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THE SECONDARY STAR IN AM CVn

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Abstract. The spectrum of AM CVn shows no definite sign of a secondary star, but through black body calculations of the spectra of the primary, disc and secondary objects, we find that if a one-temperature model for the secondary is assumed, a secondary which is cooler than 5000 K may be present without being seen in the spectrum. There is some excess flux in the visible part of the spectrum, which indicates the presence of an object of approximately 10 000 K. The best fit is given by a two- temperature model of the secondary, indicating that illumination of the secondary by the hot primary and the disc is an important effect.

Key words: stars: binaries: close – stars: cataclysmic variables – stars: individual: AM CVn.

1. Introduction

The effect of irradiation on low-mass stars is a subject that is only at the beginning of exploration, and it has never, to our knowledge, been investigated for helium-rich stars. However, a careful study of this effect may provide valuable clues to the mystery of the AM CVn stars.

If these stars are compact binaries with a hot primary, then the mass losing secondary will certainly be subject to high irradiation, which may seriously affect the appearance and evolution of the system. Thus, by investigating how irradiation affects a low-mass helium-rich degenerate or semi-degenerate object, we may find out what we can expect to observe in the AM CVn systems if they are compact binaries (Fig. 1).

Fig. 1. AM CVn, drawn to scale. The binary separation is $0.229R_\odot$. The radius of the primary is $7.0 \times 10^{-3} R_\odot$, the volume averaged Roche-lobe radius of the secondary is 0.045 $R_\odot$ and the distance from the center of the secondary to the inner Lagrangian point is 0.059 $R_\odot$. The disc has a tidal radius of 0.11 $R_\odot$ and its thickness at the edge is $2.6 \times 10^{-3} R_\odot$. The secondary is assumed to be semi-degenerate.

2. Detection of the secondary in AM CVn

The secondary star in AM CVn has never been definitely detected, although several indications of its presence have been found in the spectrum and the light curve. The variations in the light curve are dealt with thoroughly elsewhere in these proceedings, so we shall concentrate on the possible ways of detecting the secondary spectroscopically. There are a few points worth noting:

- An almost certain sign of mass-transfer would be line splitting or periodic line shifts. However, no significant line splitting is observed with the earlier assumed orbital period of 1051 s. For this period, the upper limit of the orbital velocity is found to be $v \sin i < 50$ km/s (Robinson & Faulkner 1975). Periodic line shift has not been investigated for the period of 1028 s, which is now assumed to be the orbital period.
- The spectrum of AM CVn is characterized by broad, shallow and asymmetric absorption lines. This is quite different from the spectrum of single DB white dwarfs, but it is characteristic of mass-transferring systems and may be explained by Doppler velocities in the disc (Patterson et al. 1992, 1993).
- The visual spectrum shows mainly wide HeI absorption lines. However, there is also a distinct HeII emission line at $\lambda = 4686$ Å (Patterson et al. 1992). The HeII emission is most probably due to NLTE effects, in which case it is an indication of temperatures greater than 120 000 K. At such a high temperature all the He

would be ionized, and we would not observe HeI lines. The fact that both are seen, can be explained by the presence of more than one object. The HeII line reversal could originate in the hot primary object surrounded by cooler material in a disc where HeI absorption is possible.

- Another way of detecting the secondary is from the continuum spectrum. If the secondary has a different temperature than the primary or the disc, the maximum of its flux will be at a wavelength different from the disk spectrum. If the flux of the secondary is not too low compared with the rest of the system, this should create a bump in the continuum spectrum. In AM CVn no such bump has yet been detected, but whether this is because there is no secondary or because it is too faint is not known.

3. The binary model of AM CVn

The modulations in the light curve can either be explained as pulsations (Clemens 1995) or as being due to aspect variations in a binary system (O'Donoghue 1995). In the following we will describe the secondary object in a binary model for AM CVn. At the moment, the most reasonable guess seems to be that the binary period is 1028 s, while the 1051 s period is the superhump period with a beat period at 13.38 hours (Warner 1995). This can be used to determine the mass ratio, $q = 0.084$.

