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Spectral observations of AG Draconis during quiescence and outburst (1993–1995)

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Abstract. High and intermediate resolution observations of the blue and the Hα spectral regions of the symbiotic star AG Dra at quiescence and during an active phase in 1994 and 1995 were performed. Variations of profiles, fluxes and radial velocity data of a number of emission lines are investigated. The width (FWHM) of all of these lines was very large at times close to the 1994 light maximum. The emission measure of the surrounding nebula was also calculated using Balmer continuum emission on the basis of U photometric observations from the literature. It turned out that at the times of the 1994 and 1995 visual light maxima the emission measure has increased by a factor of 15 and 8 respectively, compared with its quiescent maximal value. After the 1995 light maximum the profiles of the Hβ and Hγ lines contained a broad emission component that indicated a hot stellar wind. The velocity of this wind and the mass-loss rate of the hot secondary giving its rise, were equal to 800 $\mathrm{km\,s^{-1}}$ and $2\,10^{-7}$ $\mathrm{M_{\odot}\,yr^{-1}}$. A view that the observed presence of a hot wind and the increase of the emission measure together can be considered as an argument in support of the thermonuclear outburst model is discussed. Moreover, we argue that a shocked wind region with X-ray luminosity of about 10 $\mathrm{L_{\odot}}$ must be present in this system when the hot wind exists.

Key words: stars: binaries: symbiotic – stars: activity – stars: individual: AG Dra – stars: mass-loss – line: profiles

1. Introduction

Symbiotic stars are characterized by the simultaneous presence of a cool continuum and a high excitation emission lines in the optical spectrum and are interpreted as interacting binary systems consisting of a cool luminous primary and a hot compact (subdwarf, white dwarf) secondary component. In some cases the secondary component could be a main sequence star, surrounded by an accretion disk. Symbiotic stars possess dense gaseous nebulae, which appear as a result of the mass-loss of one or both components. The mass-loss is realized at some stages of the evolution of the components and its presence determines the regime of their interaction. The emission profiles of the symbiotic stars in many cases are composite and their morphology depends on the nebula's velocity field, which on its side is determined by the components' interaction. That is why investigation of the interaction in the symbiotic stars is of prime importance for understanding their nature.

The star AG Dra (BD +67°922) is a known symbiotic system with high galactic latitude, large barycentric velocity $\gamma = -148\,\mathrm{km\,s^{-1}}$ and a relatively early spectral type (K). Its photometric period is about 550^{d} (Meinunger 1979; Skopal 1994). The consistency of this period with the orbital period of the binary is confirmed by radial velocity variations of the cool primary component, measured by Garcia & Kenyon (1988), Mikolajewska et al. (1995) and Smith et al. (1996), as well as by polarization variations as measured by Schmid & Schild (1997). AG Dra is a metal poor symbiotic binary that is enriched in the heavy s-process elements and situated in the galactic halo (Smith et al. 1996).

The system has undergone a large number of outbursts episodes (Luthardt 1983; Skopal & Chochol 1994; Skopal 1994), and several outburst models have been proposed.

The first model was proposed by Leibowitz & Formiggini (1992) as a result of analysing the continuum energy distribution in the wavelength region $\lambda\lambda$ 1250–7000 ÅÅ using low dispersion UV and optical spectra. It was found that the energy distribution is not typical of a disk, which excludes the possibility of the outbursts being driven by accretion. On the other hand the variability of the continuum of AG Dra during its active phase 1980–1986 does not follow the evolutionary pattern of the thermonuclear model. For this reason the authors suppose the outbursts to be associated with the liberation of mechanical energy in the atmosphere of the giant.

The second model for the activity of AG Dra was proposed on the basis of ultraviolet and optical spectroscopic data by Mikolajewska et al. (1995), who consider that thermonuclear runaway on the surface of a white dwarf is realized in this system. They established an increase of the bolometric luminosity at constant radius during the early stages of each observed outburst, followed by an expansion at roughly constant luminosity.

ROSAT X-ray data of AG Dra were analysed by Greiner et al. (1997). The analysis revealed very high temperature of the hot component even during the quiescent state. This observational fact requires hydrogen burning near its surface and excludes the possibility of a thermonuclear event. Greiner et al.

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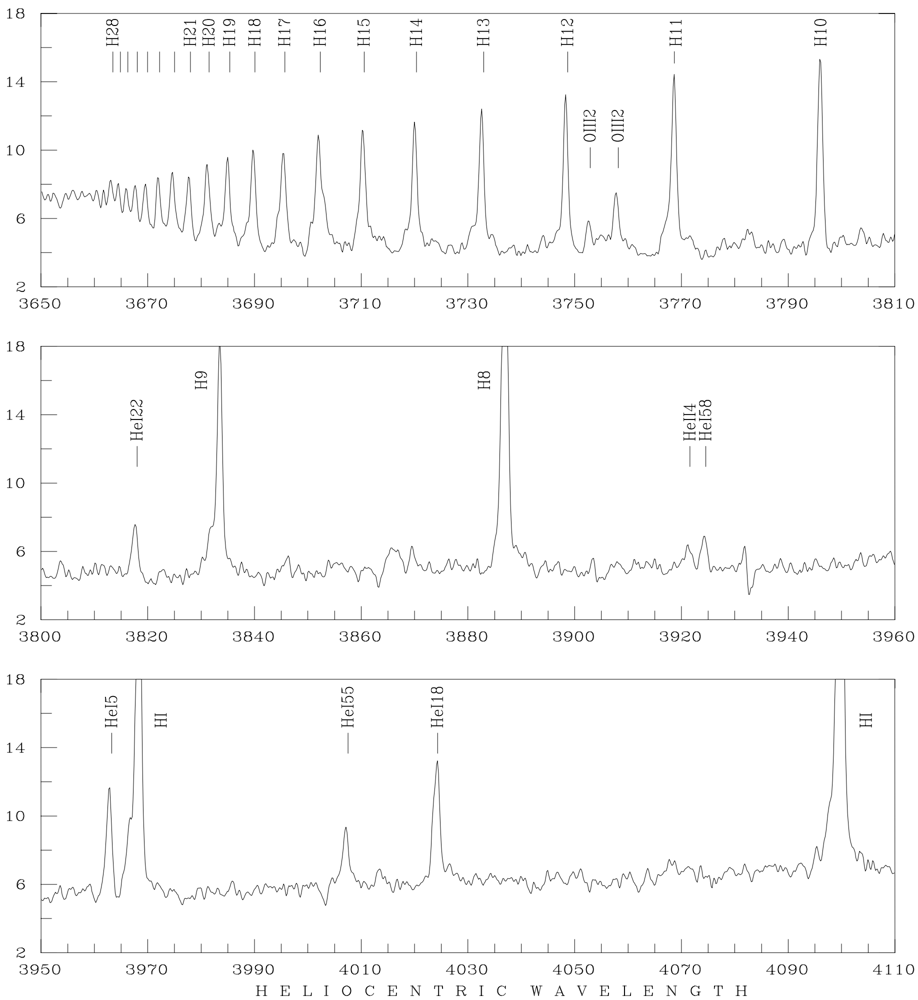

Fig. 1. Sections of the spectrum, taken on JD 2 449 995.36. The ordinate scale is in arbitrary units.

fitted the X-ray spectrum with a blackbody model representing this component. During quiescence it is supposed to be in a steady state burning, as the burning rate is equal to the accretion rate. During the optical outbursts the accretion rate increases and causes accumulation of matter not included in the burning process. The hot component is both expanding and cooling while maintaining constant luminosity. The expansion is restricted either as a result of the finite excess mass accreted or by a wind driven mass-loss from the expanding photosphere. However, there is no theoretical possibility of an increase in the bolometric luminosity in the framework of this scenario as proposed by Mikolajewska et al. (1995). To explain the growth of the UV continuum during the 1995 outburst Greiner et al. need to search for an additional emission mechanism in the surrounding nebula.

