratio of about 0.16. Such a value means that the primary component has a mass about 1 M$_\odot$ and might be similar to the hot components of symbiotic binaries, where a white dwarf with extended atmosphere spectroscopically resembles A to F supergiants. Alternatively, the primary component can be in a stage of planetary nebula birth, when the hot nucleus surrounded by an optically thick envelope is source of the wind, which supports the accretion disk of the secondary component.

The various spectral lines exhibit quite different characteristics and provide information about the components and structure of circumstellar matter in the system. Hα is the only line with an emission component. The emission profile appears to be double-peaked with a central depression. Stationary emission has a width of about 400 km s^{-1} and a height of the profile of 40 to 60% above continuum level. Several absorption components are variable and deepest at phases near the primary minimum. A component with about zero velocity is always present. It must be formed in a circumbinary envelope.

Other Balmer lines are often split into two or more components and, similarly to Hα, the main component is of zero velocity. To estimate the effective

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temperature and gravity of the primary component we tried to fit observed H_β - H_δ profiles with the synthetic ones. The Balmer line profiles in the spectra taken at phase 0.8 are double peaked, with one component belonging to the primary and the second probably originating in the circumbinary envelope. The first component is rather sharp with steep wings indicating a surface gravity lower than the limit $\log g = 2.5$ of the Kurucz models. Therefore, NLTE effects play an important role. Moreover, the higher abundance of He, indicated by strong He lines, could affect the model of the atmosphere. Preliminary analysis with the SYNSPEC42 code (Hubeny et al. 1995) suggests that $T_{\rm eff} = 15\,000$ K and $\log g = 2$.

Helium lines usually have some strange components and exhibit deep profiles at phases, where the effect of the disk is expected.

Table 1. Parameters of the gaussians used to model contributions. Continuum level is in units of continuum at phase 0.292

Phase	Continuum level	Primary component velocity ($\mathrm{km\,s^{-1}}$)	Stream depth	Stream velocity ($\mathrm{km\,s^{-1}}$)
0.065	0.65	-9	0.50	-95
0.121	0.77	-36	0.46	-98
0.169	0.90	-53	0.36	-102
0.292	1.00	-62	0.30	-125

Several features can be recognized in the UV resonance doublet of C II 1335/6 Å. In Paper I, we identified the absorptions caused by the disk in the spectra taken during the primary eclipse and used them to calculate the rotational velocity of the disk. Moreover, we pointed out the existence of a feature at phases 0.065 to 0.292, which was not explainable by the known contributors to that profile. Our Fig. 2 and Table 1 present an attempt to compose the profile from various sources:

- The circumstellar component represented by a gaussian curve with a truncated maximum at radial velocity $+13.5\,\mathrm{km\,s^{-1}}$; depth is 1.2 of the continuum (truncated at 0.12) and FWHM $54\,\mathrm{km\,s^{-1}}$.

- The primary component represented by a gaussian curve at the velocity given by the radial velocity curve $V_0 + K_1 \sin\phi$; depth is 0.445 of the continuum and FWHM $80\,\mathrm{km\,s^{-1}}$. In contrast to normal stars of similar spectral classification, these absorption features in V505 Mon are rather narrow, probably due to the reduced carbon abundance.

- The component originating in the disk is present at phase 0.065, with velocity $-135\,\mathrm{km\,s^{-1}}$, depth 0.365 and FWHM $22\,\mathrm{km\,s^{-1}}$.

- The component of unknown origin, presumably a stream from the primary to a disk of the secondary component; FWHM is always $60\,\mathrm{km\,s^{-1}}$.

