On the Evolutionary Stage of the Interacting Binary AU Mon

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Received 2014 May 20; accepted 2014 August 09; published 2014 September 23

ABSTRACT. We present a study of the evolutionary stage of the interacting binary and Double Periodic Variable AU Mon. A multi-parametric $\chi^2$ minimization is made between the observed parameters and those predicted by the grid of nonconservative and conservative evolutionary models by Van Rensbergen et al., finding the model that best represents the current stellar and system parameters. According to this model, the system started with initial masses $4\ M_\odot$ and $3.6\ M_\odot$ and orbital period 3.0 days, 196 million years ago, and at present undergoes a Case-B mass-exchange episode. This evolutionary stage is consistent with the reported existence of a circumprimary accretion disk. However, the implied high mass transfer rate contrasts with the absence of significant orbital period change if the mass exchange is conservative. We show that this can occur if the system has recently entered a nonconservative stage of mass transfer and the efficiency of mass and angular momentum loss satisfy certain conditions.

1. INTRODUCTION

AU Mon (GCRV 4526, HD 50846, HIP 33237) is an interacting binary of orbital period 11.113 days consisting of a mid-B dwarf primary (or gainer) of temperature 17000 ± 2000 K accreting matter from a G-type giant secondary (or donor) of temperature 5750 ± 250 K (Peters 1994, Desmet et al. 2010). The system and stellar parameters were recently determined by Djurašević et al. (2010) from the modeling of the CoRoT light curve assuming a semidetached configuration; they also find evidence for a geometrically thin and optically thick circumprimary accretion disk.

The system is characterized by a long photometric cycle of 416.9 days (Desmet et al. 2010), and it is considered a member of the Galactic Double Periodic Variables, intermediate mass binary systems showing a long photometric cycle lasting about 33 times the orbital period (Mennickent et al. 2003, 2008, 2012a; Poleski et al. 2010). Peters (1994), based on finding that the UV absorptions associated with the gas stream (e.g., those observed in the lines Si II 1264 and Si IV 1402) were weaker when the system was faint, ascribed the long-period variation to changes in the mass transfer rate due to cyclic expansion and contraction of the secondary. This interpretation was challenged by Desmet et al. (2010) who, based on the long-term behavior of ground-based photometry, interpreted the long variability as attenuation of the total light by some variable circumbinary material. These authors also studied very accurate CoRoT space photometry finding suborbital frequencies of unknown origin.

Optical and UV spectra were used to model the temperature and structure of the accretion disk and the gas stream of AU Mon by Atwood-Stone et al. (2012). That paper is a good source of references for the past literature of this interesting object. The disc found by these authors is about twice the size found by Djurašević et al. (2010); they argue that this is not inconsistent, since one model fits the optically thick disc component whereas the other is sensible to the optically thin disc envelope. It seems well-established that the system shows stronger absorption lines during the low state (Peters 1994; Atwood-Stone et al. 2012; Barra & Mennickent 2011). The eclipse-mapping reconstruction of the accretion disc by Mimica & Pavloski (2012) indicates a clumpy disc structure.

In this paper we study the evolutionary stage of AU Mon. To our knowledge, no study of this type exist in the literature; hence we expect to contribute to the understanding of this interesting object. In § 2 we present our methodology, in § 3 our results, and in § 4 a discussion. We end in § 5 with a summary of our main results.

2. METHODOLOGY

In this Section we compare the system parameters with those predicted by binary evolution models including epochs of nonconservative evolution. The stellar and system parameters given by Djurašević et al. (2010) were chosen since they provide the more realistic set of parameters in the literature, incorporating in their model not only the stellar components but also the H$\alpha$ emitting circumprimary accretion disc. The parameters are given in Table 1; in this paper we use subscript h and c for the hot and cool star, respectively. In our study the orbital period of 11.1130374(1) days is taken from Desmet et al. (2010). We discuss the effect of the uncertainties associated with the system parameters in our methodology.

