A model of AW UMa

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ABSTRACT

The contact binary AW UMa has an extreme mass ratio, with the more massive component (the current primary) close to the main sequence, while the low mass star at \( q \approx 0.1 \) (the current secondary) has a much larger radius than a main sequence star of a comparable mass. We propose that the current secondary has almost exhausted hydrogen in its center and is much more advanced in its evolution, as suggested by Stepień. Presumably the current secondary lost most of its mass during its evolution with part of it transferred to the current primary. After losing a large fraction of its angular momentum, the binary may evolve into a system of FK Com type.

Key words: stars: eclipsing – stars: binary – stars: evolution

1 INTRODUCTION

Since its discovery (Paczyński 1964), AW UMa has played a crucial role in our understanding of contact binaries by forcing all theories to explain both, its extremely low mass ratio of \( q \sim 0.08 \), and the apparent equality of effective temperatures of both components. Eclipsing binaries of W UMa type are in direct contact, sharing a common envelope around both components. Lucy (1968a,b) was the first to recognize that the convection of gas within a common envelope equalizes the entropy, and hence the effective temperature is approximately uniform and the colours of both components remain constant throughout the orbital phase. Yet, as the components have very different masses, most nuclear energy is generated in the more massive component (the current primary), and it has to be redistributed throughout the common envelope. It was shown that this process is unstable on thermal (Kelvin-Helmholtz) time scale, which leads to relaxation oscillations, with the matter being transferred from the more massive component to the less massive star, and vice versa (Lucy 1976, Flannery 1976, Robertson and Eggleton 1977, Yakut and Eggleton 2005, and references therein). If we assume, that the mass ratio reversal took place during previous evolution of such systems, the current secondary was the initial primary while the current primary was the initial secondary. Hereafter, we shall use “the primary” instead of “the current primary” and “the secondary” instead of “the current secondary”.

Hazlehurst (1970) was the first to suggest that contact binaries may be evolved off the zero age main sequence. Stepień (2003, 2006) suggested that the secondary is the more advanced in its evolution, in analogy with the “Algol paradox”. It is not clear if this assertion is generally correct. We propose this is likely applicable to systems with extreme mass ratios, like AW UMa (Mochnacki and Doughty 1972), because the secondary’s radius is so much larger than it would be on the main sequence. This “radius excess” is the primary reason to suspect that the secondary is very advanced in its evolution.

2 PARAMETERS OF AW UMA

The following parameters of AW UMa were found on the Hipparcos website in Strasbourg: \( V = 6.90 \) mag, trigonometric parallax \( \pi = 15.13 \) mas, spectral type F1. Assuming the bolometric correction \( BC = -0.1 \), these are combined to obtain the absolute magnitude of AW UMa:

\[
L = 6.61 \, L_\odot
\]

Assuming all the luminosity is due to the primary, our model on the Main Sequence gives

\[
M_1 = 1.61 \, M_\odot, \quad X = 0.7, \quad Z = 0.02, \quad (\text{by mass})
\]

where \( M_1 \) denotes the mass of the primary component. This is consistent with a rather wide range of observational determinations of the total mass of the system (1.3 or 1.7 \( M_\odot \) (Rensing et al. 1985), 1.4 or 1.9 \( M_\odot \) (Ruciński 1992) which strongly depended on the assumed value of the mass ratio \( q \) in the interpretation of the radial velocity data. The binary period is

\[
P_{\text{bin}} = 0.4387 \, \text{d}
\]

For many years the mass ratio was adopted following
Mochnacki and Doughty (1972, Fig. 1) as \( q = 0.08 \). However, new high-quality data obtained at the David Dunlap Observatory in 2006 (Ruciński, private communication) suggest that this value is too low and may be larger, \( q = 0.1 \pm 0.02 \). As the new result has not been published yet, we consider three values: \( q = 0.08, 0.10, 0.12 \). This choice of mass ratio slightly affects the size of the low mass secondary’s Roche lobe, following Eggleton (1983).