The size and masses of the system can now be found from Kepler's laws. Since we know that the secondary must fill its Roche lobe, the mean density is given by $\overline{\rho} = 107 P_{\rm orb}^{-2}$ (h) gcm^{-3} (Faulkner, Flannery and Warner 1972). By assuming a structure for the secondary, we can now express the mass, radius and binary separation as functions of the period, P. With the above density, the secondary must be either degenerate or semi-degenerate. Warner (1995) shows that if the secondary is degenerate and in thermal equilibrium, its mass will be 0.033 $M_\odot$ and the mass of the primary determined from the mass ratio, becomes 0.39 $M_\odot$. If, on the other hand, the secondary has been driven out of thermal equilibrium, and is only semidegenerate, he finds that its mass will be 0.092 $M_\odot$, which gives a primary mass of 1.09 $M_\odot$. This latter structure seems more credible, since Savonije et al. (1986) have shown that a mass loosing helium star will be driven out of thermal equilibrium for masses lower than 0.36 $M_\odot$ because the thermal timescale becomes comparable or longer than the timescale for orbital decay due to mass transfer or gravitational radiation. They also find that from this moment in the binary evolution, the secondary becomes strongly subluminous. Assuming the semi-degenerate secondary solution, the sizes of the system are easily found. The resulting system is shown in Fig. 1.

4. One-temperature black body models

To search for the secondary in the continuum spectrum, we fit as the first approximation a spectrum consisting of a disc with a number of rings each with a blackbody temperature. The temperature in the disc (Fig. 2) is determined from the assumed mass transfer rate of $1 \times 10^{-9} M_{\odot}/\mathrm{yr}$. We use the temperature of $T_{\rm eff} = 150\ 000$ K, the inclination of 40° and a distance of 275 pc. Otherwise we use the same parameters as given in Fig. 1. The result is displayed in Fig. 3 together with the observed IUE spectrum (Solheim 1992), *U,B,V,R,I* data (Massacand, Bard & Solheim 1996) and *J* and *K* data (Probst 1983). The model has been made to fit the data in the far ultraviolet, and we see that it is a good fit at short wavelengths. However in the visible region and at longer wavelengths the fit is not so good. This may be due to the effects of a secondary with a significantly lower temperature than the primary. The effect of adding a secondary is illustrated in Figs. 4 and 5.

We see that the secondary with $T_{\rm eff} = 5000$ K or less does not make a significant contribution to the spectrum, so a cool secondary may be present and not observed, but this does not explain the discrepancy between the observed spectrum and the model at visible wavelengths. The secondary with $T_{\rm eff} = 10\ 000$ K fits the spectrum very well in the visible region, filling up the gap between the model and the observed spectrum. At longer wavelengths, however, this model gives a higher flux than observed. The models with the secondaries of both $T_{\rm eff} = 8000$ K and $T_{\rm eff} = 12\ 000$ K temperatures do not fit the observational data at the longest wavelengths with sufficient accuracy. At this point it is important to remember that at these low temperatures a black body is no longer a good approximation, and more detailed calculations are needed to find what the spectrum of such a system would really look like. This crude model may nevertheless give us some clues which temperatures are expected in the secondary. We conclude that an one-temperature model for the secondary fits the observations if the temperature is either less than 5000 K or it is approximately 10 000 K. However, these models

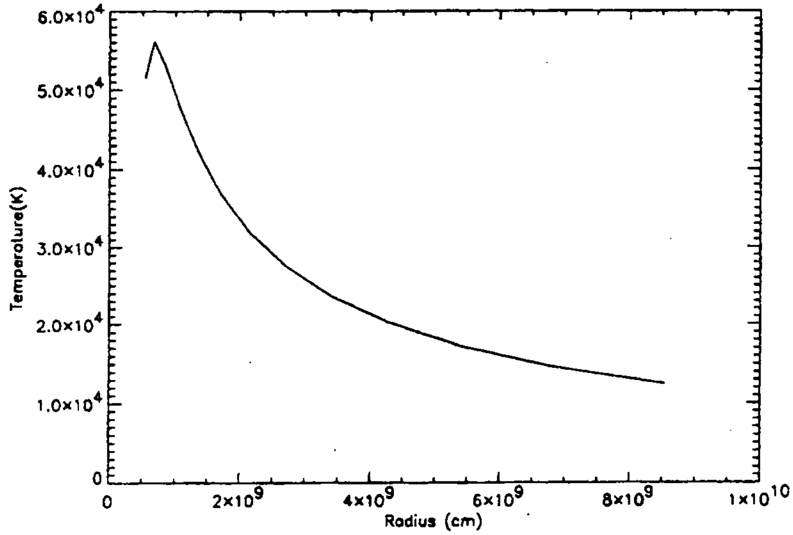

Fig. 2. The temperature profile in the disc.