High-resolution observations of the emission lines in the visual have a fundamental importance for dynamical examination of the nebulae surrounding symbiotic systems. The star AG Dra is comparatively faint for observations with high resolution in both quiescence and outburst phases, and its visual line spectrum has been insufficiently studied. We extensively observed this object in both the quiescent stage before its 1994 outburst and the 1994–1995 outburst phase. In this paper we analyse its high and intermediate resolution data in order to consider the behaviour of some visual emission lines at different stages, which would shed light on the manner of the interaction of its components. We also search for observational evidence to support any single outburst model.

2. Observations and reduction

We acquired five photographic spectra in 1993 and 1995 with the Coudé spectrograph of the 2m RCC telescope of the National Astronomical Observatory Rozhen (Table 1). The observations were performed in the region from 3600 Å to 5000 Å, with a reciprocal linear dispersion of 18 Å mm^{-1}. The first two spectrograms were taken on Kodak IIaO emulsion sensitized with hydrogen with a resolution of 0.4 Å. The rest of the spectrograms are on ORWO ZU emulsion whose resolution is 0.5 Å. All exposures were comparatively deep but the continuum could be detected only in two cases when the star was the brightest and the atmospheric conditions were very good. The spectra were digitized with the Joyce Lobel microdensitometer and a ReWiA package was used for wavelength and density calibration, as well as for calculation of the radial velocities and the equivalent widths. Sections of the spectrum taken on JD 2 449 995.36

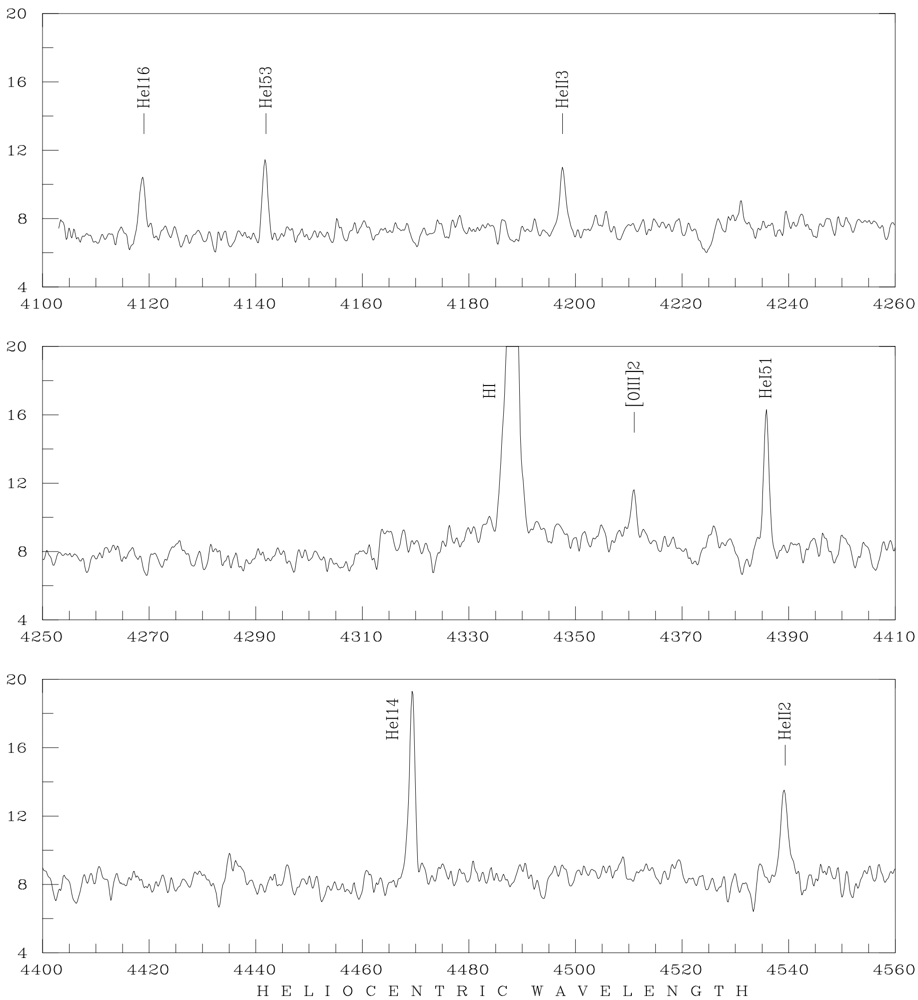

Fig. 1. (continued)

where the fainter line features are most clearly seen are displayed in Fig. 1. The lines with measured radial velocities are marked. At this time the star was in a declining phase following the secondary (July 1995) light maximum. The strongest lines are not seen in this figure, but the upper part of their profiles is similar to those in Figs. 3 and 4.

In our work we consider the intensity of the relatively strong lines whose equivalent width errors are not greater than 30%. Unfortunately it turned out that the spectrogram of JD 2 449 995.36 has had decreased sensitivity of its photographic emulsion in the wavelength region $\lambda\lambda \gtrsim 4470$ Å and that is why the intensities only of these lines whose wavelengths are less than this limit were investigated. Among the other spectrograms only that of JD 2 449 994.42 was used for the intensity investigation, as the continuum in the other cases was not well detected. The error of the level of the local continuum for both of these spectrograms was not greater than 10%. The line fluxes were obtained by means of the B and V photometric estimates of Montagni et al. (1996) taken during this time. The monochromatic continuum fluxes at the positions of the emission lines considered were calculated via linear interpolation of the fluxes at the positions of the sensitivity maxima of the B and V photometric systems.

In addition some CCD frames were obtained with the same spectrograph mainly in the period January – August 1994. The Hα region was observed on almost all nights. The regions of the Hβ, Hγ and He II 4686 and a region centered at 4500 Å and containing the He I 4471 and He II 4542 lines were observed on a few occasions. The spectral range of 110 Å gave us the possibility of observing the [O III] 4363 and He I 4388 lines together with Hγ. The resolving power was generally 15 000, and only for the spectra taken on JD 2 449 024.51 and JD 2 449 376.64 was it 30 000 (Table 1). The data were processed with the *pcIPS* program of Smirnov et al. (1992). As in the case of the photographic spectra, the ReWiA package was used for obtaining the dispersion curve and for calculating the radial velocities and the equivalent widths. Some absorption lines of the K star spectrum in the Hα region were used for measuring the radial velocity of the cool component.

The line fluxes were obtained by means of the B, V and R photometric data of Hric et al. (1994), Skopal (1996), Skopal et al. (1995) and Montagni et al. (1996). Since there are no R data during the time when the initial five of our Hα spectra were obtained while the system was at the quiescent stage, we used the data of Montagni et al. (1996) taken at the end of 1995 and the beginning of 1996, when the visual light of the system had

