Astron. Astrophys. 364, 557–562 (2000)

ASTRONOMY
AND
ASTROPHYSICS

Analysis of the U-band orbital variation of the symbiotic binary AG Draconis during quiescence

N.A. Tomov[1], **M.T. Tomova**[1], **and A. Ivanova**[2]

[1] Institute of Astronomy and Isaac Newton Institute of Chile Bulgarian Branch, National Astronomical Observatory Rozhen, P.O. Box 136, 4700 Smolyan, Bulgaria (rozhen@mbox.digsys.bg)
[2] Institute of Astronomy, National Astronomical Observatory Rozhen, P.O. Box 136, 4700 Smolyan, Bulgaria

Received 15 October 1999 / Accepted 24 October 2000

Abstract. The photometric U orbital variations of the symbiotic binary AG Dra, caused by occultation of a bright gaseous region by the K giant in this system, are used to derive the emission from the circumbinary nebula, that is supposed to be generated by the cool giant's wind. Assuming spherical symmetry and constant expansion velocity for the wind, and that the giant has the same intrinsic continuum energy distribution of α Boo, we derive a cool giant's radius of 28÷32 $R_\odot$ and a distance of 1560÷1810 pc. We conclude that the cool giant does not fill its Roche lobe, which is contrasting with the intense, accretion powered X-ray emission.

Key words: stars: binaries: symbiotic – stars: individual: AG Dra – stars: mass-loss – stars: circumstellar matter – stars: distances – stars: fundamental parameters

1. Introduction

The photometric behaviour of many symbiotic stars is characterized by an alternance of quiescent periods and active phases. In a number of cases cyclic light variations are observed in the quiescent periods which could be caused by occultation of a hot stellar object, an accretion disk and/or a part of the circumbinary gas component. That is why symbiotic stars are interpreted as interacting binary systems possessing dense gaseous nebulae, which are generated during quiescence from the stellar wind of their primary components being in the most cases normal cool giants or Miras. The emission of the symbiotic nebula in many cases predominates in the wavelength region of the U photometric system.

The star AG Dra (BD +67°922) belongs to the group of yellow symbiotics and consists of a cool primary of the spectral type K, probably more luminous than a normal class III giant (Huang et al. 1994; Mikolajewska et al 1995; Greiner et al. 1997) and a hot compact companion, accreting matter from the primary. Its photometric history includes many active phases separated by quiescent periods.

During quiescence the U light of AG Dra displays a 550^{d} periodicity with an amplitude of about one magnitude. This periodicity is related to the orbital motion of the binary as confirmed by the radial velocity curve of its cool component (Garcia & Kenyon 1988; Mikolajewska et al. 1995; Smith et al. 1996). Important characteristics of the U light curve are the changes in the phases and shapes of the orbital maxima as well as the variations by more than 20% of their fluxes (Hric et al. 1993, 1994; Friedjung et al. 1998). The decrease of the flux at the time of the orbital minimum is supposed to be caused by an occultation of a bright region that surrounds the hot companion (Mikolajewska et al. 1995; Friedjung et al. 1998). It was proposed as well (Friedjung et al. 1998; Gonzalez-Riestra et al. 1999) that the flux variations of the orbital maxima are due to variation of the giant's wind.

The quiescent B and V light variations of AG Dra with a period of about 360^{d} and an amplitude of $0\overset{\mathrm{m}}{.}10 \div 0\overset{\mathrm{m}}{.}15$ are probably caused by an intrinsic variability of the cool giant, whose radiation becomes more important at longer wavelengths (Bastian 1998; Friedjung et al. 1998). The continuum of the giant also contributes to the U flux, but its variations at the time of the orbital maximum are determined primarily by changes of the emissivity of the nebula, since they are significantly larger than $0\overset{\mathrm{m}}{.}15$ up to about $0\overset{\mathrm{m}}{.}30$.

Many times AG Dra has been in a state of increased activity (after 1936, 1951, 1966, 1980 and 1994), characterized by one or more light maxima. The reason for this activity is probably related to the nature of its cool component, which drives the eruptions of the hot companion (Friedjung 1997; Greiner et al. 1997; Galis et al. 1999). These eruptions are induced by variations of the accretion rate which are due to variations of the mass-loss rate of the giant rather than to an elliptical motion, since its radial velocity curve shows no sign of a measurable eccentricity (Mikolajewska et al. 1995; Smith et al. 1996; Galis et al. 1999). Consequently the investigation of the reasons for the brightenings of AG Dra is turned to the study of the nature of its cool component. One task, discussed in this study, is to estimate its absolute size, which from its side is related to obtaining the distance to the system.