3 OUTLINE OF THE PROBLEM

We propose a model in which the secondary was a star of \(~ 1.5 \, M_\odot\). It evolved off the main sequence, and it was stripped of most of its mass, down to the present \( 0.14 - 0.18 \, M_\odot \). Some mass was transferred to the primary, some was lost from the binary. Also, some angular momentum was lost from the binary. We assume that a complicated evolution of AW UMa can be approximated with a model in which the primary has a structure of a single star, somewhat evolved off the Zero Age Main Sequence (ZAMS), while the secondary has a structure of a single star evolved up to the formation of its helium core, and stripped of most of its mass. In other words, we approximate the evolution of the two components of AW UMa with the evolution of two single stars.

4 EVOLUTIONARY CALCULATIONS

We adopt the initial chemical composition of AW UMa as \( X = 0.7 \), \( Z = 0.02 \), (by mass), and we use the evolutionary code as described in the readme file in:

[link]

This code follows evolution of a single, spherically symmetric star of a constant mass, in a standard manner. When necessary, the code was modified to take into account a rapid mass loss (Stage II, see below). As concerns input physics, we use the Livermore opacities (OPAL, Iglesias and Rogers, 1996) supplemented with molecular and grain opacities as given by Alexander and Ferguson (1994). We use, as well, the Livermore equation of state (Rogers et al., 1996, Rogers, 2001). Nuclear reaction rates are calculated according to Bahcall and Pinsonneult (1995) updated according to Adelberger et al. (1998). This code has been already used in some previous works (e.g., Dziembowski et al., 2001). A grid of stellar models was calculated, with masses \( M_{2,0}/M_\odot = 1.00, 1.28, 1.79 \), evolved from ZAMS until all hydrogen was burned out in their cores and helium cores were formed. This was referred to as Stage I in our evolution. During this standard evolution, the initial convective cores of the 1.28 and 1.79 \( M_\odot \) models vanish and - during a short interval before the helium isothermal cores are fully formed and while in the radiative equilibrium - the rest of the hydrogen is burned out. The initial mass of the secondary \( M_{2,0} \) is the first parameter of our grid. We consider these models as possible progenitors of the secondary of AW UMa. The only constraint we put on the initial mass of the primary

\[ M_{1,0} \] is that it is significantly lower than \( M_{2,0} \) to ensure that this star will be only slightly evolved when the secondary’s radius reaches its Roche lobe. But we do not have to assume an extreme initial mass ratio of the components because a significant amount of initial mass of the secondary may be lost into the interstellar medium.

A degree of exhaustion of hydrogen in the interiors of these three models, \( X_{c,0} \), is the second parameter of our grid. We have only considered \( X_{c,0} \) as low as 0.0241 (by mass) or less (see Table 1). Adopted values of \( X_{c,0} \) are not explicitly shown in Figs. 1-3 to preserve their clarity. In these, for each line style representing a different \( M_{2,0} \), the model tracks are shifted towards the left as the amount of hydrogen exhausted during Stage I increases.

Next, for each \( M_{2,0} \), we were stripping mass of the three evolved models assuming thermal equilibrium - the evolution was frozen, i.e. there were no time dependent terms. This was Stage II, during which the mass was reduced to \( M_2/M_\odot = 0.18, 0.16, 0.14 \), consecutively. The value of \( M_2 \) is the third parameter of our grid of models. This way, following Stage II, we had 27 initial models, which were next evolved with no additional mass loss - this was Stage III. We looked at the radii of the models, expecting that some will be expanded enough to be acceptable as a model for the secondary of AW UMa.

The 27 stellar model tracks are our guesses for what the secondary’s evolution might be like. The primary star was just assumed to have the mass of \( M_1 = 1.61 \, M_\odot \), and willing to accept matter from the secondary. The only possible way