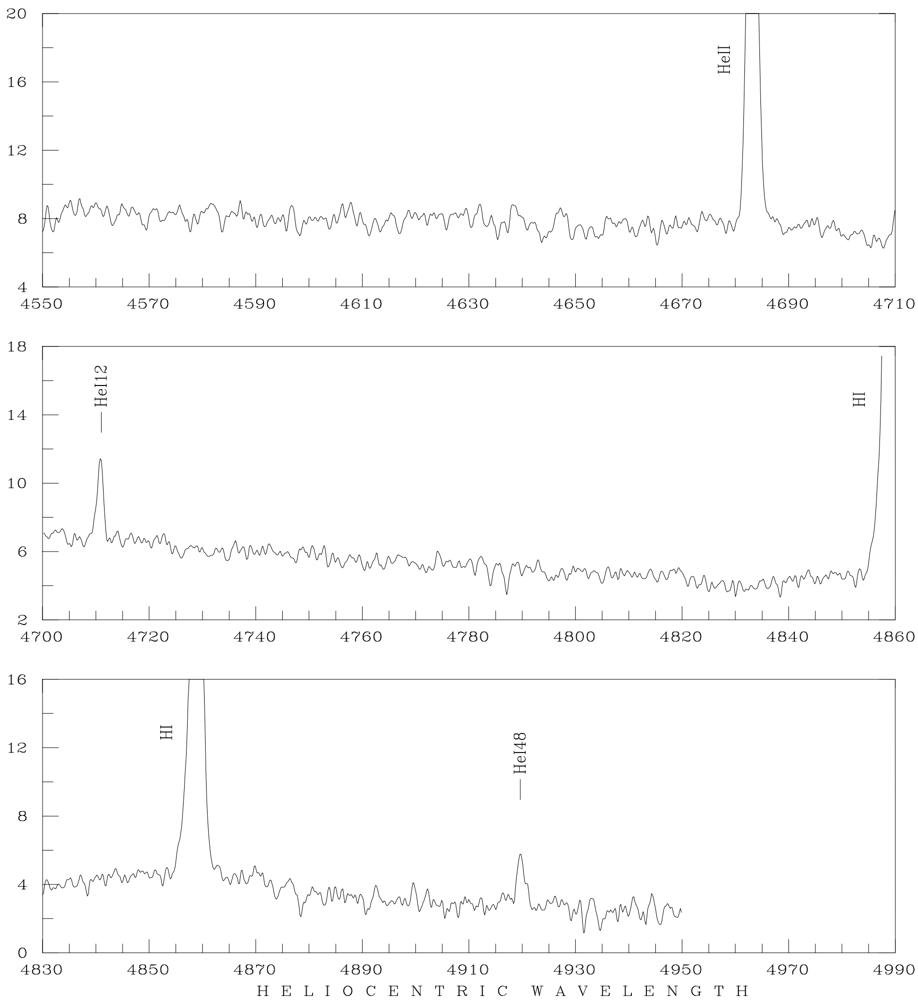

Fig. 1. (continued)

practically reached its value before the 1994 outburst (Mattei 1995). The Hα flux on August 17 was also obtained using the R photometry of Montagni et al. (1996). The spectrum on June 24 was taken during the time of increasing light, when R data are also absent in the literature, and only the equivalent width was obtained for this time.

The line fluxes were corrected for interstellar reddening. We used the value $E(B-V)=0.06$ (Mikolajewska et al. 1995; Greiner et al. 1997) and the extinction law by Seaton (1979).

Since we did not find systematic differences between the velocities of the lines of a given element in our observational data, the velocities of all elements have been obtained as arithmetical means of the velocities of all lines detected. The radial velocity data are listed in Table 2 and the line fluxes in Tables 3, 4 and 5.

We used the Skopal (1994) ephemeris $\mathrm{JD(U_{min})} = 2\,442\,514.4+552.4\times$E since its derivation is based on the greatest number of photometric data. The zero epoch is that of the photometric minimum, when the system's cool component is in front of the hot component.

3. The emission measure

The hydrogen spectrum gives us the most significant information about the emissivity of one symbiotic nebula. However using the data of the hydrogen lines we cannot perform quantitative analysis of the behaviour of the emission measure of the nebula of AG Dra during the outburst phase, since their optical depth is large (see the next section) and the observed flux does not provide a correct estimate of the number of emitting atoms. Moreover we have no data at the times of the light maximum during the active phase.

The variations of the emission measure in 1994 and 1995 can be investigated using Balmer continuum emission. We consider the variations of the flux at the position of the maximal sensitivity of the U photometric system using the data of Hric et al. (1993), Skopal et al. (1995), Hric et al. (1996) and Montagni et al. (1996). This position is close to the Balmer limit. The blending of the Balmer lines with high numbers causes absence of Balmer discontinuity, i.e. it produces an apparent continuum which on the long wavelengths-side of the Balmer limit in the interval $\lambda\lambda$ 3650÷3660 Å (Fig. 1) has the same flux as on the short wavelengths-side. For this reason we used the value of the emission coefficient on the short wavelengths-side.

Table 1. List of the observations

Date	JD 2 449 000+	Phase	Detector; obs. region[a]	Exposure (minutes)	State of the system[b]
1993 Feb 6	024.51	0.785	CCD; Hα	60	Q
1993 Mar 16	062.51	0.854	Phot. IIaO	205	Q
1993 Apr 11	089.38	0.902	Phot. IIaO	255	Q
1994 Jan 2	354.59	0.383	CCD; Hα	2×20	Q
1994 Jan 24	376.60	0.422	CCD; Hα	30	Q
1994 Jan 24	376.64	0.422	CCD HeII 4686	30	Q
1994 Feb 2	385.52	0.439	CCD; Hα	30	Q
1994 May 19	492.47	0.632	CCD; Hα	2×20	Q
1994 Jun 24	528.32	0.697	CCD; Hα	2×20	A
1994 Jun 24	528.38	0.697	CCD; Hβ	20	A
1994 Jun 25	529.35	0.699	CCD; λλ 4500 Å	10+20	A
1994 Jun 25	529.45	0.699	CCD; Hγ	10+20	A
1994 Aug 17	582.27	0.795	CCD; Hα	20	A
1994 Aug 17	582.29	0.795	CCD; Hβ	20	A
1994 Aug 17	582.32	0.795	CCD; λλ 4500 Å	2×20	A
1994 Aug 17	582.35	0.795	CCD; Hγ	20	A
1995 Oct 3	994.42	0.541	Phot. ZU	272	A
1995 Oct 4	995.36	0.543	Phot. ZU	360	A
1995 Nov 2	1024.33	0.595	Phot. ZU	345	A

[a] All photographic observations were made in the region λλ 3600÷5000 Å.
[b] Q = quiescent, A = active

Table 2. Radial velocity data in units of km s^{-1}

JD 2 449 000+	Phase	H I: All lines	H I: Hα(core)	He^1 I	He^3 I	He II	O III	[O III] 4363	Abs. lines	State of the system[a]
024.51	0.785	−146.69	−106.45						−150.39	Q
									±0.08	
062.51	0.854	−146.73		−144.30	−138.29	−144.51				Q
		±3.16		±1.88	±3.59	±1.56				
089.38	0.902	−149.07		−166.64	−145.09	−150.72				Q
		±1.45		±1.20	±1.48	±1.76				
354.59	0.383	−137.18	−98.75						−141.12	Q
									±0.44	
376.6	0.422	−128.08	−86.81			−140.18			−138.62	Q
									±0.50	
385.52	0.439	−137.18	−99.77						−144.79	Q
									±0.50	
492.47	0.632	−146.28	−111.12						−152.71	Q
									±0.52	
528.3	0.697	−151.14	−125.98						−153.00	A
		±4.13							±0.97	
529.4	0.699	−214.73		−188.22	−191.51	−169.32				A
582.3	0.795	−149.01	−110.23	−162.80	−176.27	−165.60			−151.25	A
		±8.27							±0.95	
994.42	0.541	−140.68		−150.52	−149.56	−156.68	−162.67	−174.01		A
		±1.18		±2.68	±0.30	±0.25				
995.36	0.543	−145.73		−149.61	−146.78	−160.40	−169.22	−157.64		A
		±1.08		±3.77	±3.10	±1.59	±2.14			
1024.33	0.595	−137.69			−144.38	−149.00				A
		±0.33			±9.09					

[a] Q = quiescent, A = active

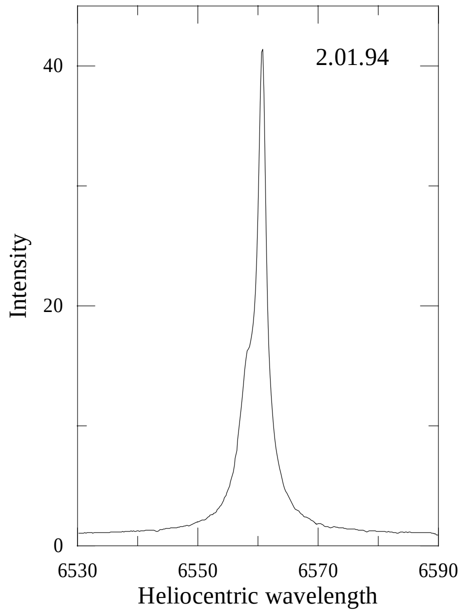

Fig. 2. Hα profile of AG Dra normalized with respect to the local continuum.