At the present time there is no good knowledge of some of the fundamental parameters of the system AG Dra like the distance, radius and luminosity of the cool component (Friedjung et al. 1998; Gonzalez-Riestra et al. 1999; Galis et al. 1999).

Send offprint requests to: N.A. Tomov

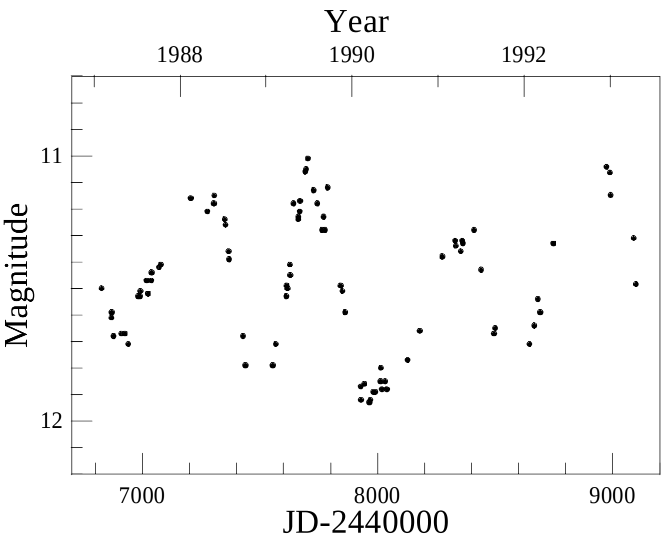

Fig. 1. Photoelectric U observations of AG Dra.

To derive the radius and the distance we used the radiation at the wavelength of the U photometric system, as the continuum fluxes of the circumbinary nebula and the giant are of the same order at this wavelength. The circumbinary nebula is optically thin in the U region providing possibility its whole continuum emission to be observed. It is considered as formed by the giant's wind. If its ionized portion extends to the giant we will be able to compose one system of two equations with two unknown quantities – the distance to the system and the radius of the cool giant using the nebular and the giant's emission. Moreover the U photometric variations give possibility to make some conclusions about the emitting region(s) of the nebula.

2. The photometric data analysis

For our investigation we used the photoelectric observational material, obtained in the period JD 2 446 700 ÷ 2 449 200 after the time of activity of AG Dra in 1985–86, since this material actually is the best sample of photometric U data, taken during quiescent state of the system. These data were obtained during four orbital cycles (Fig. 1) in the framework of the international campaign for symbiotic stars launched by Hric & Skopal (1989), and are presented in the papers of Hric et al. (1993) and Hric et al. (1994). For our calculations we used the U magnitudes of $11\overset{\rm m}{.}1$ and $11\overset{\rm m}{.}9$ giving the mean value of the light at the times of the orbital maximum and minimum on JD 2 447 700 and JD 2 448 000. They were selected because the data set is complete around these times and can be used for a reasonable estimate of the maximum and minimum fluxes. The magnitudes were converted into continuum fluxes without correcting for the emission lines included in the wavelength region of the U photometric system as we were not provided with spectral data during the time of these photometric observations.

The fluxes were corrected for the energy distribution of AG Dra in the U spectral region. The continuum of this star on the long wavelengths-side of the Balmer jump is considerably weaker, which leads to a reduction of the flux at 3650 Å. The corrections were made by means of the spectrum in Fig. 3 of Mikolajewska et al. (1995). It turned out that the observed U flux is 20% smaller than the real flux at 3650 Å. This amount was added to the observed flux.

Finally the fluxes were corrected for the interstellar reddening. We used the value $E(B-V)=0.06$ (Mikolajewska et al. 1995; Greiner et al. 1997; Gonzalez-Riestra et al. 1999) and the extinction law by Seaton (1979). So the U magnitudes used by us led to dereddened continuum fluxes of $0.257\,10^{-12}$ erg cm^{-2} s^{-1} Å^{-1} and $0.122\,10^{-12}$ erg cm^{-2} s^{-1} Å^{-1} for the considered times of the orbital maximum and minimum, respectively. In this case the flux difference of $0.135\,10^{-12}$ erg cm^{-2} s^{-1} Å^{-1} corresponds to the amplitude of the light variations.