We inspected the 561 conservative and nonconservative evolutionary tracks by Van Rensbergen et al. (2008), available at the Center de Données Stellaires (CDS), looking for the best match for the system parameters found for AU Mon. Models with...
Table 1

The Stellar Parameters Used in this Paper (from Djurasević et al. [2010]) to Find the Best Evolutionary Model for AU Mon

| Quantity | Value | Quantity | Value |
|----------|-------|----------|-------|
| $M_e$    | $\pm 0.2 \, M_\odot$ | $M_\Delta$ | $7.0 \pm 0.3 \, M_\odot$ |
| $T_e$    | $5754 \, K$ | $T_\beta$ | $15885 \, K$ |
| $\log T_e$ | $3.760 \, K$ | $\log T_\beta$ | $4.201 \pm 0.025 \, K$ |
| $L_e$    | $96.4 \, L_\odot$ | $L_\Delta$ | $1380.4 \, L_\odot$ |
| $\log L_e$ | $1.984 \pm 0.036 \, L_\odot$ | $\log L_\Delta$ | $3.140 \pm 0.160 \, L_\odot$ |
| $R_e$    | $10.1 \pm 0.5 \, R_\odot$ | $R_\Delta$ | $5.1 \pm 0.5 \, R_\odot$ |

3. RESULTS

We find the best model for the system with $\chi^2 = 0.045$ and another nearby model with $\chi^2 = 0.050$. Both solutions are clearly separated from the other models, having much lower $\chi^2$ values, as illustrated in Figure 1. The two nearby points at the 2nd solution represent two subsequent time steps in the same model. Parameters for both solutions are given in Table 2. In order to test the stability of our result with the errors of the parameters given in Table 1, we performed several trials moving the input parameters between the values allowed by their uncertainties. We obtained in 86% of the cases the aforementioned best solution, and in the remaining 14% the second solution. Hence, our results are robust regarding the errors of the input parameters. No other solution was found. This result might be interpreted as the probability of the best solution regarding the second one.

The absolute $\chi^2$ minimum corresponds to the conservative model with initial masses of 4 $M_\odot$ and 3.6 $M_\odot$ and initial orbital period of 3.0 days. The best model gives a temperature of $4966 \pm 11 \, K$ and a luminosity of $3.791(1) \, K$. The parameters for the model with second lower $\chi^2$ are also given. The hydrogen and helium core mass fractions are given for the cool ($X_{ch}$ and $Y_{ch}$) and hot star ($X_{ch}$ and $Y_{ch}$). Errors represent the full grid step at a given parameter.
16900 K for the B star, which is consistent with the most frequently quoted effective temperature for the B star, and better than the relatively low value given by Djurašević et al. (2010). The best fit is reached at the time corresponding to the model indicated by large crosses, characterized in Table 2. Stellar sizes are proportional to the symbol size.

burst of mass transfer, the first one in the life of this binary (Fig. 3). The donor is an inflated ($R_c = 11.0 \, R_\odot$) and evolved 1.5 $M_\odot$ star with its core completely exhausted of hydrogen. According to the best model the system has now an age of $1.96 \times 10^8$ yr, a mass transfer rate $\dot{M}_c = -7.6 \times 10^{-6} \, M_\odot$ yr$^{-1}$, and a mass ratio $q = 0.25$.

The small difference between $\dot{M}_g$ and $\dot{M}_c$ for this model in Table 2 is a purely numerical effect due to the iterative process of calculation; the transferred mass equals the accreted mass in the long-term, i.e., according to the best model AU Mon is in a conservative mass transfer stage. Moreover, this model is fully conservative at all epochs. The system is found 264,000 years after the beginning of the mass transfer. In this interaction episode the gainer has eventually accreted $2.47 \, M_\odot$.

The second solution presented in Table 2 has $\dot{M}_c = -1.4 \times 10^{-7} \, M_\odot$ yr$^{-1}$. In this case the system started with initial masses of 4 $M_\odot$ and 2.4 $M_\odot$ and an orbital period of 2.5 days; it is now in the 2nd episode of Roche-lobe contact during its lifetime and has a mass ratio $q = 0.35$ (Fig. 4). This figure is larger than the value $q = 0.17$ reported by Desmet et al. (2010) and also larger than those found with the best solution, viz. $q = 0.25$. The second solution gives an older system ($2.24 \times 10^8$ yr) and less massive and smaller stars than the best solution.