Table 3. Equivalent widths and fluxes of Hα

JD 2 449 000+	Phase	W_λ (Å)	F×10^{-12} erg cm^{-2} s^{-1}	State of the system[a]
024.51	0.785	84	50.84	Q
354.59	0.383	174	106.04	Q
376.60	0.422	184	112.12	Q
385.52	0.439	159	96.86	Q
492.47	0.632	117	71.27	Q
528.32	0.697	98		A
582.27	0.795	104	130.94	A

[a] Q = quiescent, A = active

The nebula's contribution to the continuum of the star at the position of the U system during quiescence is not less than 60%. This estimate is taken as a ratio of the U orbital amplitude and the flux at the phase of the photometric maximum based on the assumption that the orbital variations are due to an occultation of a part of the ionized region(s) of the nebula (Mikolajewska et al. 1995). That is why we will consider the quiescent U flux of the AG Dra system is dominated by its circumbinary nebula. When the U magnitude was converted into a continuum flux, we did not make correction for the emission lines included in the wavelength region of the U photometric system, as the spectrum in this region was not observed during the photometric observations.

On calculating the emission measure we adopted the helium abundance of 0.1 which is thought to be typical of the symbiotic nebulae (Vogel 1993; Vogel & Nussbaumer 1994). Since the He II 4686 line is appreciably more intense than the He I lines, we assume that helium is entirely in a state of double ionization and the continuum of the gas is produced by H and He II. We used the emission coefficients of these elements, determined by recombinations and free-free transitions, whose values for different wavelengths and temperatures are listed in the books of Osterbrock (1974) and Pottasch (1984). Mikolajewska et al. (1995) obtained an electron temperature for the nebula of AG Dra of about 15 000 K. In our calculations we assume the same temperature in both the quiescent and the outburst states of the system. Analysis of some of the emission lines (Sects. 4, 5) shows a region of a stellar wind produced by the hot secondary (see Sect. 5) present in the surrounding nebula during the active phase. The temperature of this region is probably higher than 15 000 K. Using the wind parameters and supposing an electron temperature of 20 000 K, we obtain the U continuum flux of this region to be 2.4 10^{-14} erg cm^{-2} s^{-1} $Å^{-1}$, which is negligible compared with the observed U flux (see below). Therefore the observed U flux is emitted practically by the rest of the ionized region(s) of the nebula and that is why we use the values of the emission coefficients of H and He II for an electron temperature of 15 000 K.

We also adopt the distance to the system of 2 500 pc proposed by Mikolajewska et al. (1995) and Greiner et al. (1997).

In quiescence the U magnitude of AG Dra is equal to $11^{\rm m}$ at the phase of the photometric maximum and about $12^{\rm m}$ at the phase of the photometric minimum (Hric et al. 1993). The dereddened continuum fluxes of 0.23 10^{-12} erg cm^{-2} s^{-1} $Å^{-1}$ and 0.09 10^{-12} erg cm^{-2} s^{-1} $Å^{-1}$ corresponding to these magnitudes yield quiescent emission measures of $n_{\rm e}^2V = 3.4\,10^{59}$ cm^{-3} and $n_{\rm e}^2V = 1.3\,10^{59}$ cm^{-3}. Mikolajewska et al. (1995) obtained values one and a half times higher than ours by fitting dereddened optical spectra with a K4 giant and H I continuum emission with an electron temperature of 15 000 K. The emission measure increased by a factor of 15 during the 1994 outburst. The light estimate of Skopal et al. (1995) $\rm U = 8^{\rm m}_{.}05$ on 23 July (JD 2 449 556.52), at the first visual maximum, yields an emission measure of $n_{\rm e}^2V = 5.1\,10^{60}$ cm^{-3}. The U light of the system did not reach its quiescent value between its 1994 and 1995 outbursts. The magnitude $\rm U = 9^{\rm m}_{.}91$ taken on 18 March 1995 (JD 2 449 794.60) by Montagni et al. (1996) gives an estimate of $n_{\rm e}^2V = 9.1\,10^{59}$ cm^{-3}. During the second light maximum (July 22 1995, JD 2 449 921.39) the magnitude of AG Dra was about $\rm U = 8^{\rm m}_{.}70$ (Hric et al. 1996), which leads to an emission measure of $n_{\rm e}^2V = 2.8\,10^{60}$ cm^{-3}. At the end of February 1996 it was $\rm U = 10^{\rm m}_{.}39$ (Montagni et al. 1996), which provides an emission measure of $5.8\,10^{59}$ cm^{-3}. If we have an estimate of the electron density in the nebula of AG Dra we can calculate the approximate size of the spherical emitting volumes when deriving the emission measure. The electron density cannot be obtained using our data and moreover simultaneous UV estimates are not known by us. Neverthless we could estimate the size of the emitting region using an electron density of 10^{10} cm^{-3} (Mikolajewska et al. 1995). During quiescence the radii of this region are found to be $\rm R_{max} = 0.6$ AU at the phase of the photometric maximum and $\rm R_{min} = 0.4$ AU at the phase of the photometric minimum. At the times of the first and second visual maxima during the outburst phase the radii of the emitting region increased to $\rm R = 1.5$ AU and $\rm R = 1.3$ AU.

4. Description and analysis of the emission line spectrum

4.1. The Balmer lines

4.1.1. The Hα line

In our spectra the Hα profile is single-peaked, with a shoulder on the short wavelengths-side at all phases (Fig. 2). In some cases this shoulder is highly pronounced and in the rest of them, where scarcely visible, it produces a general asymmetry only. In contrast to some other symbiotic systems like EG And and AG Peg (Oliversen & Anderson 1982; Oliversen et al. 1985; Boyarchuk et al. 1987) the Hα line of AG Dra during the period of our observations had unusually extended low intensity wings which practically reached the continuum level at about $1000\,\mathrm{km\,s^{-1}}$ from the center of the line. It should be emphasized that the asymmetry was related to the upper part of the profile and the wings were always symmetrical.

Robinson et al.(1994) investigated double-peaked profiles of AG Dra and found an acceptable fit for an accretion disk with inner radius of $1.1\,10^{8}$ cm and outer radius of $1.3\,10^{10}$ cm. If we suppose the existence of a disk having such a small size, it would have appeared most probably as a result of accretion of a stellar wind. But in this case, the wind of the giant will give rise to a circumbinary nebula, as well as the accretion disk. This nebula will also contribute to the emission lines, which will not due to the accretion disk alone.

The initial five of our Hα spectra (Table 1) are related to the quiescent stage and the spectra of June and August 1994 were taken immediately before and after the moment of the first light maximum (July 1994), when the V light increased by more than one magnitude (Skopal & Chochol 1994, Montagni et al. 1996). The width (FWHM) of the line was 90–100 $\mathrm{km\,s^{-1}}$ during the quiescent stage and the shoulder was below the level of the half maximum. The intensity of the wings varied during this period (Fig. 5), which led us to suppose that different numbers of emitting hydrogen atoms were observed at different phases. The variation in the number of emitting atoms could be due to an occultation of a bright region around the hot component of the system, as was supposed by Mikolajewska et al. (1995).

The fact that the wings are symmetrical and the features leading to an asymmetry are located in the upper part of the profile gives reason to suppose these features are a sign of self-absorption. Similar features are present in the Hα profile of the AG Peg system where they signal the same process. Our supposition is based also on the established fact that in both systems AG Peg (Boyarchuk 1966a) and AG Dra (Boyarchuk 1966b) the Balmer decrement differs greatly from the theoretical one because of self-absorption. In the final analysis we consider the profile variations are due to two factors during the period of our observations. The first of them is a variation in the emitting-atom number. It determines the intensity of the wings and is probably due to an occultation of the emitting region. The second one is a variation of the optical depth, which causes the changes of the upper part of the profile and is related to the orbital motion, too.

During the outburst the appearance of the profile remained the same, but the shoulder was above the level of the half maximum. The width of the line increased to about $150\,\mathrm{km\,s^{-1}}$. The intensity of the wings also increased considerably (Fig. 5).

The behaviour of the flux at the phases of observation is displayed in Fig. 6. It decreased by a factor of 2.2 in the phase interval of 0.4. The spectra taken on JD 2 449 024.51 and JD 2 449 582.27 are approximately at the same phase, one coming from the quiescent stage and the other from the outburst. Comparison of the fluxes in those moments indicates an increase by a factor of 2.5.