For realizing our calculations we must determine the ionized portion of the nebula. Fig. 1 shows that the U-light curve of AG Dra is well covered by observation near the orbital maxima. In the figure the cycle-to-cycle variations are clearly seen. Friedjung et al. (1998) came to the conclusion that the variation of the maximum flux is caused by changes of the cool giant mass-loss rate. The variation of the maximum flux is determined by variation of the number of recombinating H$^+$ ions in the nebula. If the hot companion does not ionize the whole nebula, but only part of it, when changing the mass-loss rate of the giant, the volume of the ionized region will change too, because the hot companion having a constant photon flux in the Lyman continuum is able to ionize always the same amount of gas. To observe different numbers of recombinating H$^+$ ions in the different orbital maxima will be possible when the hot companion has an excess of luminosity providing them the possibility to ionize always the whole nebula (excepting its portion occulted by the cool star) on changing the mass-loss rate of the giant. That is why we will perform our calculations supposing that the circumbinary nebula of AG Dra is a region of ionized hydrogen.

The next step of our consideration is to estimate the contribution of the stellar components of the system. The flux of the hot companion was determined supposing that it radiates as a blackbody and using the ratio of the fluxes at 1340 Å and 3650 Å of a blackbody with the same temperature and the observed flux at wavelength λ 1340 Å. Gonzalez-Riestra et al. (1999) have obtained a mean value of the dereddened quiescent flux at this wavelength of about $0.28\,10^{-12}$ erg cm^{-2} s^{-1} Å^{-1} and Zanstra temperature of the companion of 110 000 K. On the basis of these data we derived an U-band flux of $F^{\rm hot}=0.007\,10^{-12}$ erg cm^{-2} s^{-1} Å^{-1}.

Let us consider the contribution of the cool component. The dereddened optical spectrum of AG Dra was fitted with that of a K giant and H$^{\rm o}$ continuum emission with electron temperature $T_{\rm e}=15\,000$ K (Mikolajewska et al. 1995). We obtained the flux of this component supposing that it has the same continuum energy distribution like α Boo and the rest of the observed U flux is a nebular emission. We calculated the 3650 Å/ 5500 Å flux ratio of α Boo and scaled it to the dereddened visual flux of AG Dra. Using the flux of AG Dra in its orbital minimum, when the nebular emission can be supposed to be negligible, we obtained for the flux of its cool component $F^{\rm cool} = 0.075\,10^{-12}$ erg cm^{-2} s^{-1} Å^{-1}.

After subtraction of the fluxes of the two stellar components from the observed flux at the orbital maximum the nebular continuum turned out to be $F^{\rm neb} = 0.175\,10^{-12}$ erg cm^{-2} s^{-1} Å^{-1}. The contribution of the nebula near orbital minimum is 0.040 10^{-12} erg cm^{-2} s^{-1} Å^{-1}, close to that of the red giant.

The shape of the U light curve indicates that the region emitting a flux, equal to the orbital amplitude is not partially occulted at the time of the orbital maximum only. This means that it is located most probably around the hemisphere of the giant facing the hot companion. The density of this small region is probably much higher than the mean density of the unocculted part of the nebula, since the radiation of the whole occulted part of 0.135 10^{-12} erg cm^{-2} s^{-1} Å^{-1} is by a factor of about 3 greater than the radiation of the unocculted part. One cause for the appearance of this small high density region was suggested by Galis et al. (1999), who assumed that the strong radiation pressure from the hot component tends to stop the matter of the giant's wind approaching the hot component and photoionization creates an ionized region with a higher density and emissivity.

3. The mass-loss rate

Besides the U photometric data, for our calculations the mass-loss rate of the giant is needed as well. The mass-loss rate of the cool components of the symbiotic stars is not an observed quantity and is difficult to determine. This quantity for AG Dra was estimated by Mikolajewska et al. (1995) using the radio flux at 4.9 GHz from Seaquist & Taylor (1990) and adopting a wind velocity of 30 km s^{-1}. This estimate, however, depends on their assumed system distance of 2.5 kpc, and cannot, therefore, be used for our purposes.