4. DISCUSSION

4.1. On the Mass Transfer Rate in AU Mon

The mass transfer rate is one of the important parameters we get from the comparison with the grid of synthetic models. Our results can be compared with those found in the literature. For instance, Atwood-Stone et al. (2012) gives $\dot{M}_c = 2.4 \times 10^{-9} \, M_\odot$ yr$^{-1}$, obtained from the physical parameters of the gas stream incorporated into the line profile models,
although they say that their estimate should be considered to be a low limit. Actually, by lowering the stream temperature it is possible to obtain larger mass transfer rates for the same emissivity. Peters (1987) reports \( \dot{M}_c \geq 10^{-12} \, M_\odot \, \text{yr}^{-1} \), measured from the redshifted absorption components in UV lines, viz. the resonance lines of Mg II, Al II, III and Si II, but she indicates that this measurement is model-dependent and complicated by variability of underlying features. We notice also that the origin of UV lines measured by Peters is not necessarily the stream or the accretion disc. Peters (1987) mentions the similitude of variability of underlying features. We notice also that the origin of these absorption components (Rosales & Mennickent 2012). The second alternative could produce a mismatch between system ages, the true system being older or younger, still inside the mass transfer burst but with lower \( \dot{M}_c \). The rapid changes in \( \dot{M}_c \) during the mass transfer event make it quite sensitive to the age of the system. However, we notice that the same methodology (and models grid) applied to \( \beta \) Lyrae has resulted in system parameters in close agreement with those previously calculated by other authors (Mennickent & Djurašević 2013). This result gives support to the methodology used in this paper, and drives our attention to the possible existence of outflows carrying out mass and angular momentum from the system, in such a way as to keep constant the orbital period. This possibility is explored in the next subsection.

4.2. On Mass Flows and Angular Momentum Loss

We have pointed out the inconsistency between the relatively high mass transfer rate and the constancy of the orbital period in the conservative regime. The situation is completely different for the nonconservative case. The models by Van Rensbergen et al. (2008) parametrize mass and angular momentum loss from the system through the parameters \( \beta \) and \( \eta \), respectively. The mass loss is driven by radiation pressure from a hot spot located in the stream impact region on the stellar surface or accretion disc edge. The mass loss extracts angular momentum from the system and in this particular model only from the gainer. According to the models of Van Rensbergen et al. (2008), particular pairs of the parameters \( \beta \) and \( \eta \) should result in a constant orbital period. Now we follow closely the reasoning given by Garrido et al. (2013).

The mass and angular momentum loss from a system during mass transfer can be described with the \((\beta, \eta)\)-mechanism (see

\[ \frac{\dot{P}}{P} = -\frac{3(1-q)\dot{M}_c}{\dot{M}_c}, \]

(Huang 1963). For the AU Mon parameters this equation gives \( \dot{P}/P = 1.58 \times 10^{-5} \, \text{yr}^{-1} \), or 15 s per year, which is definitely not observed. For these calculations we have used \( \dot{M}_c \) from Table 1 and \( \dot{M}_c \) from Table 2 but the results do not change qualitatively taking both parameters from the fit. The above result raises the question why the relatively high mass transfer rate does not produce a change in the observed orbital period. We propose a solution for this puzzling result.

Desmet et al. (2010) proposed that the long cycles in AU Mon are due to attenuation of light by a variable circumbinary envelope. This view was motivated by the constant shape of the orbital LC through the long cycle. However, we must note that a bipolar wind like that inferred for the Double Periodic Variable V393 Sco (Mennickent et al. 2012b) is also a possibility. In any case, photometric and spectroscopic evidence for mass and angular momentum losses have been given for this system (Peters 1994, Desmet et al. 2010). These outflows could bring enough angular momentum to keep constant the orbital period. In fact, Garrido et al. (2013) show that, under some parameter combinations, the effect of mass and angular momentum loss compensates that of mass transfer, producing a constant orbital period, a fact already suggested by Mennickent et al. (2008).

This can happen even for relatively high \( \dot{M}_c \), DPV systems (e.g., OGLE0515532-6925581; Garrido et al. 2013) and could also be happening in AU Mon as we will show in the next section.