The wavelength position of Hα was measured at two places on its profile – in the upper part of the core of the line, where it is practically symmetrical, and in wing area. The radial velocity data of the core are scattered (Fig. 7), which is easily explained by assuming that this part of the line is influenced by self-absorption. The behaviour of the velocity of the wings is different and is identical to that of the other Balmer lines within the range of error. It turned out this velocity is very close to that of the mass center of the system at most phases of observation.

Table 2 shows that the lines of H I on JD 2 449 529.40 have a large negative radial velocity, which differs from the rest of the velocities, but is close to those of the lines of the other elements at this particular time. In our opinion the values of these velocities are not due to random error and seems to be emission observed from an area of the nebula whose movement is towards the observer, caused probably by an expanding envelope.

Let us compare our continuum emission measure with those calculated using our Hα data and assuming Menzel case B. At phases close to the photometric maximum during quiescence, the values of the Hα flux produce values of the emission measure in the interval from $2.3\,10^{59}\,\mathrm{cm^{-3}}$ to $2.6\,10^{59}\,\mathrm{cm^{-3}}$. The emission measure of the nebula increased during the outburst phase, as is seen from its quantity of $n_{\mathrm{e}}^{2}V = 3.1\,10^{59}\,\mathrm{cm^{-3}}$, determined by the H$\alpha$ flux obtained on JD 2 449 582.27. These values were calculated with an effective recombination coefficient corresponding to an electron temperature of 15 000 K (Pottasch 1984).

4.1.2. The other hydrogen lines

On the spectra taken in 1993 when the AG Dra system was at the quiescent stage, the lines of Balmer series were visible as far as H 13, but the absence of those having higher numbers was probably due to the low density of the spectrograms. The profiles of many lines had asymmetry. Using a CCD camera in June and August 1994 we were only able to observe the lines Hβ and Hγ (Figs. 3, 4). All of these data revealed single peaked profiles of the Balmer members, i.e. they were ordinary nebular lines. On JD 2 449 529 the widths of Hβ and Hγ were about $170\,\mathrm{km\,s^{-1}}$ and on JD 2 449 582 about $125\,\mathrm{km\,s^{-1}}$.

In October 1995, when the light of the star was decreasing after its second maximum (July 1995), the lines of Balmer series were visible as far as H 30(Fig. 1). The profiles of Hβ and Hγ consisted of two components: a central narrow component with width (FWHM) equal to about $100\,\mathrm{km\,s^{-1}}$ and a broad component, whose width was much greater (Figs. 3, 4). The rest of the Balmer members had one component profile, which

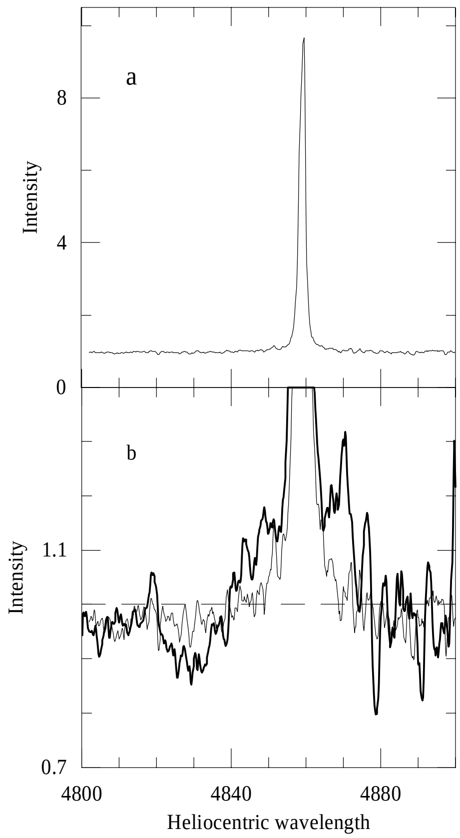

Fig. 3. a The profile of Hβ, based on a CCD frame on JD 2 449 582.29. **b** The area of the wings of this line, compared with the case when a broad component is present (the thick line). The level of the local continuum is marked with a dashed line.

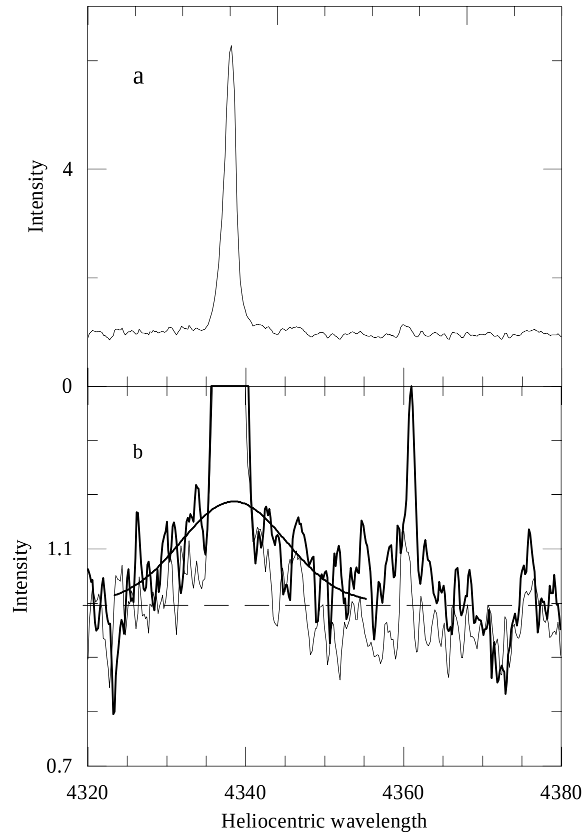

Fig. 4. Same as Fig. 3 for the line Hγ. The line [O III] 4363 is seen as well.

in most cases had asymmetry. Their width was approximately the same. The line H 8 is badly blended with the line He I 3889 and is inappropriate for investigation. The line Hϵ was also not investigated because of blending, most probably with the corresponding Pickering line and the H line of Ca II. Unfortunately it was not possible in this time to observe the line Hα, which in the other cases always had only one component. The line fluxes of Hβ and Hγ are listed in Table 4.

The profile of the broad component of Hγ observed on JD 2 449 995.36 is displayed in Fig. 4, while the profile of Hβ was not analysed because of the decreased sensitivity of the spectrogram in its region (see Sect. 2). Moreover we could not investigate the broad components of these lines using the spectrogram of JD 2 449 994.42 because of its higher noise. The error of the local continuum in the Hγ region of the spectrum taken on JD 2 449 995.36 is not greater than $\pm$5%. The observed spectrum in the region of the broad component was corrected through removing some weak emission lines of O II as well as the strongest absorption lines of the giant. Then it was analysed by fitting with a Gaussian function and its FWHM turned out to be equal to 1080$\pm$330 km s^{-1}.This procedure allows us to obtain its equivalent width and the line flux with an error of about 60%, explained first of all by the error of the local continuum. In this way we consider the FWZI of the line to be determined

Table 4. Fluxes of the lines displaying two components – a narrow (N) and a broad (B) one in units of 10^{-12} erg cm^{-2} s^{-1}

JD 2 449 000+	Phase	Hβ N	Hγ N	Hγ B	He II 4686 N	State of the system[a]
376.64	0.422				11.00	Q
528.38	0.697	44.56				A
529.45	0.699		37.54			A
582.32	0.795	31.92	18.13			A
994.42	0.541	33.08	10.08		17.50	A
995.36	0.543		7.51	2.38		A

[a] Q = quiescent, A = active

from that distance from its center where the fit reaches the level of the noise – 780 km s^{-1}. Taking into account the error of the local continuum again, we are inclined to increase this value to 800 km s^{-1}.