Van Winckel et al. (1993) suggested that the Hα emission profile of the symbiotic stars affected by self-absorption can be an indicator for the mass-loss rate of their cool components, whose atmospheres are ionized by a hot source. They created a classification system of the symbiotic stars, based on their Hα profiles. Later this idea was quantitatively considered by Schwank et al. (1997). They calculated a variety of models of an expanding atmosphere of a cool giant of S-type symbiotic system. The atmosphere of the giant is irradiated and ionized from the outside by the hot stellar component. Schwank et al. also calculated the Hα emission profile at phase when this component is in front of the giant, taking into account the optical depth of the atmosphere and supposing that the line is mainly due to recombination. The profile includes an absorption which moves from the center of the line to its short wavelength-side depending on the velocity of the absorbing particles. When the mass-loss rate of the giant increases, the ionized portion decreases and the transition zone between the ionized and the neutral volumes shifts outwards approaching the hot component. An outward shift of this zone in a region with higher velocity gradient leads to an increase of the difference between the velocity of the absorbing particles and that of the underlying recombination region, and, consequently, to a blue shift of the absorption. So the position of the absorption can be an indicator of the mass-loss rate.

Taking into account the relation between the Hα profile of the symbiotic stars and the mass-loss rate of their cool components we decided to search another star having Balmer emission characteristics close to that of AG Dra and a known mass-loss rate of its cool component.

A good comparison object seems to be AG Peg whose cool component loses mass at a rate of $1{-}2\,10^{-7}\,M_\odot$ yr^{-1} (Vogel & Nussbaumer 1994; Mürset et al. 1995; Proga et al. 1998). Let us compare the Balmer emission spectrum of the two systems. The characteristics and the orbital variations of the Hα profile of AG Peg were studied by Boyarchuk et al. (1987), and those of AG Dra during its quiescent state – by Tomova & Tomov (1999). Hα profiles of these stars can be also found in other works (e.g. Ivison et al. 1994; Viotti et al. 1998). In both symbiotic systems the intensity of Hα emission varies with the orbital phase as a result of both changes of the optical depth and of the giant's occultation. The maximum intensity is around the phase of the light maximum, when the hot component is closer to the observer. The orbital variations of the profile of this line in the two systems are also similar, being due also to optical depth changes. At the phases of the maximal intensity it is single-peaked with a blue shifted absorption producing a small shoulder or a general asymmetry only.

The profiles of the two stars are shown in Fig. 2. They are different from the theoretical profiles of Schwank et al. (1997), as the absorption is far away from the center of the line. This is due to the peculiar structure of the circumbinary nebulae of these stars. We used the Hα profile of AG Peg observed on 30 June 1986 before the photometric maximum, instead of that of 29 July 1991 which is nearer to the maximum but after it (Ivison et al. 1994). These data indicate that the Hα line reaches its maximum intensity probably a somewhat earlier than the light maximum, being more intense on 30 June 1986. The wings of the two lines in Fig. 2 are symmetric. As for comparison, we have divided the profiles of the two stars, as illustrated in the lower panel of the figure.

Let us now compare some other characteristics of the two systems in the light of the theoretical treatment of Schwank et al. (1997). These authors have shown that the Hα profile affected by the optical depth depends on the luminosity of the hot stellar component, the separation, the mass-loss rate of the cool giant and the velocity law of its wind. The AG Peg system (Boyarchuk 1966; Kenyon et al. 1993) as well as the AG Dra system (Mikolajewska et al. 1995; Greiner et al. 1997) have high luminosity hot companion, whose ionizing radiation probably reaches the innermost layers of the giant's wind where its density is the highest and where the bulk of the energy of the line is emitted. Then it will not be necessary to compare the companion's luminosities and the separations but only the velocity laws and the mass-loss rates. The velocity laws are different, but since the energy is emitted mostly from the layers near the giant's surface, the velocities and their gradients in these layers are low having probably close values. On the other hand there

