Astron. Astrophys. 318, 53–59 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Is the symbiotic binary EG And an eclipsing system?*

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Received 6 October 1995 / Accepted 10 May 1996

Abstract. We present all available UBV photometry of the symbiotic binary EG And obtained during the last 10 years. The light curves display a double wave through one orbital cycle. It is shown that this behaviour cannot be explained by eclipses of the two detached sources of the continuum radiation. The present models of EG And are not able to simulate satisfactorily variation in both the far ultraviolet and the optical continuum.

Key words: stars: binaries: symbiotic – stars: individual: EG And

1. Introduction

EG And is one of the brightest symbiotic stars. It is a binary consisting of a late type M giant (Kenyon & Fernandez-Castro 1987) and a hot low mass compact star as indicated by observations in the ultraviolet (e.g. Mürset et al. 1991). It is a quiet symbiotic – no outburst has been observed until now.

EG And is a very low excitation object among the symbiotics. Only a few nebular lines of [NeIII], [OIII] and variable emission lines of the hydrogen Balmer series are present in the optical spectrum. However, the ultraviolet spectrum displays a strong continuum; it is rich in emission lines such as CIV, HeII, [OI], NV and NIV. EG And has been studied intensively by the IUE satellite. Recently Vogel (1991) – hereafter V91 and Vogel, Nussbaumer & Monier (1992) explained variations in the far UV continuum by the effect of Rayleigh scattering of the hot component light by the neutral wind of the cool component, assuming a very high orbital inclination ($\sin i$ = 0.99 ± 0.01). They estimated the giant's radius to be $\sim 75\,R_\odot$ and the ratio of bolometric luminosities of the two stars $L_{\rm cool}/L_{\rm hot}$ = 60. Vogel (1993) considers the broad HeII 1640 Å line profile as a proof of a fast wind from the hot component.

The spectroscopic orbit of the giant component has been derived by many authors, recently by Munari (1993). The orbital period is about 482 days (an average value of all independent derivations – see below in Sect. 2). The mass function is very small, between 0.01 and 0.02 $M_\odot$.

Large changes are observed in the hydrogen line profiles. It was found that they vary periodically along orbital motion displaying a minimum of the flux at inferior conjunction of the red giant and vice versa (Smith 1980, Oliversen et al. 1985, Skopal et al. 1990, 1991, Munari 1993). The behaviour in the optical continuum is characterized by a periodic wave-like variation through the orbital cycle. Light curves exhibit two very broad minima during the orbital period observed around spectroscopic conjunctions (e.g. Skopal et al. 1991). A model of the circumstellar matter, located mostly between the components, was suggested by Skopal, Vittone & Errico (1993) – hereafter SVE93 – to explain these variations in the optical continuum as well as in the Hα line profiles. SVE93 suggest that this wave-like variation can be produced by a different projection of the circumbinary nebulosity into the line of sight at different orbital phases. They found that the orbital inclination is $\sim 45°$. This result was independently confirmed by Munari (1993). However, Blanco & Mammano (1995) – hereafter BM95 – suggested that the secondary minimum in the UBV light curves could be caused by an *eclipse* of the cool giant envelope by an extended bright region near the hot component.

At present, there are three different approaches to explain properties in the spectrophotometric data observed. One, claiming the orbital inclination is very high ($\sim 90°$) and studying an ionization model as responsible for changes in the ultraviolet, but ignoring behaviour in the optical continuum (V91, Vogel et al. 1992). Second, a model in which both components of the binary have a stellar wind. This model was used to explain variations in the Hα line profile and some properties of selected ultraviolet lines (Tomov 1995). The third approach attempts, above all, a reliable explanation of the variation in the optical continuum and the hydrogen line profiles by the presence of the circumstellar matter between the components of the binary (Skopal et al. 1991, SVE93, Skopal 1995a, 1995b, 1996), but no adequate application to far ultraviolet continuum has been done. This approach leads to a much lower orbital inclination.

The main aim of this contribution is to present all available UBV photometry, to describe its periodic variation, and to show that the light curves cannot be reproduced by eclipses of the two detached sources of the continuum radiation. The above mentioned models are discussed in more detail in the sense of the variation in both the ultraviolet and the optical continuum.