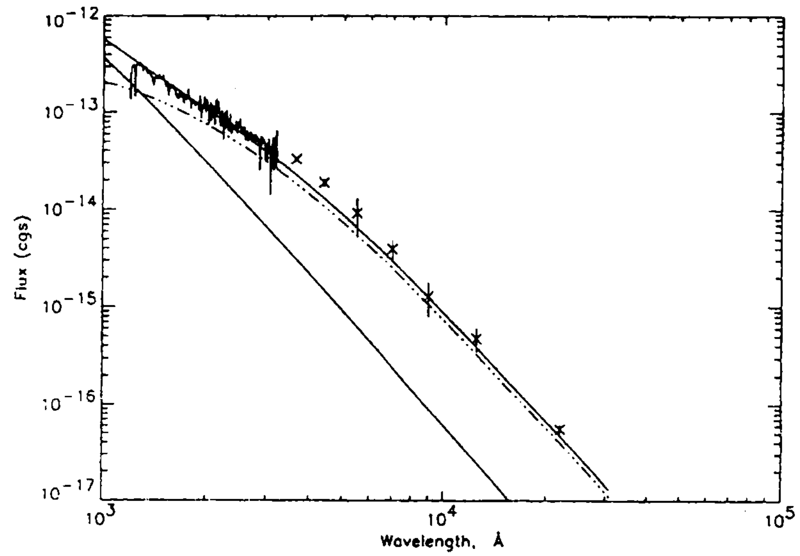

Fig. 3. The observed spectrum of AM CVn and the black body model spectrum consisting of a hot white dwarf and an accretion disc. The spectrum of a star with $T_{\rm eff}$ = 150 000 K is shown by the lower solid line and the spectrum of the disc is the dash-dotted line. The upper solid line is the sum of the star and the disk. The IUE spectrum for $\lambda < 3000$ Å and the photometric data ($\times$ signs) in the *UBVRIJK* system are also shown.

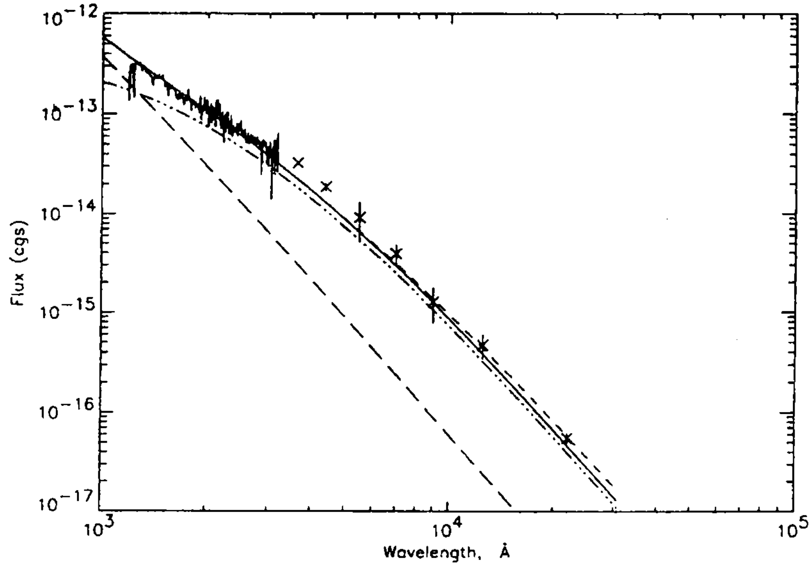

Fig. 4. The observed and model spectra with a secondary of 5000 K added to the model. The lower dashed line is for the white dwarf as in Fig. 3. The dash-dotted line is for the disk. The solid line is the sum of the star and the disk. The upper dashed line is the sum of the star, the disk and a secondary object of 5000 K temperature.