3. Similar systems

V505 Mon, as an eclipsing system, seems to be prototype of the small group of emission-line binaries with similar characteristics. All these binaries, listed

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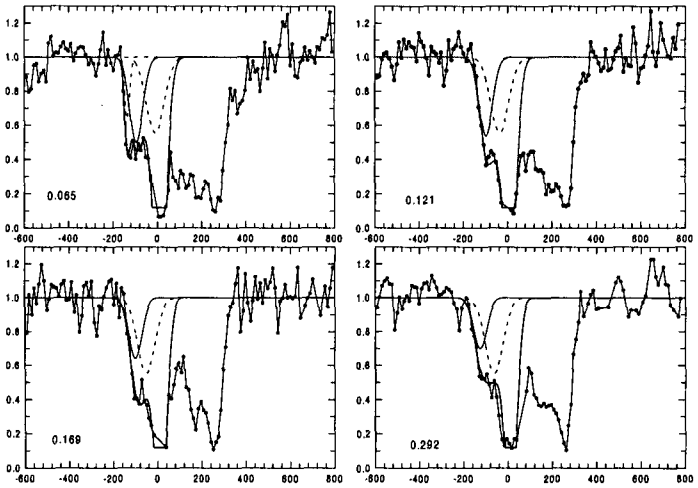

Figure 2. The C II 1335/6 profile in different orbital phases given by ephemeris (1). The normalized fluxes versus radial velocities in km s^{-1} are presented. The contributions by the primary component and by the disk are displayed by broken lines, the stream component and the resulting profile by full lines. A line also connects the open circles representing the measurements.

in Table 2, except V505 Mon are non-eclipsing. In the spectra of these objects only one set of lines is visible, which gives quite a large mass function. Their supergiant classification is questionable. The orbits are circular and the common characteristics of Be stars, large rotational velocity, V/R changes, long term variability and sudden brightness changes are absent. Of course, β Lyrae fulfils these criteria, but it does not belong to this group: in binaries we have in mind neither component fills its Roche lobe. In all cases, the light curves possess short-time variability of the order of 0.1^m. FY Vel displays a β Lyr type light curve with the amplitude 0.3^m. An eclipse can be present, however the light curve can be explained as ellipsoidal, due to a component close to its Roche lobe.

Table 2. The list of binaries with invisible massive companion

Variable	HD/ HDE	P/d	$f(m)$ $M_\odot$	Parallax (mas)	Source
V742 Cas	698	55.9	3.1	2.16±0.77	Sahade et al. 1992
V505 Mon	48914	53.8	4.7	1.11±0.88	Mayer et al. 2001
FY Vel	72754	33.7	8.9	1.45±0.52	Thackeray 1971
V447 Sct	173219	58.4	5.0	-1.41±1.05	Hutchings, Redman 1973
V1362 Cyg	190467	56.8	1.6	1.30±0.72	Hill et al. 1976
V2174 Cyg	235679	225.3	5.9	0.27±0.87	Bolton, Hurkens 2001

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In the cases that the Hipparcos parallax is meaningful, one gets the following absolute visual magnitudes: -2.25 (V742 Cas; B5 II), -3.38 (FY Vel; B2 Ia) and -2.18 (V1362; B5 II) - always considerably fainter than the supergiant classification would suggest. Anyway "luminosity uncertain" might be also considered as characteristic. For V505 Mon one can find Ib (Hoag & van Smith 1959) to III; for V1362 Cyg B1 Ve (Hiltner 1956), but Hutchings & Redman (1973) find that some features indicate B2 Ib; and in the case V2174 Cyg, Walborn (1971) notes that, "luminosity is uncertain because the helium-to-hydrogen is abnormally large." Another characteristic of this group is weak abundance of carbon.

Apparently, the primary component only mimics the supergiant nature - in spite of the fact that, not only the classification, but also photospheric gravity acceleration corresponds to high luminosity. There are about a dozen Be supergiants known (Hiltner 1956; Garrison et al. 1977). The question arises as to whether also some others among them are not binaries of this type.

Acknowledgments. The participation of DC at the colloquium was enabled by the IAU Travel Support and VEGA grant 1157. We would like to thank Jan Budaj for the help with computations using the code SYNSPEC42.

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