A new age determination for $\gamma^2$ Velorum from binary stellar evolution models

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ABSTRACT

We derive a new age for the $\gamma^2$ Velorum binary by comparing recent observations to our set of binary models. We find that it is very unlikely the stars have not interacted, which implies that previous estimates of the age from single-star models of $3.5 \pm 0.4$ Myrs are incorrect. We prefer an older age of $5.5 \pm 1$ Myrs that agrees with the age of other lower mass stars in the Vela OB association. We also find that our favoured binary model shows the components of the binary have interacted in a Case B, post main-sequence, mass-transfer event. During the mass-transfer event, the envelopes of both components where radiative and therefore the damping of tidal forces are relatively weak. This explains why the binary is still eccentric after mass-transfer.

Key words: binaries: general – stars: Wolf-Rayet – binaries: close – stars: individual: $\gamma^2$ Velorum – stars: fundamental parameters

1 INTRODUCTION

The binary $\gamma^2$ Velorum contains the closest example of a Wolf-Rayet (WR) star to the Sun. It is a double-lined spectroscopic binary and an extremely useful tool in understanding the evolution of Wolf-Rayet stars as the masses, luminosities and mass-loss rate can all be determined. Recent observations by North et al. (2007) have refined the parameters of the binary orbit and the stellar components. A key parameter that was estimated was the lower limit age of both stars to be $3.5 \pm 0.4$ Myrs.

Jeffries et al. (2009) have taken this lower limit of 3.5 Myrs as the age and suggested that the system was one of the last to form in the Vela OB association, based on the observation that the other stars are estimated to be older than 5 Myrs. The age of $\gamma^2$ Velorum was derived by fitting non-rotating single-star isochrones to the secondary. This method assumes that the stars have never interacted and the stars are not rotating. For an average rotation rate the age would increase by about 25 percent to 4.4 Myrs. Meynet & Maeder (2000). Then assuming no binary interaction initially seems reasonable as the system has an orbital eccentricity of 0.3 and naively this means that the system never came into contact. Further consideration however finds that the orbital separation is small enough, $\approx 100R_\odot$, that it is almost impossible for the stars not to interact through either Roche-Lobe Overflow (RLOF) or the more extreme Common-Envelope Evolution (CEE). We therefore suggest that the two stars did interact in a timescale short enough that tidal circularization either did not occur or was not strong enough to achieve a completely circular orbit. We note that North et al. (2007) do state that such interaction is possible and implies that their derived age should only be considered a lower limit. This was not considered by Jeffries et al. (2009) when they used their age in their study.

We note that the observed parameters of $\gamma^2$ Velorum depend upon the assumed distance for the system. In this work we have used the distance derived by North et al. (2007) from fitting the binary system of $336^{+8}_{-7}$ parsecs. This is greater than the Hipparcos distance of $258^{+41}_{-34}$ parsecs and similar to the distance estimate from a single measurement by the VLTI that gave a distance to $\gamma^2$ Velorum of $368^{+38}_{-13}$ parsecs (Millour et al. 2007). We have accounted for the uncertainty in the distance to the binary by including an error of $\pm 0.1$ dex in the luminosities of the binary components.

There is a large amount of literature showing how binary interactions can change the evolution of both stars in a binary (Podsiadlowski et al. 1992; Wellstein & Langer 1999; Vanbeveren 2001; Izzard & Tout 2005; Vanbeveren et al. 2007; Cantiello et al. 2007; Eldridge, Izzard & Tout 2008; Stancil & Eldridge 2009). However, while there are many different sources of single-star evolution models and they mostly agree with each other (e.g. Smartt et al. 2009), there are no widely available binary equivalents. Construction of a set of binary models is not a simple process because rather than only needing to vary initial mass to obtain different
evolution, the initial binary separation and initial mass of the secondary must also be varied. This increases the computer time required to cover the full range of possibly evolutionary paths.

Here we use the set of detailed binary evolution models created by Eldridge, Izzard & Tout (2008) to determine a new age for γ² Velorum. First, considering the possible ages of the 9M⊙ WR star. Second, searching through our binary models for systems that agree with the masses and orbital separations of the system today. Third, the age of the secondary star is considered. Afterwards, our results and the implications of the new age we derive are discussed.

2 ESTIMATING THE AGE FROM STELLAR EVOLUTION MODELS

The stellar models we used were calculated with the Cambridge STARS code and were described in Eldridge, Izzard & Tout (2008). Here, we restrict ourselves to use models with a metallicity mass fraction of Z = 0.020, which we take to be Solar. These models are all based on circular orbits. However as discussed by Hurley, Tout & Pols (2002) circular and eccentric orbits with the same semi-latus rectum should produce equivalent evolution.

2.1 The age of the Wolf-Rayet star

It is difficult to accurately determine the age of a WR star. The star has lost at least half of its initial mass which could have been 20 to 100M⊙. However it is possible to estimate an age range for a WR star from its current mass and WR subtype. The star is designated as WR11 in the catalogue of van der Hucht (2001) and is identified as a WC star. This means it is a highly stripped star that has lost all its hydrogen and most of its helium with the atmosphere dominated by carbon. We therefore search through our stellar models and record the age of WC stars with masses between 8.4 and 9.6M⊙, the inferred mass of the WR star in γ² Velorum. Here we consider the WR star alone and not the companion or binary orbit. We assume a model is a WC star when there is no hydrogen present and (X_C/3 + X_O/4)/Y ≥ 0.03, where X_C, X_O and Y are the mass fraction abundance of carbon, oxygen and helium respectively (Maeder & Meynet 1994).