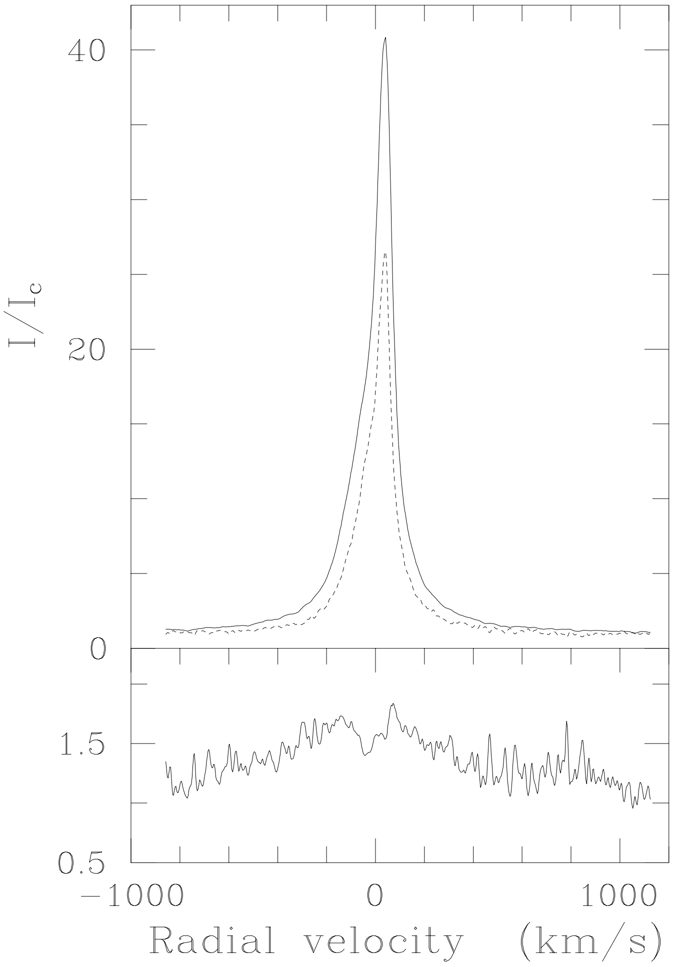

Fig. 2. Upper panel: Hα profiles of AG Dra (solid line) taken on 2 February 1994 (Tomova & Tomov 1999), and of AG Peg of 30 June 1986 (from Ivison et al. 1994). Lower panel: AG Dra over AG Peg profile ratio.

is similarity of the profiles morphology and according to the treatment of Schwank et al. (1997) the mass-loss rates must be probably close as well. Supposing that the mass-loss rate of the giant of AG Peg is $1{\div}2\,10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$, for its counterpart in the AG Dra system we adopt $2.0{\div}2.5\,10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$. As it will be shown in the next section, the mass-loss rates smaller than the lower limit lead to stellar radii below 28 $R_\odot$. So small values are probably not plausible, as the cool component of the AG Dra system is supposed not to be a normal giant, but K-type bright giant (Huang et al. 1994; Mikolajewska et al. 1995; Smith et al. 1996).

4. The method of calculation and results

Having the fluxes of the components of the binary AG Dra we can compose a system of two equations with two unknown quantities – its distance and the radius of its primary. The effective temperature of this component was estimated by Smith et al. (1996) and amounts to be 4300 K. The cool giant's continuum can be fitted with a function giving the energy distribution of α Boo, since, according to Griffin & Lynas-Grey (1999) the effective temperature of this star is 4290±30 K the same as that of AG Dra. This function consists of two parts, the first part is related to the radiation of a blackbody with a temperature of 4300 K and the second one to the energy distribution of α Boo. At the wavelength of the U band the second part has a value of $C_\alpha = 0.788$. Then the first equation is:

$$F^{\rm cool} = \frac{2\pi hc^2R^2}{d^2\lambda^5}\frac{1}{{\rm e}^{hc/\lambda kT}-1}C_\alpha \times 10^{-8}\ , \qquad (1)$$

where R is the cool giant's radius and d – the distance.

Let us now consider the second equation. We suppose that the emitting circumbinary nebula is formed by a wind with spherical symmetry and a constant velocity and has an inner boundary the radius of the giant, as only a small portion occulted by it is not an ionized region. To give an expression to the flux of the nebula the state of ionization of helium is need to be known. We calculated the ratio of the emission measures of the neutral and ionized helium, allowing that the lines of the He$^{\rm o}$ are pure recombination lines. That is really the case when the electron temperature is 15 000 K (Mikolajewska et al. 1995). We used visual line fluxes of He$^{\rm o}$ and the flux of the He II 4686 line from the paper of Gonzalez-Riestra et al. (1999) at a phase, close to the maximum light. Since these data are related to quiescence of the system, we used the sum of the fluxes of the narrow and broad emission components of the line He II 4686. In this way we obtained a ratio He^{++}/He^{+} of about 0.5. This result shows that the singly ionized helium is dominant in the nebula and we assume that the nebular emission mostly is continuum emission of hydrogen and neutral helium. For this flux we have