There are different mechanisms of emission line broadening and one of them is the electron (Thomson) scattering. Let us consider the possibility that the broad components of the lines Hβ and Hγ are determined by electron scattering. The Hγ total flux, which is a sum of the fluxes of the two components, is equal to 9.89 10^{-12} erg cm^{-2} s^{-1}. With the parameters of the nebula adopted by us in Sect. 3 this yields an emission measure of $n_{\rm e}^2 V = 1.4\,10^{59}$ cm^{-3}. Assuming a constant electron density of 10^{10} cm^{-3} (Mikolajewska et al. 1995) we obtain a

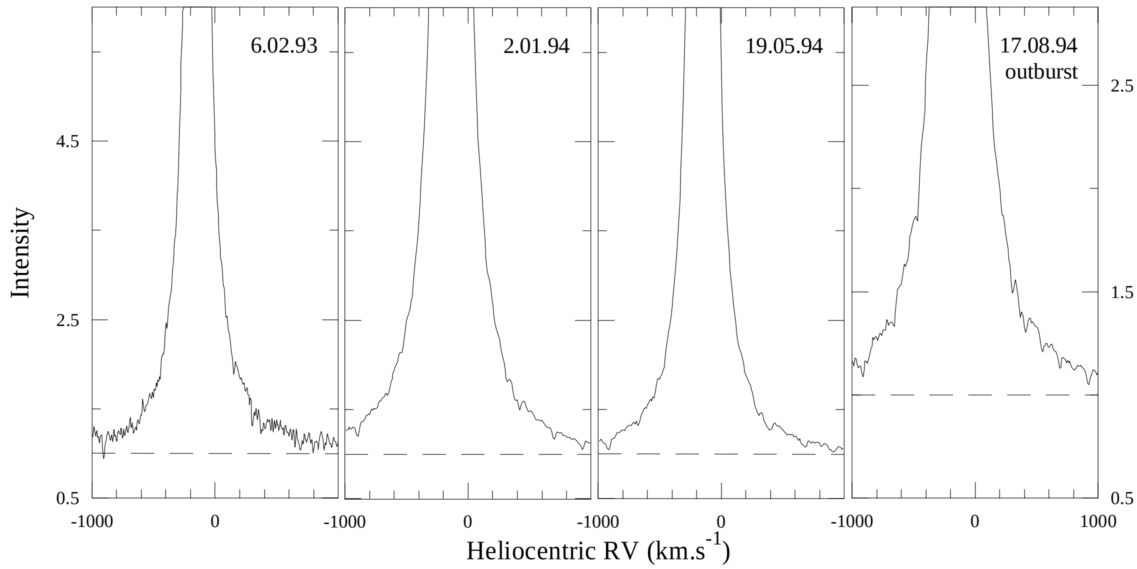

Fig. 5. Variations of the wings intensity of the Hα line during quiescence and outburst. For a direct comparison of the intensities the ratio of the ordinate scales has been chosen to be equal to the ratio of the continuum fluxes at the position of Hα.

Table 5. Fluxes of one component lines during the active phase in units of 10^{-12} erg cm^{-2} s^{-1}

JD 2 449 000+	Phase	He I 3965	He I 4009	He I 4026	Hδ 4102	He I 4121	He I 4144	He II 4200	[O III] 4363	He I 4388	He I 4471	He II 4542	He I 4713
529.4	0.699									4.66	3.97	3.19	
582.3	0.795									2.24	2.56	0.92	
994.42	0.541	0.95	0.58	1.32	7.36	0.53	0.75	0.46	0.33	1.14	1.25	0.63	0.76
995.36	0.543	0.97	0.51	1.25	7.32	0.49	0.52	0.43	0.38	0.82	1.20		

radius of 6.9 10^{12} cm of the spherical volume with this emission measure. If the broad component was produced by Thomson scattering it would appear in a region with an optical thickness of about 0.3. Using this optical thickness and an electron density of 10^{10} cm^{-3}, we obtain 4.5 10^{13} cm for the radius of this region, which corresponds to an enormous emission measure of 3.8 10^{61} cm^{-3}. Since this result is in disagreement with the previous one, we conclude that the broad component is probably not produced by Thomson scattering. Another possible interpretation of this component will be given in Sect. 5.

4.2. The helium lines

During the time of our observations the lines of He I had one component profile (Fig. 1). In June and August 1994 using a CCD camera we observed only the lines with wavelengths $\lambda\lambda$ 4388 Å and 4471 Å. On JD 2 449 529.40 they were fairly broad and their widths were equal to 96 km s^{-1} and 130 km s^{-1}. On JD 2 449 582.33 the widths were 74 km s^{-1} and 96 km s^{-1} respectively. In the beginning of October 1995 the arithmetical mean value of the singlets widths was about 85 km s^{-1} and of the triplets about 90 km s^{-1}.

The fluxes of all of the helium lines observed by us are listed in Table 5. It is seen that those of He I 4388 and He I 4471 have decreased by a factor of about 2 during the period JD 2 449 529–2 449 582.

The radial velocity data of each group of the helium lines, both singlets and triplets, are listed in Table 2. The radial velocities are close to the velocity of the mass center of the system at most phases of observation.

4.3. The lines of elements with high ionization degree

Only the lines of the elements He II and O III are included in this group, which are present in the spectrum of the star in both its quiescent and active phases.

The observation in the quiescent phase (see Table 1) revealed a single-peaked profile of the line He II 4686. Its width was equal to about 65 km s^{-1}. Unfortunately it was missed in our observations during the 1994 outburst. In October 1995 a broad component was observed in the profile of this line, as for Hβ and Hγ but more uncertainly. At this time its width was 115 km s^{-1}. Data of the flux of the He II 4686 line are listed in Table 4. It increased by a factor of 1.6.

The spectrum on JD 2 449 376.64 is at phase 0.422, which is close to the maximal light phase. Then we can compare the emission measure derived from the He II 4686 line with this one of hydrogen based on Balmer continuum emission. The quies-

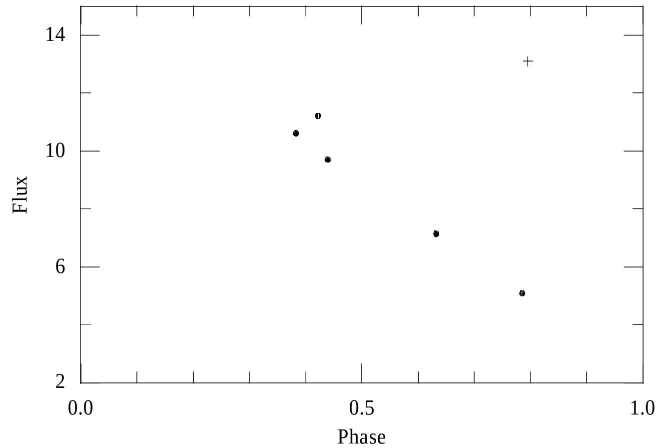

Fig. 6. Hα flux in units of 10^{-11} erg cm^{-2} s^{-1} as a function of phase. The flux during the outburst is marked with a cross.

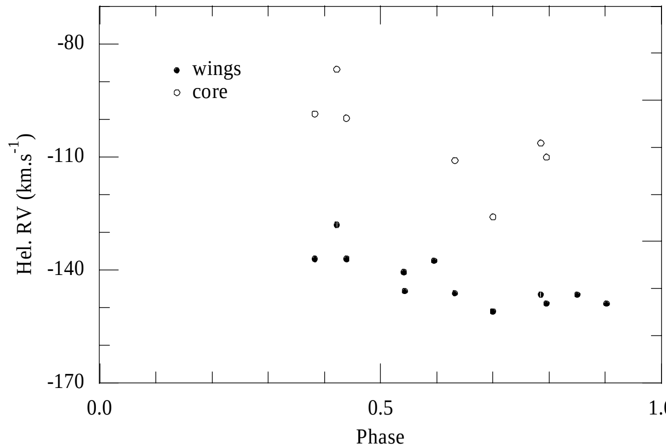

Fig. 7. Balmer radial velocities as a function of phase. The value of -214.73 km s^{-1} (Table 2) is not displayed in the figure.

cent hydrogen emission measure is $n_e^2 V = 3.4\,10^{59}$ cm^{-3} at the phase of the photometric maximum. The photometric data of Montagni et al. (1996) on JD 2 449 994.42 provide a value of $n_e^2 V = 1.4\,10^{60}$ cm^{-3}. The flux data of the He II 4686 line in Table 4 indicate $n_e^2 V = 6.2\,10^{58}$ cm^{-3} and $n_e^2 V = 9.9\,10^{58}$ cm^{-3} for He/H = 0.1. The comparison shows that the helium emission measure is in better agreement with the hydrogen one during outburst, as their ratio in this case is 0.07. In quiescence this ratio is 0.18. The radii of the region emitting the He II 4686 line at the two times of its observation differ slightly and in the two cases are about 0.4 AU.