\[
\begin{array}{cccc}
\text{Track} & M_{2,0} & M_2 & X_{c,0} & M_{He,0} \\
\hline
a & 1.79 & 0.18 & 2.71e-4 & \\
b & 1.79 & 0.18 & 7.31e-3 & \\
c & 1.79 & 0.18 & 2.41e-2 & \\
d & 1.28 & 0.18 & 0.0268 & \\
e & 1.28 & 0.18 & 0.0145 & \\
f & 1.28 & 0.18 & 0.0015 & \\
g & 1.00 & 0.18 & 0.1059 & \\
h & 1.00 & 0.18 & 0.0598 & \\
i & 1.00 & 0.18 & 0.0423 & \\
j & 1.79 & 0.16 & 1.68e-3 & \\
k & 1.79 & 0.16 & 1.44e-2 & \\
l & 1.79 & 0.16 & 2.41e-2 & \\
m & 1.28 & 0.16 & 0.0441 & \\
n & 1.28 & 0.16 & 0.0268 & \\
o & 1.28 & 0.16 & 0.0145 & \\
p & 1.00 & 0.16 & 0.0879 & \\
q & 1.00 & 0.16 & 0.0598 & \\
r & 1.00 & 0.16 & 0.0423 & \\
s & 1.79 & 0.14 & 2.71e-4 & \\
t & 1.79 & 0.14 & 7.31e-3 & \\
u & 1.79 & 0.14 & 2.41e-2 & \\
v & 1.28 & 0.14 & 0.0268 & \\
w & 1.28 & 0.14 & 0.0145 & \\
x & 1.28 & 0.14 & 0.0015 & \\
y & 1.00 & 0.14 & 0.0255 & \\
z & 1.00 & 0.14 & < 1e-6 & < 1e-7 \\
\end{array}
\]

1 Dr. Ruciński writes that the DDO data indicate velocity field deviations from the contact model and will require special investigation.
for it to influence evolution of the secondary is through the value of the secondary’s Roche lobe radius, $R_{\text{L2}}$, being a function of $M_2$ and $M_1$, for a given binary period, $P_{\text{bin}}$.

The mass and angular momentum loss from the system was, for simplicity of the argument, ignored. But we may interpret the whole process as analogous to the evolution of short-period Algols, as there exist among them objects with extreme mass ratios and very short orbital periods (e.g., R CMa: $M_2 = 0.17 M_\odot$, $M_1 = 1.07 M_\odot$, $P_{\text{bin}} = 1.14$ days; for more examples see Sarna and de Greve 1996, and Ibañogu et al. 2006). So the evolutionary scheme for AW UMa could be the one for a short-period Algol, such that a progenitor is a detached close binary which lost a fraction of mass and angular momentum via magnetized wind during its main sequence life so that its period is short enough at the beginning of Stage II. An additional mass and angular momentum loss takes place during nonconservative Stage II. Nonconservative mass exchange is accepted in many models of Algol formation (Sarna and de Greve 1996, Nelemans et al. 2000, Eggleton and Kiseleva-Eggleton 2002).

In Table 2 we give a few examples of binaries in which the secondary is just filling its critical Roche lobe when hydrogen in its core is nearly depleted (see Table 1). Adopting reasonable values of the mass ratio from the range 0.3-0.8 we obtain values of the orbital period in the range $P_{\text{bin}} = 0.89 - 1.37$ days. This is just an example what the initial Stage II set of parameters might be. As one can see, to obtain the present value of the orbital period of AW UMa we have to assume further mass and angular momentum loss during the mass transfer process.

5 DISCUSSION

The most important result in this analysis are Figs. 1-3 showing three possible scenarios of the secondary’s component evolution during Stage III, after we have reduced its mass to the values $M_2/M_\odot = 0.18, 0.16, 0.14$, respectively. Depending on the initial mass of the secondary $M_{2,0}$ and its chemical composition at the end of Stage I, Stage III will start at various instants and continue for significantly different time intervals.

We see that only for $M_2 = 0.18 M_\odot$ (Fig. 1) does the secondary’s radius $R_2$ exceed the secondary’s Roche lobe radius $R_{\text{L2}}$ (solid horizontal line) during the star’s evolution, so the secondary is therefore able to overflow its Roche lobe and form a common envelope. This occurs for the highest value of $M_2 = 0.18 M_\odot$. For masses $M_2 \leq 0.16 M_\odot$ the secondary will never overflow its Roche lobe (Fig. 2 and 3).

This, combined with our estimation of the primary mass $M_1 = 1.61 M_\odot$, requires the mass ratio for AW UMa to be $q \geq 0.1$.