$$F^{\rm neb} = \frac{1+a({\rm He})}{4\pi d^2}\frac{c}{\lambda^2}10^{-8}\times \left[\int_V n^2\gamma_\nu({\rm H^o},T_{\rm e})\,{\rm d}V + a({\rm He})\int_V n^2\gamma_\nu({\rm He^o},T_{\rm e})\,{\rm d}V\right], \qquad (2)$$

where V is the volume of the nebula. The quantities γ_ν are related to the emission coefficients of hydrogen and neutral helium and are determined by recombinations and free-free transitions. The particle density in the giant's wind is a function of the distance to the center and can be expressed via the continuity equation $n(r) = \dot{M}/4\pi r^2\mu m_{\rm H}\upsilon$, where $\dot{M}$ is the mass-loss rate; υ – the wind velocity, $\upsilon = 30\ {\rm km\,s^{-1}}$ (Mikolajewska et al. 1995) and $\mu m_{\rm H}$ – the mean molecular weight, $\mu = 1.4$ (Nussbaumer & Vogel 1987). The inner boundary of the region of integration is the radius of the star and the outer one – infinity. It is also necessary to have the quantities γ_ν. The position of the U photometric system is close to the Balmer limit, and the spectral observations in this region of Tomova & Tomov (1999) show another characteristic feature of the emission of AG Dra: the blending of the Balmer lines with high numbers produces an apparent continuum longward of the Balmer limit near 3650 – 3660 Å which has the same flux as the Balmer continuum excess shortward of 3650 Å. For this reason we used the values of the emission coefficients on the short wavelength side (Osterbrock 1974; Pottasch 1984). We adopt an electron temperature of 15 000 K as proposed by Mikolajewska et al. (1995) and helium abundance of 0.1 (Vogel & Nussbaumer 1994). Solving the system of equations, with the adopted values of the mass-loss rate the distance is obtained to be in the range 1560÷1810 pc, and the stellar radius – in the range 28÷32 $R_\odot$. This result shows that the size of the giant star is small compared with its Roche lobe.

Our estimates can be compared with the estimates, based on other methods. For example Smith et al. (1996) studying the IR absorption spectrum and performing an abundance analysis of the giant, concluded that its bolometric magnitude and radius are in the intervals $M_{\rm bol} \sim -1.1 \div -2.5$ and $R = 26 \div 50$ $R_\odot$. Mikolajewska et al. (1995) came to the conclusion that the distance is ∼2.5 kpc. On the other hand the observational data of HIPPARCOS satellite provided a lower limit to the distance of about 1 kpc (Viotti et al. 1997).

5. Discussion and conclusions

The availability of an estimate of the radius of the primary of AG Dra gives us the chance to calculate some other parameters too. The abundance analysis of this star performed by Smith et al. (1996) provided an estimate of the surface gravity of $\log g = 1.6$. Using this estimate and a radius of 28−32 $R_\odot$ we derive a mass of 1.1−1.5 $M_\odot$ which is in agreement with the result of the analysis of this component by Mikolajewska et al. (1995). Having the radius and the effective temperature of the star, we found its bolometric luminosity, which turned out to be in the interval 242÷316 $L_\odot$.

The values for the distance to the system lead to the reduction of some of the parameters of its hot companion obtained by Greiner et al. (1997) which are based on a distance of 2.5 kpc. Since a very hot star was observed, these authors proposed that it is in a steady state hydrogen burning near its surface allowing its luminosity to be due only to nuclear processes. A steady state burning can be realized when the burning rate is equal to the accretion rate. Greiner et al. found that if the hot companion of the AG Dra system had such an accretion rate, it will be in the range of steady burning at the surface of a white dwarf with a mass of 0.3 $M_\odot$. This mass was calculated using the core mass–luminosity relation $L/L_\odot \approx 4.6\,10^4 (M_{\rm core}/M_\odot - 0.26)$ (Yungelson et al. 1996). Making corrections of their parameters we obtained that the bolometric luminosity and the accretion rate are in the intervals 967÷1302 $\rm L_\odot$ and $1.2 \div 1.7\,10^{-8}$ $M_\odot$ yr^{-1}. The mass of the companion was calculated to be about 0.3 $M_\odot$, which leads to a minimum accretion rate for steady burning of $1.8\,10^{-9}$ $M_\odot$ yr^{-1}. So it can be concluded that these new values are also in agreement with the model of a steady state burning at the surface of a white dwarf.