Besides the line with wavelength $\lambda\lambda$ 4686 Å, the Pickering He II lines are also present in the emission spectrum of AG Dra (Fig. 1). We took data only for the lines with wavelengths $\lambda\lambda$ 4200 and 4542 Å of this series, as the rest of them are badly blended with Balmer lines. During the 1994 outburst we observed only the line He II 4542 with the CCD camera. On JD 2 449 529.35 its width was fairly broad of about 140 km s^{-1}. After this time it decreased to 100 km s^{-1} on JD 2 449 582.32. In the beginning of October 1995 the width of this line was the same. Its flux decreased by a factor of 3.5 during the period JD 2 449 529–2 449 582 (Table 5).

All lines of He II investigated by us had the same velocities within the range of the error, which were close to the barycentric velocity at most of the observation phases (Table 2).

The lines of O III with wavelengths $\lambda\lambda$ 3755 Å and 3760 Å were so weak that their radial velocities could be measured only on the spectra taken in October 1995 (Table 2).

4.4. The forbidden lines

Among the visual forbidden lines we observed only [O III] 4363, which is present in the spectrum of AG Dra only during the outburst phase. In 1994 it was scarcely visible, so that flux and radial velocity data for it could be obtained using only the spectrograms taken in October 1995 (Tables 2 and 5). At that time it had a symmetric profile, and, like the other lines, its width was also appreciable – 80 km s^{-1}.

5. The broad components and the mass-loss rate

Emission lines similar to the broad components of the Hβ, Hγ and He II 4686 lines can be radiated by a small accretion disk around the compact object, rotating with Keplerian velocity. Let us consider this possibility. For the radius of the secondary component we adopt a value of 0.11 $R_\odot$ (see below). The mass of this component is assumed by Mikolajewska et al. (1995) to be about 0.6 $M_\odot$ and by Greiner et al. (1997) to be no more than 0.6 $M_\odot$. We will take the value of 0.6 $M_\odot$. Using these data a Keplerian velocity of 1020 km s^{-1} is obtained. This velocity is comparable to the velocity of 800 km s^{-1}, which corresponds to the FWZI of the broad component of Hγ and is related to a small disk located close to the hot secondary. That sort of disk would appear as a result of accretion of a stellar wind and its luminosity would be low. In our opinion the observational facts that the broad components were present in the spectrum only during the active phase after the visual maximum and were absent during quiescence are of primary importance. If the outbursts are really thermonuclear events, there will be more favourable conditions for the existence of such a disk during the quiescent stage when accretion occurs. If the outbursts are driven by accretion, they are realized in the presence of an optically thick massive disk as the supposed one is not. Then we will assume that the broad components are due to high velocity radial outflow (stellar wind), appearing most probably as a result of the outburst itself. These components are very similar to the broad components of the visual emission line spectrum of the AG Peg system, which belong to the same lines (Hutchings & Redman 1972, Ilmas 1987, Tomov & Tomova 1992, Tomov et al. 1998) and appeared also as a result of an outburst.

A stellar wind with high velocity appears at some stages of the evolution of the secondary components in symbiotic systems and can be generated by both a compact object and an accretion disk. A view that an accretion disk probably does not always exist in the AG Dra system is expressed in the work of Greiner et al. (1997). Then we assume the possibility of it to appear occasionally – for instance during the outburst. Let us examine is there observational evidence for the existence of an accretion disk close or during the time of observation of the emission components, indicating a stellar wind as we detected. Analysis of our Hα profiles showed that they are not determined by a disk. Indeed these profiles were not obtained together with the broad components of Hβ and Hγ, but some of them are related to the time of the 1994 outburst. The recent high-resolution spectroscopy of Viotti et al. (1998) carried out in January 1995 revealed the same single-peaked Hα profile as in our observations.

The X-ray observations of AG Dra, realized in both the quiescent period from 1990 to 1993 and the 1994–1995 active phase, were analysed by Greiner et al. (1997). According to these authors the spectrum in this region probably was not emitted by a disk, as it has soft energy distribution, and the observed luminosity is much higher than can be produced by an accretion disk around a compact dwarf. On the other hand the observed soft spectrum is well fitted with a blackbody model, while assuming that the giant in the system will overfill its Roche lobe causes substantial difficulties.

Having in mind all these results basing of data, taken close to the time of observation of the broad emission components of Hβ and Hγ, we adopt the view they are probably due to a wind of a hot compact object rather than to an accretion disk.

From available line fluxes appearing in the wind of the secondary component, we determined its mass-loss rate during the 1995 outburst using one of the two methods described by Vogel (1993) and Vogel & Nussbaumer (1994). This method is based on the relation between the energy emitted in the He II 1640 line and the mass-loss rate when the wind has spherical symmetry and a constant velocity. The line is assumed to be dominated by recombination and to be optically thin. Among the two lines having broad components that indicate a stellar wind as observed, the more appropriate one for determining the mass-loss rate is Hγ, as its optical depth is probably smaller. We performed our calculations assuming the broad component of Hγ to be an optically thin line. The particle density is a function of the distance to the center and is expressed via the continuity equation. In the last section the wind velocity was obtained to be 800 km s^{-1}. We used a recombination coefficient corresponding to an electron temperature of $T_{\rm e} = 20\,000$ K (Pottasch, 1984) and a parameter μ of 1.4 (Nussbaumer & Vogel 1987), determining the mean molecular weight $\mu m_{\rm H}$ in the hot wind. As the line flux is considered to be emitted by a spherical region, the radii of integration must be determined. Since we treat the wind in the nebular approach, the inner radius is thought to be the radius of the star. The radius of the hot component of the AG Dra system according to Mikolajewska et al. (1995) is equal to 0.08÷0.09 R$_\odot$ in the quiescent phase and 0.25÷0.35 R$_\odot$ in outburst. The second of these values is probably related to the radius of the ejected shell. When the outburst event is thermonuclear, a stellar wind appears after the visual maximum (Shara et al. 1993) when the optical depth of the ejected shell has reached a value less than unity. The radius of the star at this stage is probably closer to its quiescent radius than the radius of the shell and that is why we are inclined to use the quiescent radius. Let us now consider the value of this parameter obtained from the analysis of Greiner et al. (1997). An appearance of a stellar wind from the hot component is considered by these authors to be possible when its photosphere has expanded as a result of an increasing accretion rate. In this case the radius is about 0.14 R$_\odot$. Having in mind this result, as well as the quiescent radius of Mikolajewska et al., in our investigation we will use their arithmetical mean value, which is equal to 0.11 R$_\odot$.

To determine the outer radius it is necessary to know the region of ionization of hydrogen whose size depends on the temperature of the star. According to Mikolajewska et al. (1995) this temperature is about 10^5 K during both the quiescent and the active phases. In this case the photon fluxes beyond the limits of the ground series of hydrogen and ionized helium (Nussbaumer & Vogel 1987) are sufficient for ionizing these elements in the hot wind to infinity. According to Greiner et al. (1997) the temperature of the hot star is higher and there will be the same regions of ionization in this case. Then we would consider the outer radius to be equal to infinity. In this way, having the line flux equal to 2.38 10^{-12} erg cm^{-2} s^{-1} we obtain a value of the mass-loss rate of 2.00 10^{-7} M$_\odot$ yr^{-1}. At a distance of 2 500 pc (Mikolajewska et al. 1995; Greiner et al. 1997) an appreciable mass-loss rate is necessary to be possessed by the hot companion for it to be able to emit the detected flux of the Hγ broad component, reaching scarcely 0.2 in its center above the level of the local continuum.