Such a star, having a very small mass for its radius is almost an “empty” object. Its internal structure is represented in Figs. 4-6. We arbitrarily chose the initial mass of the secondary to be $M_{2,0} = 1.79 M_\odot$ and its present mass (i.e., the secondary mass) $M_2 = 0.165 M_\odot$, enough to ensure the formation of a common envelope. For a given binary period and assuming the primary mass $M_1 = 1.61 M_\odot$ the Roche lobe radius of the secondary is $R_{\text{L2}} = 0.613 R_\odot$. Solid lines in these figures represent internal structure of the model at the time when it has a maximum radius $R_2 = 0.678 R_\odot$ during Stage III of evolution. Dotted lines show the internal structure after some time, in a more evolutionary advanced stage.

When looking at the radius versus mass dependence (Fig.4) we see that matter in the the secondary’s interior is highly concentrated towards the center resulting in a very dense and small core and very extensive low density envelope. The effect is that the bulk of the secondary appears as if it was almost empty.

The hydrogen inside the secondary is exhausted in its core (Fig. 5) and stays only in an outer shell. The thickness of the hydrogen layer will decrease during further evolution of the secondary. As we see in Fig.6, nuclear energy generation is limited to a very thin (in mass) hydrogen burning shell which becomes even thinner during further evolution of the secondary.

Our models indicate that a model of AW UMa and simi-

| $M_{2,0}/M_\odot$ | $R/R_\odot$ | $L/L_\odot$ | $q_{\text{II}}$ | $P_{\text{bin}}$ [days] |
|-------------------|-----------|-----------|-------------|------------------|
| 1.79              | 2.6       | 15.4      | 0.3         | 1.366            |
| 1.79              | 2.6       | 15.4      | 0.5         | 1.271            |
| 1.28              | 2.2       | 5.0       | 0.5         | 1.170            |
| 1.28              | 2.2       | 5.0       | 0.7         | 1.099            |
| 1.00              | 1.8       | 2.0       | 0.8         | 0.894            |

Figure 1. The time variations of the AW UMa secondary’s radius for $M_2 = 0.18 M_\odot$. The different line styles represent its different initial masses of the secondary: solid lines for $M_{2,0} = 1.79 M_\odot$, dotted lines for $M_{2,0} = 1.28 M_\odot$, and dashed lines for $M_{2,0} = 1.00 M_\odot$. For each line style three tracks are shown, corresponding (from right to left) to initial models more and more hydrogen exhausted during Stage I (see Table 1). $R_{\text{L2}}$ stands for the secondary’s Roche lobe radius.
lar to very low mass-ratio binaries involving a highly evolved secondary component encounters a limitation at the very low q end in that such secondaries cannot be made smaller than 0.165 $M_\odot$ or thereabouts.

Further evolution of such systems will depend mainly on the evolution of the more massive component. The secondary may become a degenerate dwarf and/or be consumed by the primary. In this scenario the system might evolve into a FK Com type star, as earlier proposed by Bopp and Ruciński (1981), Bopp and Stencel (1981).

Figure 2. The same as in Fig.1 but for $M_2 = 0.16 M_\odot$.

Figure 3. The same as in Fig.1 but for $M_2 = 0.14 M_\odot$.

Figure 4. An example of internal structure of the AW UMa secondary. In this figure, the internal mass-radius dependence is shown. The track parameters are, $M_{2,0} = 1.79 M_\odot$, $M_2 = 0.165 M_\odot$, $x_{c,0} = 0.014$. The model with maximal radius during Stage III (denoted with "maximum") has been chosen to represent the internal structure of the low mass AW UMa component (the secondary). A slightly more evolved model ("post-maximum") shows the direction of further evolutionary changes. For given binary period and assuming the primary mass $M_1 = 1.61 M_\odot$ and $M_2 = 0.165 M_\odot$ the Roche lobe radius is $R_{L2} = 0.613 R_\odot$.

Figure 5. The same as in Fig.4 but for the internal mass-hydrogen content relation.
Figure 6. The same as in Fig.4 but for the internal mass-luminosity relation.

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