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[*] Table 1 is only available in electronic form at CDS

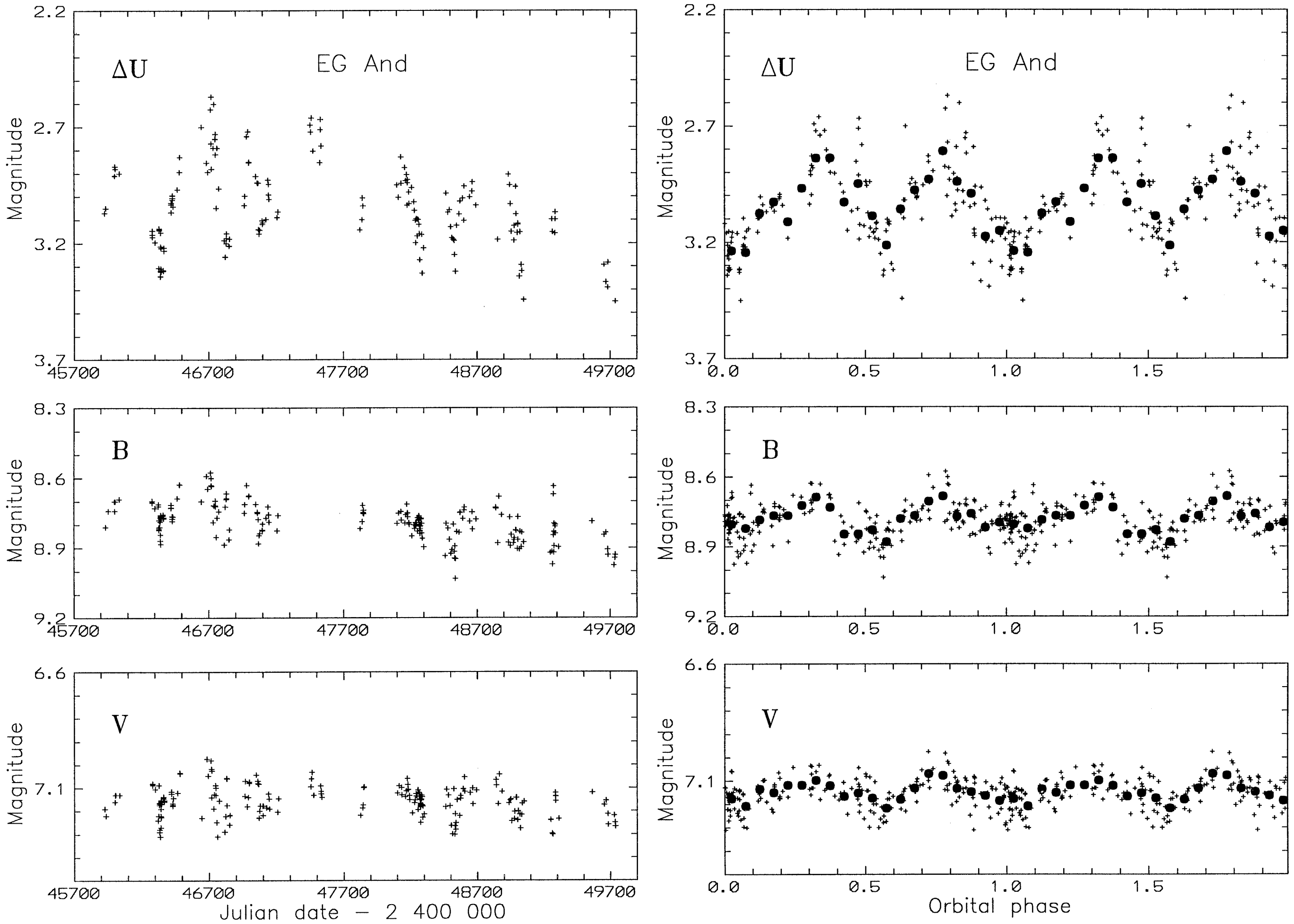

Fig. 1. UBV light curves for EG And. Left panels show evolution of the optical continuum in time. Right panels display their variation along the orbital cycle. Full circles represent 0.05 P means.