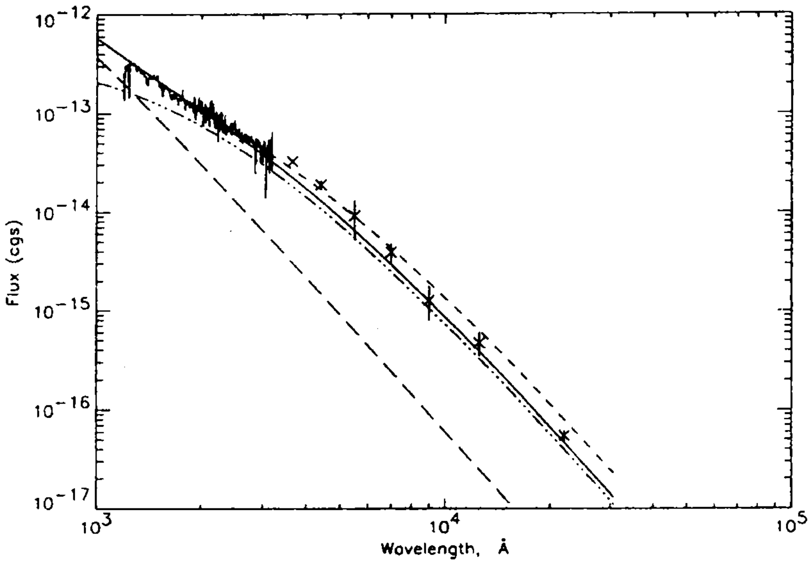

Fig. 5. The same as in Fig. 4 but for the secondary of 10 000 K temperature.

all ignore the effect of irradiation on the secondary. The primary and the disc are both very hot and luminous, and since the stars are extremely close, the irradiation on the secondary must be far from negligible. Therefore, the next step is to include the effects of irradiation. Since the peak of the combined flux is in the ultraviolet, and the secondary consists mostly of helium, an obvious start would be to study the effects of UV-radiation on a cool helium star.

5. Aspherical irradiation onto a cold star

Much of the following is inspired by the work of Ritter et al. (1994). They calculate the effects of aspherical irradiation on a low-mass star near the main sequence, but the general results for aspherical irradiation will apply to any star. However, when temperatures need to be calculated, the structure must be taken into account, and from there on the derivation differs from theirs. We also include the effects of an accretion disc, which will increase the asymmetry.

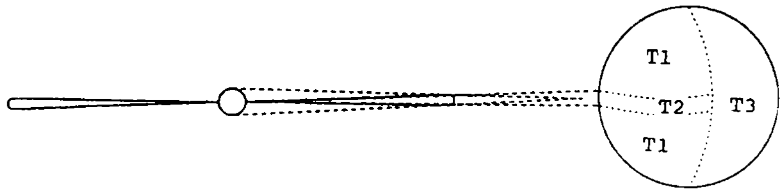

Fig. 6. The shadowing effect of the accretion disc.

If the system is tidally locked, then there will be a part of the secondary which never receives any radiation from either the primary or the disc. If the shadowing effects of the disc are included, then the radiation received on the "front" of the star is also anisotropic. Parts of the star will receive radiation from the primary and the disc, while other parts will be in the shadow of the disc (Fig. 6). The importance of this effect depends upon the distance between the stars and their respective sizes, as well as on the size of the disc. The variation in temperature across the surface must be continuous, but for simplicity we will assume that there are a few discrete temperatures. We start by assuming two temperatures; one, T_1, in the area which receives all the energy from the primary and from the edge of the accretion disc, and another (lower one), T_2, in the area of the shadow. Both temperatures are the average values in the respective areas. The higher temperature area receives the irradiative flux F_{irr_1} and covers a fraction s of the total area of the star, while the lower temperature area receives the flux F_{irr_2} and covers a fraction t of the star. The rest of the star has a temperature T_3, which is assumed to be the temperature of the unperturbed star. This covers a half of the star, i.e. $t + s = 0.5$. The total luminosity of the star is now given by a modification of the Stefan-Boltzmann law:

$$L = 4\pi R_s^2 0.5\sigma T_3^4 + s\sigma T_1^4 + t\sigma T_2^4 - sF_{\mathrm{irr}_1} - tF_{\mathrm{irr}_2} \ .$$