The secondary component of the AG Dra system is a hot compact star and the radiation in its atmosphere could be considerably influenced by electron scattering, which can be assessed by calculating the optical thickness of the hot wind for electron scattering. When the wind has spherical symmetry and a constant velocity, the optical thickness can be analytically integrated over the r^{-2} density distribution from the radius of the star to infinity, using the velocity of the wind and the mass-loss rate. The optical thickness obtained is about 0.5. Then the electron scattering affects the radiation of the hot component's atmosphere which means that the wind lines will also be broadened. This leads to overestimating the wind velocity from the line width at the level of the local continuum, so that the value of 800 km s^{-1}, obtained by us, can be considered as an upper limit.

6. Discussion

We established that the profiles of some of the visual emission lines of AG Dra indicate a hot high-velocity stellar wind in the autumn of 1995 after the secondary light maximum. Theoretical considerations (Kato 1997) show that the thermonuclear runaway on the surface of a white dwarf is connected with a mass loss, which gives rise to a stellar wind with a high velocity after the visual maximum. While the detection of such a wind in AG Dra might provide evidence for a thermonuclear event, we note that the model of Greiner et al. (1997) provides an alternative explanation for the appearance of a stellar wind at a definite phase in the optical outburst.

A typical feature of the behaviour of the AG Dra system during its 1994–1995 active phase was the growth of its nebular spectrum. According to the thermonuclear scenario (Kenyon & Truran 1983) the bolometric luminosity of the accreting object increases at the early stages of the optical outburst as a result of a temperature increase at constant radius. The outburst itself at these stages is due to the expansion of the ionized region in the symbiotic nebula which results in increasing continuum and emission line flux. According to the X-ray model of AG Dra (Greiner et al. 1997) the bolometric luminosity of the compact object remains constant during the expansion, due to the decrease of its temperature. This variation of the temperature in principle provides a possibility for increasing its visual continuum flux, but the change of its Lyman luminosity is too small to provide the observed increase of the emission measure of the nebula and the intensity of its spectrum. That is why the growth of the nebular spectrum is an observational evidence supporting the thermonuclear model. In our opinion its importance in the case of AG Dra is greater as it occurs together with a hot stellar wind. These two lines of evidence put together are a stronger argument in favour of thermonuclear runaway, than each of them taken alone, because the appearance of a stellar wind is possible also in the framework of the model for the X-ray emission of AG Dra (Greiner et al. 1997), and the nebular spectrum would be increased as a result of an accretion driven event, too (Kenyon & Webbink 1984).

Our study showed that the hot component of the AG Dra system does not produce a wind permanently, but only at times, most probably in its active periods. The cool component of this system is a late-type giant (Smith et al. 1996) with a stellar wind. Then during the period of this hot wind, the two winds must collide head-on as presented in the simplified approximation by Girard & Willson (1987). Supposing their collision region to have zero thickness, the location of the shock zone can be determined from the condition for equality of local momenta, which is $\dot{M}_{\rm hot}\upsilon_{\rm hot}/\dot{M}_{\rm cool}\upsilon_{\rm cool} = r^2_{\rm hot}/r^2_{\rm cool}$ on the line joining the two stars. The quantities $r_{\rm hot}$ and $r_{\rm cool}$ are the distances from the two components. The wind parameters of the hot companion are presented in the last section. The cool component of the system is a low-metallicity K-type bright giant having parameters $\rm M_{bol} \sim -1.1$ to -2.5 and $\rm T_{eff} \sim 4300$ K (Smith et al. 1996). For this component Mikolajewska et al. (1995) obtained a mass-loss rate of $2\,10^{-7}$ $\rm M_{\odot}\,yr^{-1}$ adopting a distance of 2.5 kpc and a wind velocity of 30 $\rm km\,s^{-1}$. Using the orbital period of Skopal (1994) and a total mass of the system of 1.5 $\rm M_{\odot}$ (Mikolajewska et al. 1995; Schmid & Schild 1997), for the separation we obtain 324 $\rm R_{\odot}$. Then the distance between the hot companion and the collision region is derived to be 272 $\rm R_{\odot}$. According to Mikolajewska et al. (1995) the luminosity and the temperature of the cool component are about 1500 $\rm L_{\odot}$ and 4000 K, providing a radius of 80 $\rm R_{\odot}$. Using the data for the bolometric magnitude and the temperature of Smith et al. (1996) we obtain the luminosity and the radius of this component in the intervals 209÷759 $\rm L_{\odot}$ and 26÷50 $\rm R_{\odot}$ respectively. If the radius is within the limits determined by these authors, we find that the collision region is located very close to the cool component, where it is possible for it to be reached by the hot wind.

The total kinetic energy of the winds is thus 10 $\rm L_{\odot}$, providing an order of magnitude estimate for the X-ray luminosity of the collision region.

Accretion is probably realized during the multiple quiescent periods of the AG Dra system. The wind of its hot component, observed by us during the 1995 outburst, has probably existed up to the time when its momentum decreased to the extent until it was no longer able to prevent accretion. (Our unpublished spectral data of April 1996 do not show a presence of broad emission components.) If we suppose the wind velocity has been invariable and follow Zamanov's approach (1993) adopting a circular orbit (Mikolajewska et al. 1995), we will obtain the next result: when the mass-loss rate of the hot component decreases to the limited value of about $2\,10^{-9}$ $\rm M_{\odot}\,yr^{-1}$, the accretion regime will be restored. In this case it would be useful to roughly evaluate the total mass lost by this component. We know neither the duration of the hot wind with good accuracy nor its possible variations. If we suppose that the hot component had a mass-loss rate of $2\,10^{-7}$ $\rm M_{\odot}\,yr^{-1}$ for a typical time of about $100^{\rm d}\div 200^{\rm d}$, the total mass lost amounts to about $5\,10^{-8}\div 1\,10^{-7}$ $\rm M_{\odot}$.

7. Conclusions

We present the results of optical observations carried out in the blue region as well as in the region of the Hα line of the spectrum of the symbiotic binary AG Dra at quiescence and during its 1994 and 1995 outbursts. We derived profiles, fluxes and radial velocity data of a number of the emission lines. Their basic characteristic was the comparatively large width (FWHM) especially in June 1994 immediately before the light maximum.

Two kinds of variations of the Hα profile were detected during the quiescent stage. The first were in the area of the wings, determined by variations of the emitting-atoms number. We consider they are due to an occultation of the ionized region(s) of the surrounding nebula, which was supposed to exist in this system by Mikolajewska et al. (1995). The second kind of variations are related to the upper part of the profile, determined by the variations in the optical depth. The wing intensity and the line width increased considerably during outburst.

The He II 4686 line flux was observed to have increased at one time after the light maximum during the 1995 outburst by a factor of 1.6 compared with its quiescent value at a phase close to maximal light.

The emission measure was obtained with continuum flux at the wavelength of the U photometric system, assuming that in the quiescent stage of the star all of this flux is emitted by its nebula. The photometric data used were from the literature. The quiescent emission measure undergoes orbital variations of about $n_{\rm e}^2V = 3.4\,10^{59}$ $\rm cm^{-3}$ at photometric maximum and of about $n_{\rm e}^2V = 1.3\,10^{59}$ $\rm cm^{-3}$ at photometric minimum. At the times of the two maxima of the visual light during the active phase the emission measure was increased by a factor of 15 and 8 respectively compared with its quiescent maximal value.

Radial velocities of the emission lines were close to the system's mass center velocity at most observation phases. No Balmer progression was ascertained. The radial velocity of the cool primary was measured using some absorption lines of the K spectrum in the region of Hα.

After the visual light maximum in 1995, the profile of the lines Hβ and Hγ consisted of two components: a central narrow component and a broad component that most probably indicates a stellar wind. The velocity of this hot wind was equal to 800 km s^{-1} and it was probably produced by the compact secondary of the system. The mass-loss rate was estimated of 2.00 10^{-7} M$_{\odot}$ yr^{-1}. In our opinion the two sorts of observational evidence the high velocity radial outflow of gas and the increase of the emission measure during outburst, can be considered together as an important argument supporting the thermonuclear model.

We conclude also that at the time of existence of the broad emission components the symbiotic binary AG Dra has been at a stage of colliding stellar winds. The ratio of their momentum rates allows the possibility of the hot wind reaching the giant. The mechanical energy of the winds is 10 L$_{\odot}$, which is an upper limit of the X-ray luminosity of the collision region.

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