2. Observations

This contribution is based on broad band UBV photometry. We collected the available data in Table 1. We present differences of EG And – HD3914 (V=7.00, B–V=0.44) in magnitudes. In cases when EG And – HD4143 was measured, we used a conversion between these standards according to Hric et al. (1991): HD4143 – HD3914 = 4.640, 2.722 and 1.563 in the U, B and V band, respectively. The brightness of EG And in V and B was obtained from that of HD3914, in the U band we present only differential magnitudes (Fig. 1). In this paper we use the ephemeris for the primary minima (∼inferior conjunction of the cool giant) as

$$\mathrm{Min} = \mathrm{JD}\,2\,446\,336.7 + 482 \times \mathrm{E}. \qquad (1)$$

The zero epoch corresponds to the first well-defined minimum in the U band (Skopal et al. 1988) and the period is an average value of the orbital spectroscopic periods obtained from those published by Munari et al. (1988), Skopal et al. (1988), Skopal et al. (1991), Vogel et al. (1992) and Munari (1993).

3. Optical photometry

3.1. Light curve as a function of orbital phase

The behaviour of the UBV light curves as a function of orbital phase is shown in Fig. 1. A modulation displaying a double wave during the orbital period in all colours is the most significant feature of the EG And light curve. The very broad minima are located around orbital phases 0 and 0.55 that correspond to the inferior and superior conjunction of the red giant, respectively. The amplitude of the light curve becomes lower at longer wavelengths. We observe $\Delta U_{\max} \sim 0.5$ mag, $\Delta B_{\max} \sim 0.25$ mag and $\Delta V_{\max} \sim 0.2$ mag (cf. Fig. 1). A period search in the UBV data was performed by using Stellingwerf's (1978) method of phase minimization. The best period of ∼240 days (one half of the orbital period) and its alias of ∼480 days (the orbital period) are clearly indicated in all bands (Fig. 2).

3.2. No reflection effect in the optical continuum

Some spectrophotometric parameters of spectral lines display a wave-like modulation resembling that of a reflection effect

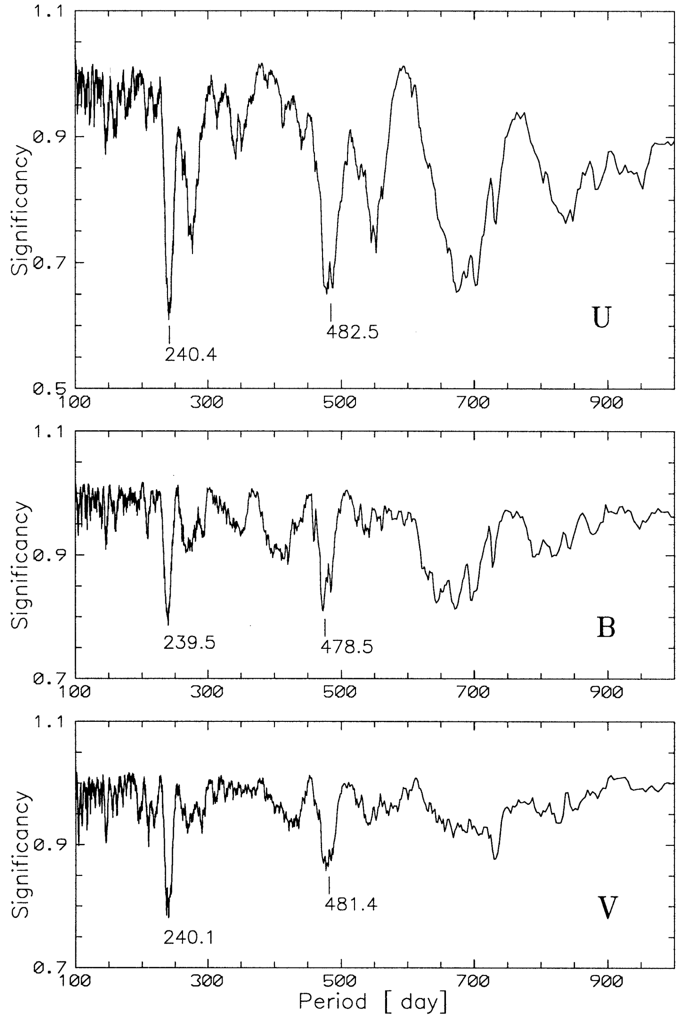

Fig. 2. Periodograms over the range 200–1000 days of the phase minimization of the U, B and V band data in Table 1. The orbital period corresponds to the 480-day peak.