Alternative explanations for the apparent inconsistency between high mass transfer rate and constancy of the orbital period are: (1) that the models do not completely reproduce the physics of the system, and (2) that the density of initial parameters in the grid of binary star evolutionary models is not enough to adequately fit the object. The first alternative is impossible to handle without extra (currently unavailable) theoretical mass loss prescriptions. We notice however that the view that AU Mon is the result of heavy mass loss from an initially much more massive binary conflicts with the absence of nebulosity in optical and infrared field images, for instance those provided by the Wide field Infrared Survey Explorer in four bands centered at 3.4, 4.6, 12 and 22 \( \mu \) (Wright et al. 2010). In addition, the spectral energy distribution up to 22 \( \mu \) does not show evidence of a circumbinary dust shell, but it is dominated by the two stellar components (Rosales & Mennickent 2012). The second alternative could produce a mismatch between system ages, the true system being older or younger, still inside the mass transfer burst but with lower \( \dot{M}_c \). The rapid changes in \( \dot{M}_c \) during the mass transfer event make it quite sensitive to the age of the system. However, we notice that the same methodology (and models grid) applied to \( \beta \) Lyrae has resulted in system parameters in close agreement with those previously calculated by other authors (Mennickent & Djurašević 2013). This result gives support to the methodology used in this paper, and drives our attention to the possible existence of outflows carrying out mass and angular momentum from the system, in such a way as to keep constant the orbital period. This possibility is explored in the next subsection.

1 Please see http://irsa.ipac.caltech.edu/Missions/wise.html.
Here the mass transfer efficiency is described by

\[ \beta = \frac{\dot{M}_h}{\dot{M}_c}, \]

i.e., the fraction of mass lost by the donor accreted by the gainer. The angular momentum loss \( \dot{J} \) for a given mass loss \( \dot{M} (\equiv \dot{M}_c(1 - \beta)) \) is determined by \( \eta \) according to

\[ \dot{J} = \sqrt{\eta} \dot{M}_c(1 - \beta) \frac{2\pi a^2}{P}, \]

with \( a \) being the orbital separation and \( P \) the orbital period. It can be shown (see, e.g., Podsiadlowski et al. [1992]) that whenever \( \beta \) and \( \eta \) remain constant throughout the considered period of time (with indices \( i \) for initial and \( f \) for final), the resulting period variation is given by

for \( 0 < \beta < 1 \):

\[ \frac{P_f}{P_i} = \left( \frac{M_{ai} + M_{hi}}{M_{ai} + M_{hi}} \right) \left( \frac{M_{df}}{M_{ai}} \right)^{3(\sqrt{\eta(1 - \beta)} - 1)} \left( \frac{M_{hf}}{M_{hi}} \right)^{3(\sqrt{\eta(1 - \beta)} - 1)}, \]

for \( \beta = 0 \):

\[ \frac{P_f}{P_i} = \left( \frac{M_{ai} + M_{hi}}{M_{ai} + M_{hi}} \right) \left( \frac{M_{ai}}{M_{ai}} \right)^{3(\sqrt{\eta - 1})} \left( \frac{M_{hf}}{M_{hi}} \right)^{3(\sqrt{\eta - 1})} e^{3\sqrt{\eta(M_h - M_c)}}. \]

If one assumes that mass is lost with the specific orbital angular momentum of the gainer, it can be shown that this yields

\[ \eta = \left( \frac{M_c}{M_c + M_h} \right)^4, \]

resulting in \( \eta \ll 1 \). On the other hand, if one assumes that matter is lost by the formation of a circumbinary disc a typical value is \( \eta \approx 2.3 \) (Soberman et al. 1997).

We have calculated the possible \( \beta - \eta \) combinations allowing that the period remains stable between the observational boundaries established during 31.2 years. We find the same result for the two \( \dot{M}_c \) listed in Table 2 (Fig. 5).

Above the curve defined by the points the period increases too much; the case for large \( \beta \) (little mass loss) and/or small \( \eta \) (little angular momentum loss). Below the curve is where the period decreases too much; the case for small \( \beta \) (much mass loss) and large \( \eta \) (much angular momentum loss).

The assumption of specific gainer orbital angular momentum loss (the one used in the calculation of the models; eq. [8]) yields \( \eta \approx 0.00046 \) for this system. This is too low to fall into the constant period region; under this assumption, irrespective of \( \beta \), the period will increase (much) more than allowed by the observations. Based on this result we argue that another source of angular momentum loss is present in the system. Notice that for \( \eta \approx 2.3 \), representative for angular momentum loss from a circumbinary disc (Soberman et al. 1997), there is a mass loss (\( \beta \approx 0.5 \)) compatible with a constant period in this system. Interestingly, this is the same value needed in the Double Periodic Variable OGLE 05155332-6925581 for constancy of the orbital period (Garrido et al. 2013).