Now we have to calculate T_1 and T_2 which can be found through a detailed study of the effects of irradiation on the atmosphere. A few things are evident:

- The opacity of helium is much smaller than that of hydrogen, so the incoming energy will penetrate to a larger depth in this star than it would do in a hydrogen atmosphere.
- Some of the energy will be used perform mechanical work within the atmosphere. The importance of this depends on the structure of the star, so it will be necessary to determine how the energy is transferred for each of the two possible structures.
- Part of the energy may go to enhance the rate of mass transfer, and unless there is some other mechanism which slows this effect down, it may have serious consequences for the system.

Fig. 7 illustrates what happens to the spectrum if the secondary has two distinct temperatures. In this model we have neglected the shadowing effect of the disc, and we have assumed that the energy added to the "front" of the secondary is not transferred to the other side. Since only half of the star is now assumed to be hot, the illuminated side can be allowed to be hotter than what we previously found to be the upper limit to the temperature. The temperatures that are found to fit the spectrum best are $T_{\mathrm{eff}} = 12\ 000$ K and $T_{\mathrm{eff}} = 3000$ K when the other parameters are as earlier. Better calculations are needed to make any definite conclusions, but so far we can say that even a very simple two-temperature model makes a better fit to the spectrum than the one-temperature models shown in Figs. 4 and 5. This indicates that irradiation on the secondary certainly is an important effect, and cannot be neglected if we wish to understand the observations of AM CVn.

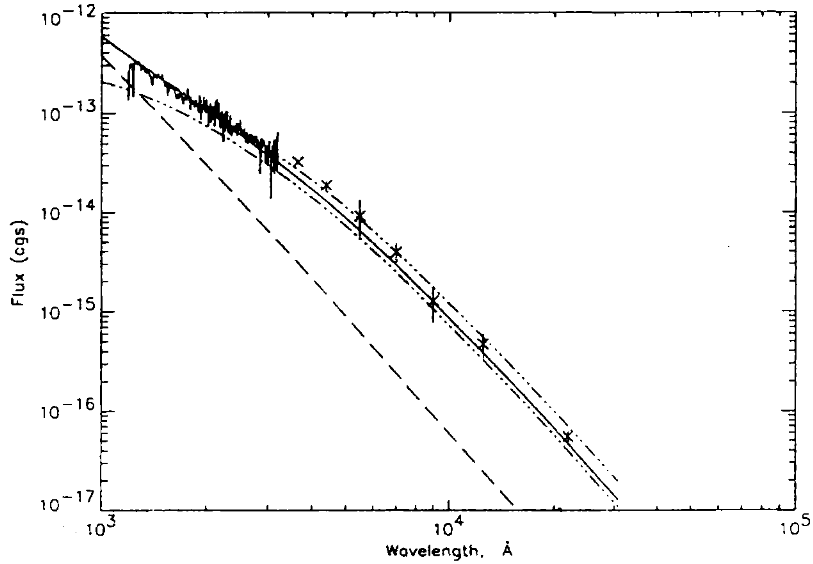

Fig. 7. The observed and model spectra with a two-temperature secondary. The temperature is 12 000 K on the illuminated side and 3000 K on the not illuminated side. The lower dashed line is for the white dwarf model, the lower dash-dotted line is for the disk, the solid line is for the star plus the disk and the upper dash-dotted line is for the star plus disk and plus a secondary object with the effect of illumination.

6. Conclusion

Through blackbody calculations of a hot white dwarf, a disc and a cool secondary, we conclude that a secondary cooler than 5000 K may be present in AM CVn without making a significant contribution to the spectrum. This agrees well with the calculations of Savonije et al. (1986), who found that a secondary with extremely low mass, like what we expect for the secondary in AM CVn, would be highly subluminous. A secondary of 10 000 K may also fit the data well in some parts of the spectrum. However, the model with two temperatures seems to give a better approximation to the observed spectrum, indicating that irradiation on the secondary is important. A closer study of this effect is under way.

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