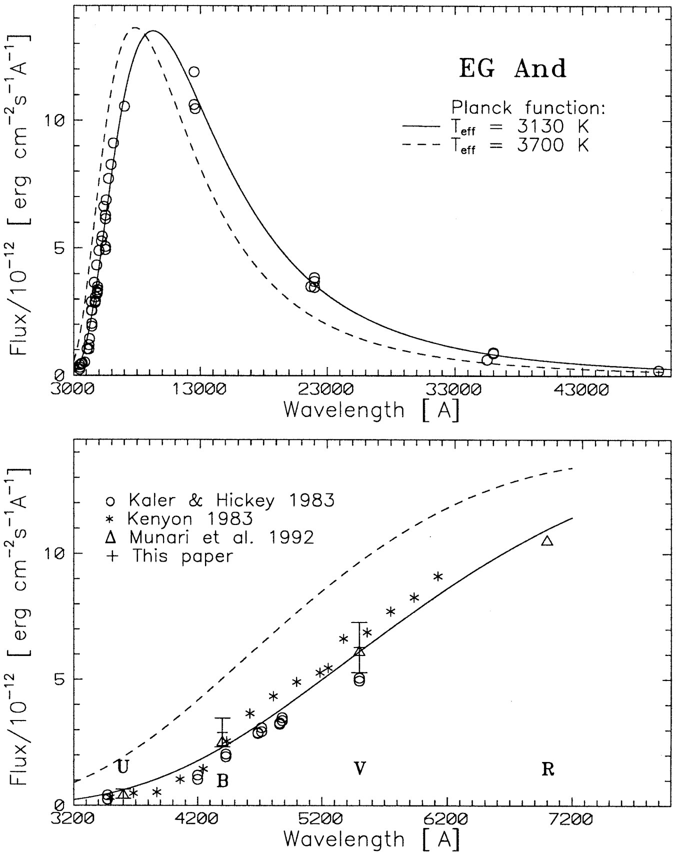

Fig. 3. Top panel: observed energy distribution of the EG And radiation in the optical/infrared spectral region dereddened with $E_{\rm B-V}$ = 0.05. It is fitted well with a black body of 3131 K. Bottom panel shows a detail covering just the optical region. This demonstrates that the hot star contribution in this region is negligible with respect to the radiation of the red giant even in the U band. The error bars represent relevant variations in observed magnitudes (cf. Fig. 1).

– a minimum and maximum flux observed around the inferior and the superior conjunction of the red giant, respectively. Such behaviour was reported by Smith (1980) and Munari (1993) for the equivalent widths of Hα, by Skopal et al. (1991) for fluxes in Hγ, and by Munari (1989) for spectral line fluxes and the short wavelength continuum in the ultraviolet region. Munari suggested that this variability is the result of modulated visibility of the cool giant side heated by the hard radiation field of the hot component. However, it is not possible to explain the W-shaped optical light curve of EG And by the reflection effect, because of the presence of the secondary minimum at the position of the superior conjunction of the red giant (orbital phase ∼0.5), at which a maximum of the reflected light should be observed.

3.3. Radiation in the optical and infrared region

Fig. 3 shows optical and infrared measurements published by Kaler & Hickey (1983), Kenyon (1983) – representative data were taken from his Fig. 5.1, Kenyon & Gallagher (1983), Kenyon, Fernandez-Castro & Stencel (1988), Fernandez-Castro et al. (1985), Bopp (1984), Munari et al. (1992) and mean values of the B, V magnitudes presented in this paper. The magnitudes were converted to absolute fluxes with the calibration of Henden & Kaitchuck (1982) and Gillett, Merrill & Stein (1971), and corrected for $E_{\rm B-V}$ = 0.05 (Mürset et al. 1991). This clearly shows that the optical spectral region is dominated by the radiation of the cool component. This result is important for the following discussion on eclipses in Sect. 3.4.

In addition we found that the observed energy distribution in the optical/infrared spectrum is possible to fit by a black body of T = (3131 ± 37) K. As the fit to observations is pretty good, this temperature can be considered to be the effective temperature of the red giant in EG And. It is of interest to note here that there is a discrepancy between our finding of the effective temperature of 3131 K and that currently accepted for an M2-3 III giant – the present spectral classification of the giant in EG And (Kenyon & Fernandez-Castro 1987) – being of 3700 K (e.g. Ridgway et al. 1980). Fig. 3 shows that the black body radiation of 3700 K does not match the observed fluxes in the optical/infrared region, at all. It is shifted by ∼1400 Å from the data at the maximum. It is not clear what could be a proper cause of this difference. Possibly the TiO and VO bands, used by Kenyon & Fernandez-Castro (1987), are not reliable temperature indicators in the case of EG And to express the overall energy distribution. According to our finding the spectral type of EG And should be as late as M6, which results from the spectral type/effective temperature calibration of Ridgway et al. (1980) and Tsuji (1978). On the other hand, one could speculate that the radiation of the giant's photosphere is totally re-radiated by material above it, where the LTE conditions occur, and thus only simulates a later spectral type.