If the above scenario is correct, AU Mon should be the second Double Periodic Variable with high mass transfer rate and constant orbital period after OGLE 05155332-6925581. Other DPVs as V 393 Sco and DQ Vel also show stable orbital periods, but their mass transfer rates are not as large and the time baseline used for period determination is shorter than for AU Mon (Mennickent et al. 2012a; Barria et al. 2013, 2014). It is possible that the same phenomenon causing the long cycle in DPVs keeps the orbital period constant.

If AU Mon is in a nonconservative stage, how can we trust in the best model described in Table 2, which is conservative? The good agreement between observed parameters (stellar luminosities, radii, masses, and temperatures), orbital period, and semi-detached condition with those predicted by the best model strongly suggests that the departure from the conservative stage has no practical influence when comparing with a grid of 561 conservative and nonconservative evolutionary models. We think that the finding of the best model is not by chance but gives us an important physical insight. A good match with the conservative model can be possible if AU Mon started losing mass and angular momentum relatively recently in its binary life history. From the error in the stellar masses \( \epsilon_M \) and the value for the mass transfer rate \( \dot{M} \) we estimate this time to be of the order of \( \epsilon_M/M \sim 40000 \) years using \( \epsilon_M = 0.3 \ M_\odot \). Within this time no appreciable departure from the conservative model is expected. In this case most of the binary star evolution has been...
conducted under a conservative regime even during the mass transfer episode lasting a tiny fraction of the binary age. For the above considerations the parameters derived from the best model could be a good representation of the system at the current stage.

5. CONCLUSIONS

We have studied the evolutionary stage of the interacting binary and Double Periodic Variable AU Mon applying the methodology of a multi parametric $\chi^2$ minimization between the observationally derived parameters and those of the grid of synthetic binary star evolutionary models by Van Rensbergen et al. (2008). A best model is found, followed by a close solution in the $\chi^2$ space. Parameters for both models are given in Table 2. It is still possible that the evolution of AU Mon follows another evolutionary route, but there is no way to inquire about this possibility, due to our current limitation on the processes of mass and angular momentum loss in close interacting binaries. The relevant physics known to date and a model for mass-loss is included in the grid of models considered in this paper. Keeping this in mind, our main results can be summarized as:

1. We find AU Mon presently inside an episode of mass transfer with age 196 million years. This evolutionary stage is consistent with the reported existence of a circumbinary accretion disc.

2. The best model indicates that the system has a donor exhausted of hydrogen in its core, transferring mass at relatively high rate of $7.6 \times 10^{-6}$ M$_\odot$/yr.

3. As the orbital period is relatively constant and $\dot{M}_e$ rather high, we speculate that outflows could be extracting angular momentum from the system, keeping constant the orbital period. This view is consistent with reported observational evidence for mass loss by Peters (1994) and the hypothesized circumbinary material by Desmet et al. (2010). Furthermore, we show that under certain conditions of mass and angular momentum losses, the system orbital period can be kept constant even at high mass transfer rate regimes.

4. The good agreement between the observed stellar and system parameters and those predicted by the best (conservative) model suggests that the nonconservative mass exchange is relatively recent, the previous evolution having been conducted mostly under a conservative regime.

5. We find that if matter is lost forming a circumbinary disc a mass loss rate about half the mass transfer rate ($\dot{\beta} \approx 0.5$) should keep the orbital period constant.

We acknowledge the anonymous referee who helped us to improve a first version of this paper. REM acknowledges support by VRID 214.016.001-1.0, Fondecyt grant 1110347 and the BASAL Centro de Astrofisica y Tecnologias Afines (CATA) PFB–06/2007. REM also acknowledges Petr Harmánc for useful discussion on AU Mon during 2012 October in Prague (and 2013 June in Rodhes) and the hospitality of Pavel Koubsky during a research stay in this city. REM acknowledges Nicky Mennekens and Jan Budai for useful discussions during the preparation of this paper.

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