We summarize the main results of our analysis as follows:

- The variations of the U flux between the different orbital maxima are due to variations of the amount of the emitting gas in the circumbinary nebula. This is possible only if the hot companion has an excess of luminosity, which makes it able to ionize always the whole nebula (but some region occulted by the cool star) when the giant changes its mass-loss rate.
- The shape of the U light curve indicates that the flux equal to the orbital amplitude is emitted by a small high-density region located most probably around the hemisphere of the giant which faces the hot companion.
- The cool giant's mass-loss rate was estimated from the Hα profile to be in the range $2.0 \div 2.5\,10^{-7}$ $M_\odot$ yr^{-1} on the basis of the theoretical models of Schwank et al. (1997), and from the similarity with the Hα profile of AG Peg.
- Using the mass-loss rate and the U fluxes of the different components of the system we calculated its distance and the radius of its cool giant to be in the ranges 1560÷1810 pc and 28÷32 $R_\odot$, respectively.

Acknowledgements. The authors thank the referee Dr. R. Viotti whose remarks contributed to improve the paper. N.T. is also grateful to Dr. M. Friedjung and Dr. N. Markova for their comments and helpful advices.

References

Bastian U., 1998, A&A 329, L61

Boyarchuk A.A., 1966, AZh 43, 976

Boyarchuk A.A., Belyakina T.S., Tarasov A.E., Glagolevski Yu.V., 1987, Ap&SS 131, 775

Friedjung M., 1997, In: Mikolajewska J. (ed.) Physical Processes in Symbiotic Binaries and Related Systems. Proc. of the International Conf., Copernicus Foundation for Polish Astronomy, Warsaw, p. 105

Friedjung M., Hric L., Petrik K., Galis R., 1998, A&A 335, 545

Galis R., Hric L., Friedjung M., Petrik K., 1999, A&A 348, 533

Garcia M.R., Kenyon S.J., 1988, In: Mikolajewska J., Friedjung M., Kenyon S., Viotti R. (eds.) The Symbiotic Phenomenon. IAU Coll. 103, Kluwer, p. 27

Gonzalez-Riestra R., Viotti R., Iijima T., Greiner J., 1999, A&A 347, 478

Greiner J., Bickert K., Luthardt R., et al., 1997, A&A 322, 576

Griffin R.E.M., Lynas-Gray A.E., 1999, AJ 117, 2998

Hric L., Skopal A., 1989, IBVS 3364

Hric L., Skopal A., Urban Z., et al., 1993, Contr. Astron. Obs. Skalnaté Pleso 23, 73

Hric L., Skopal A., Chochol D., et al., 1994, Contrib. Astron. Obs. Skalnaté Pleso 24, 31

Huang C.C., Friedjung M., Zhou Z.X., 1994, A&AS 106, 413

Ivison R.J., Bode M.F., Meaburn J., 1994, A&AS 103, 201

Kenyon S.J., Mikolajewska J., Mikolajewski M., Polidan R.S., Slovak M.H., 1993, AJ 106, 1573

Mikolajewska J., Kenyon S.J., Mikolajewski M., Garcia M.R., Polidan R.S., 1995, AJ 109, 1289

Mürset U., Jordan S., Walder R., 1995, A&A 297, L87

Nussbaumer H., Vogel M., 1987, A&A 182, 51

Osterbrock D.E., 1974, Astrophysics of Gaseous Nebulae. W.H. Freeman and Company, San Francisco, p. 73, 74

Pottasch S.R., 1984, Planetary nebulae. Reidel, Dordrecht, p. 73

Proga D., Kenyon S.J., Raymond J.C., 1998, ApJ 501, 339

Schwank M., Schmutz W., Nussbaumer H., 1997, A&A 319, 166

Seaquist E.R., Taylor A.R., 1990, ApJ 348, 313

Seaton M.J., 1979, MNRAS 187, 73p
Smith V.V., Cunha K., Jorissen A., Boffin H.M.J., 1996, A&A 315, 179
Tomova M.T., Tomov N.A., 1999, A&A 347, 151
Van Winckel H., Duerbeck H.W., Schwarz H.E., 1993, A&AS 102, 401
Viotti R., Badiali M., Cardini D., Emanuele A., Iijima T., 1997, ESA SP-402, 405
Viotti R., Rossi C., Muratorio G., 1998, A&AS 128, 447
Vogel M., Nussbaumer H., 1994, A&A 284, 145
Yungelson L., Livio M., Truran J.W., Tutukov A., Federova A., 1996, ApJ 466, 890