3.4. No eclipses

Fig. 1 shows that there is no evidence in the light curve of a sudden change in the star's brightness that could be ascribed to the eclipse of stellar disks of the components in the binary. Moreover, Fig. 3 demonstrates that there is no bright extra light in the UBV region besides that coming from the red giant. A scatter in observed fluxes reflects real variations of the EG And brightness shown in Fig. 1. In spite of these facts, BM95 tried to explain the secondary minimum in the UBV light curves in terms of the eclipse of the cool component (pseudo)photosphere by an extended bright region near the hot component. However, this interpretation leads to a conflict with (1) the observed energy distribution in the optical region and (2) possible radii of the binary components.

To the point 1: If this were the case, we could write Pogson's equation for the depth, Δm, of the *secondary* minimum as

$$\Delta m = m_{\rm ecl} - m_{\rm out} = -2.5 \log \frac{L_{\rm h} + fL_{\rm c}}{L_{\rm h} + L_{\rm c}}, \quad (2)$$

where $L_{\rm h}$ and $L_{\rm c}$ are luminosities of the hot and the cool component, respectively, and the coefficient f (<1) denotes the respective fractional loss of light expressed in terms of the total light of the cool component (e.g. f=0 corresponds to a total eclipse). As the depth of the secondary minimum $\Delta \rm U > \Delta V$ (cf. Fig. 1), then, according to Eq. 3, it is simple to show that $(L_{\rm c}/L_{\rm h})_{\rm U} > (L_{\rm c}/L_{\rm h})_{\rm V}$, or

$$(L_{\rm U}/L_{\rm V})_{\rm c} > (L_{\rm U}/L_{\rm V})_{\rm h} > 1, \quad (3)$$

where the last nonequivalence results from well-known fact that the contribution of the blue continuum becomes weaker towards longer wavelengths in the optical domain. Thus the last relation implies $L_{\rm U} > L_{\rm V}$ for the cool giant in EG And, which is, however, in a strong conflict with the observed energy distribution presented in Fig. 3.

To the point 2: In accordance with the eclipse scenario, BM95 suggested that the giant's radius is larger than 159 or $245 R_\odot$ for the mass ratio $M_{\rm c}/M_{\rm h}$ = 2.5 or 1.3, respectively (see their Table 2). However, corresponding Roche lobes, 133 and $117 R_\odot$, are deeply under the suggested radii. It would mean that about 40% or 90% of the volume of the giant star is not bound by the gravity of the mass center of the star – an evident conflict with the basic physics. In addition, the wave-like shape of the light curve cannot be explained by the two detached sources of the continuum. This would lead to unrealistic radii for both components. Therefore Skopal et al. (1991), SVE93, Skopal (1995a, 1995b, 1996) suggested that the circumstellar matter located mostly *between* the components of the symbiotic binary within its common potentials is responsible for such a wave-like variation in light curves and other spectrophotometric parameters of EG And and V443 Her. In this model the observed modulation of the light is produced by a different projection of the optically thick circumstellar nebulosity into the line of sight along the orbital cycle.

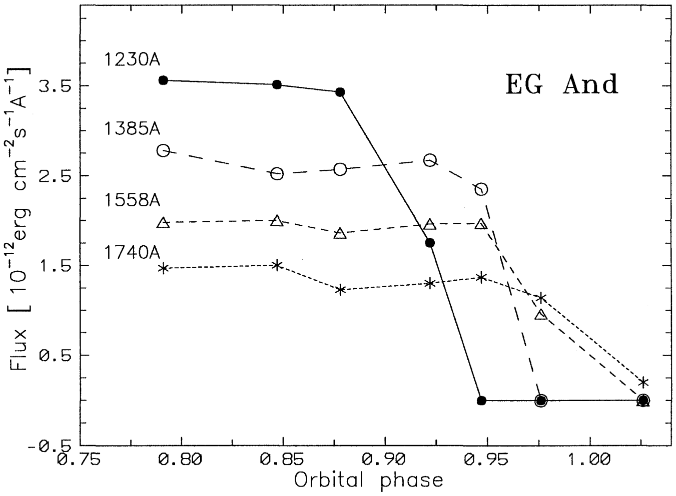

Fig. 4. Ultraviolet light curves for EG And according to the data published by Stencel (1984).

4. Ultraviolet properties

The variation in the ultraviolet continuum and the HeII 1640 Å line was discussed by some authors in terms of the total eclipse of the hot component by the cool giant. In this section we shall show that this interpretation is not unambiguous.

4.1. The ultraviolet continuum

The behaviour in the far ultraviolet continuum (1200 to 1500 Å) around the minimum of the optical light (φ = 0) is shown in Fig. 4. V91 and Vogel et al. (1992) ascribed it to the effects of Rayleigh scattering of the hot component light by the giant's wind. In their model the neutral wind material is shaped in a cone surrounding the red giant and the area behind it, as results from the ionization model of the cool wind proposed by Seaquist, Taylor and Button (1984) – hereafter STB. This geometry constrains the orbital inclination to be very close to 90° to pass the line of sight through a large enough amount of neutral wind of the cool giant to get the observed attenuation of the ultraviolet light. Therefore the authors state that EG And is an eclipsing binary. However, owing to (i) the presence of Rayleigh scattering at the far UV region and (ii) a special type of the cool wind in V91 model, this interpretation is not *unambiguous*.

Ad (i): Here we emphasise that the variation in the far ultraviolet continuum, both its decline depending on wavelength (Fig. 4) and its shape (Fig. 1 of V91) at phases, when the system approaches the inferior conjunction of the cool giant, confirm its nature as caused by Rayleigh scattering. On the other hand if a total eclipse of the hot star light took place, we would have to observe a *simultaneous* decline of the light in all wavelengths from the position of the first contact time, but it is not so (cf. Fig. 4). At the minimum of the ultraviolet flux (~ 0 for $\lambda < 1500$ Å) we are not able to distinguish between the attenuation by Rayleigh scattering and that caused by a total eclipse. This is due to a limiting sensitivity of the IUE satellite ($\approx 10^{-14}$erg cm^{-2}s^{-1}Å^{-1}), which causes that all the fluxes attenuated by Rayleigh scattering under this limit are observed at the zero level, and thus can simulate a total eclipse of the hot component light. However, we still cannot exclude the presence of a real total eclipse, but, at least, such interpretation of the far UV light curves is not unambiguous.

Ad (ii): V91 has artificially constructed a special type of stellar wind law, in order to get such values of the column density, $n_{\rm H}$, of neutral hydrogen that are just needed for fitting the far UV continuum. V91 claims the wind to be *stable* within a distance of $\sim 3R_{\rm cool}$ from the centre of the cool giant. Further, beyond this limit, the wind is accelerated to v_∞ $\sim$30 km s^{-1} (cf. Fig. 4 of V91). However, in accordance with the geometry of EG And (separation of the components $\sim$330 $R_\odot$, mass ratio $M_{\rm cool}/M_{\rm hot} \sim 3$, $3R_{\rm cool}$ $\sim$250 $R_\odot$ $>>$ $R_{\rm Roche} \sim$ 155 $R_\odot$: Skopal et al. 1991, V91, SVE93, Munari 1993) it means that there is a *stable* and dense ($n_{\rm H} \sim 10^{25}$ cm^{-2}, see Fig. 7 of V91) material within the common potentials of the binary as it must be formed mostly by the gravitational power of the stars. On the other hand, such a 'wind' model rather matches a model of the circumstellar matter in EG And suggested by SVE93 – a dense material located mostly within the common potentials of the binary and slowly expanding from distances beyond this envelope.

4.2. The HeII 1640 Å line

The disappearance of the HeII 1640Å flux on the high-resolution spectrum from 1981 October 15 ($\varphi \sim 0$) is also considered to be a proof of the total eclipse in EG And (Oliversen et al. 1985, V91, Vogel 1993). We collected all available HeII fluxes measured on high dispersion spectrograms published by Stencel & Sahade (1980), Pesce, Stencel & Oliversen (1987), Stencel (1984), Oliversen et al. (1985) and Vogel (1993), and show them in Fig. 5. The phase diagram displays a large scatter around the orbital phase 0 rather than a regular decrease expected during an eclipse. In addition, Munari (1989) proved a wave-like variation resembling a reflection effect in fluxes of the ultraviolet lines, including HeII, measured on low resolution IUE spectra. These observations also do not support the validity of the eclipse scenario. Finally, the absorption component of the P-Cygni profile of the CIV 1550 Å line also varies gradually along the orbit. They are most pronounced at superior conjunction, weaker when viewing the binary from its side (φ $\sim$0.25 or 0.75), and disappear at inferior conjunction of the red giant (see Fig. 1 of Oliversen et al. 1985, Fig. 3 of Sion & Ready 1992 and Fig. 3 of Vogel 1993). In conclusion, observation of a *gradual* variation through the orbital cycle of the parameter under consideration does not support a total eclipse in the system. This should produce a rather sudden change of it close to orbital phase of 0.

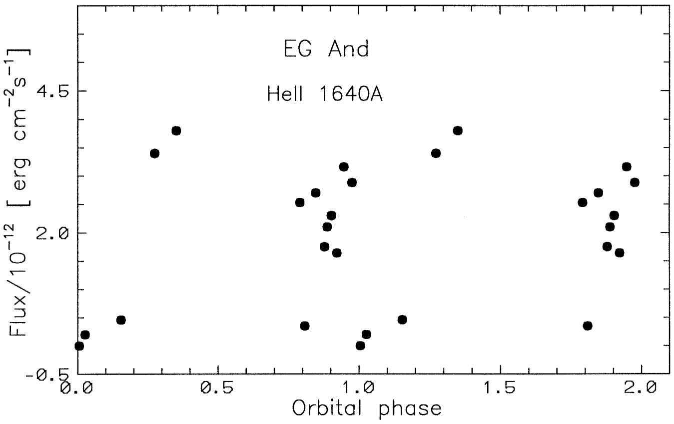

Fig. 5. Phase diagram for fluxes of the HeII 1640Å line.

5. UV/optical continuum in present models

In this section we shall discuss how the present models of EG And are able to explain the variation in the ultraviolet/optical continuum. Our discussion is based on the following observational results:

1. Attenuation of the far UV continuum is due to Rayleigh scattering of the hot component light on neutral hydrogen atoms. It means that the HI region, its shape and density, is crucial for explanation of the variation in the hot continuum.
2. The source of the optical continuum is hydrogen-recombination radiation. It implies that the HII zone, its shape, emission measure and optical properties, is important for explanation of the variation in the optical continuum.

Therefore to explain both the ultraviolet and the optical light curves means to find a relevant form of both the HI and the HII regions in the symbiotic binary, which would produce the observed variation in the UV/optical continuum.

First, we take into account the STB model which was applied to EG And by V91 (cf. his Fig. 6, also Sect. 4.1). An advantage of this model is a convincing explanation of the far UV continuum by Rayleigh scattering. However, it needs a special type of wind (see Sect. 4.1), which detracts its validity. In addition the shape of the HII zone in this model is not able to simulate the UBV light curves. The only attenuation at these wavelengths could be caused by an eclipse of a part of the HII zone by the M giant photosphere. There are no reasons for any attenuation of the optical light when viewing the system from the hot component side, and thus to match the secondary minimum.

Second, we will consider a model in which both components have a stellar wind. It is supposed that a region of ionization is formed at the interface of the colliding winds. Tomov (1995) tried to give a qualitative interpretation of the profiles, intensities and radial velocities of the Hα line, and some ultraviolet emission lines in the framework of this model. He assumes that the cool wind predominates over the hot wind and the conical surface envelopes the area behind the hot component. This surface is formed as a result of the wind interaction and represents a nebular region. In addition it is assumed that the HII region surrounds the nebular region (cf. Fig. 1 of Tomov 1995). The fact that the neutral wind material surrounds a major part of the binary in this model, will probably make difficulties in explanation of the observed narrow UV minimum. A quantitative analysis of such the case is needed. For example, in BF Cyg we observe very long-lasting partial and full eclipse phases of the far UV continuum that suggests a very wide displacement of the neutral material in the binary (González-Riestra, Cassatella & Fernández-Castro 1990). Recently Schmid (1995) treated theoretically models with a very extended and dense neutral scattering region and found that the light curves and spectra of the hot continuum for BF Cyg are not well reproduced by his models. To simulate the variation in the optical continuum is also very problematic, mainly the broad secondary minimum. Here one should consider if the HII zone is optically thin or if there can be an optically thick portion of the ionized hydrogen material. In the former case no change in the light around orbital phase 0.5 could be observed. In the latter case the geometry of such a region would be important to model a variation in the light curve due to its different projection into the line of sight at different orbital phases. However, a calculation of such the region is of a theoretical nature, and it needs to be considered in detail. Finally, we note that the variation in the continuum of EG And has not been discussed previously by the model of winds in collision.

Third, we will briefly discuss the model of circumstellar matter in the symbiotic binary given by SVE93. The idea of this model is based on the assumption of the presence of circumstellar material located mostly between the components of the binary and possessing the geometry of common potentials. Then the observed wave-like variations can be reproduced by different projection of the optically thick circumstellar nebulosity into the line of sight at different orbital phases of the binary. This model was applied to the optical light curves and parameters of the Hα line profiles of EG And (SVE93) and of V443 Her (Skopal 1996, see also Skopal 1995a, 1995b). A support for the presence of circumstellar material in EG And is indirectly expressed by the wind model of V91 (see Sect. 4.1). An observational indication of dense circumstellar material surrounding the binary is the absence of highly ionized permitted emission lines (e.g. HeII) in the optical domain, although a very hot star is present ($T_{\rm h}$ ~80 000 K [Mürset et al. 1991]). This (paradoxical) observation could be explained just due to re-radiation of the hot component light by a cooler circumbinary material, which transfers it towards the longer wavelengths. The model matches well the variation in both the UBV light curves and the spectrophotometric parameters of the Hα line profile. In addition we can estimate the orbital inclination i and the mass ratio q, as the model depends on these parameters. However, the model accounts for a very simplified geometry of the HII region – just the last common potential of binary – which can differ from the reality in more aspects (for details see Skopal 1995b, 1996). Above all, the boundary of the HII zone is not determined. The steady state STB model does not account for any gravitational interaction with circumstellar matter, but only assumes a spherically symmetric uniform wind flow from the red giant to determine the location of the ionization front. Therefore the STB model is not applicable for determination of the HI/HII boundary in the SVE93 model. In that sense the parameters for EG And, i = 45° and q = 3, derived by SVE93, can be more uncertain. Due to a low luminosity of the hot component ($\sim 10\,L_{\odot}$) and a higher density of the neutral material around the giant, the ionization front in EG And will be probably located rather close to the hot star. Then this configuration would result in a smaller HII region than was calculated by SVE93, and consequently, a higher inclination angle would be needed to produce the observed light curves. On the other hand this situation, with more extended HI zone, would be able to simulate the observed attenuation of the ultraviolet light by Rayleigh scattering even for a lower orbital inclination than $\sim 90°$ claimed by V91 and Vogel et al. 1992. We think that this concept represents the most promising way how to match the observed variation in the ultraviolet/optical continuum by a unique model.

We conclude this section by noting that the present models of EG And are not able to explain satisfactorily both the periodic wave-like variation in the optical continuum and the narrow minimum in the far UV continuum. To get a progress in this complex task, we propose to modify the STB model so to take into account orbital motions of circumstellar material in the gravitational field of binary system. Such a model then could be tested by the variation in the ultraviolet/optical continuum along the orbital cycle.

6. Conclusion

The main results can be summarized as follows:

1. The optical light curve of EG And exhibits a double wave during one orbital cycle. The broad minima are located around conjunctions of the binary components.
2. The shape of the light curve cannot be reproduced by any eclipse of the two detached sources of the continuum radiation – stellar disks. The eclipse scenario leads to conflicts with the observed energy distribution in the EG And optical spectrum and possible radii of the stars limited by their Roche lobes.
3. A close inspection of variation in both the ultraviolet and the optical continuum shows that their interpretation in terms of the eclipse scenario must be questioned.
4. None from the present models of EG And (V91, SVE93, Tomov 1995) is able to explain the observed periodic variation in both the UV and the UBV light curves.
5. The energy distribution in the optical and infrared spectrum of EG And is possible to fit well by a black body of T = (3131 ±

37) K, which is, however, far lower than 3700 K corresponding to its spectral type of M2-3III.

Acknowledgements. The author would like to express his thanks to the referee, Hilmar Duerbeck, for comments which led to improving the paper. This work was in part supported by the Slovak Academy Grant of the Astronomical Institute 1282/95.

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