We find that our models indicate a range of possible ages from 3.3 to 6.4 Myrs for WC stars with masses similar to that of the WR star in γ² Velorum. Our lower estimate of 3.4 Myrs agrees with the age derived by North et al. (2007) for the O star, although this was with older single star isochrones. The youngest WC stars are from stars with initial masses above 60M⊙ and the older WC stars are from stars with an initial mass of 30M⊙, star. Lower initial masses are preferred by the initial mass function thus initially less massive, and therefore older, stars are the preferred when we estimate the age of WR11.

2.2 The possible initial parameters for the γ² Velorum binary

We have searched through our binary models to find those with a reasonable match for the γ² Velorum system. For a certain binary model to match, we require that the following are all true at some point during the lifetime of the binary:

- The WR star is of WC type.
- The mass of the WR star is between 8.4 and 9.6M⊙.
- The luminosity of the WR star is between log(L/L⊙) = 5.1 and 5.3.
- The secondary mass is between 27 and 30M⊙.
- The orbital separation is between log(a/R⊙) = 1.8 and 2.3.
- Any interaction occurs after the main sequence (Case B mass-transfer).

As already discussed the binary is eccentric and all our models have circular orbits. We therefore assume that, for our binary systems to fit, it must have a radius somewhere in the range of separations of the observed binary. The effect of eccentricity would be for mass-transfer to begin earlier (Church et al. 2009) and thus the initial separation would be greater for more eccentric systems to obtain the same evolution as we discuss here.

We choose to only consider systems with mass-transfer after the main sequence (Case B). This is because when mass-transfer events occur on the main sequence (Case A) they happen on a nuclear timescale and the tidal forces would have more time to circularise the orbit. Post main-sequence mass-transfer occurs on a thermal timescale and therefore tidal forces have less time to circularise the orbit and the resulting binary remains eccentric.

We do not attempt to model the secondary here beyond matching its mass. The secondary does lose mass by stellar winds and mass is transferred from the primary to the secondary. The accretion rate onto the secondary is limited to M₂/τ_{thermal} where τ_{thermal} is the secondaries thermal timescale. If the mass-transfer rate is greater than this value the excess mass is lost from the system. We do not include angular momentum transfer and thermohaline mixing in this model. This is because they produce complex affects on the secondary, especially angular momentum transfer which will alter the amount of rotationally induced mixing. This makes the evolutionary outcome of the secondary uncertain (Cantiello et al. 2007; Stancliffe & Eldridge 2009). We consider the secondary in more detail in Section 2.3.

We list our models that match γ² Velorum in Table[1]. The range of initial primary masses and initial separations are narrow. The initial separations are similar to the observed separation. This indicates that the widening of the system due to stellar-wind mass-loss is countered by the mass-transfer event tightening the binary.

For each of the systems a binary interaction must have occurred. Therefore we might simply assume that γ² Velorum should be a circular orbit rather than eccentric. It is worth asking, how unusual it is for a Wolf-Rayet binary to be eccentric. Figure 3 in van der Hucht (2008) shows that in general binaries with periods of 30 days or less tend to be circular. However there are a number of systems with periods between 30 and 100 days that have eccentricities in the range of 0.3 to 0.6. This is because binaries with periods below 30 days experience Case B mass-transfer and therefore their tidal forces have a long time to circularise the orbit. The binaries with longer periods experience Case B mass-transfer, that proceeds at shorter thermal timescales giving
less time for tidal forces to circularise the orbit. These facts suggests that $\gamma^2$ Velorum is not unusual.

From the above, the assumption that binary mass-transfer events must always circularise the orbit is not true. We have estimated a circularization timescale for the models in Table 1 and compared this to the time for the CEE. The key to determine the timescale of circularization in a binary is the damping mechanism for the tides created in the star. In general stars with a convective envelope have shorter timescale than those with radiative envelopes by around two orders of magnitude (Zahn 1977; Hurley, Tout & Pols 2002). Here we concentrate on the secondary star from our favoured model with an initial mass of $31.5M_\odot$ which accretes very little mass. We find that this star has the same mass as observed for the secondary at the same time as the primary is a WC star with a mass of $9M_\odot$ and fulfills our criterion outlined in Section 2.2. However as shown in Figure 1 a basic model only just agrees with the observed luminosity and radius and $\gamma^2$ Velorum would need to be closer than 300 parsecs. This disagrees with the distances measured by North et al (2007) and Millour et al (2007). If we consider that the star can only be more distant than we have assumed as indicated by Millour et al (2007) and thus more luminous it suggests that our basic model cannot reproduce the observed secondary radius. In Figure 2 we see that the basic model agrees with the luminosity and mass simultaneously but only at the very end of its main-sequence lifetime.

Using the details given in Hurley, Tout & Pols (2002) our model has synthesized the timescale of the binary to be a few thousand years. The model does have a small convective shell just outside the helium core between 1 to 4$R_\odot$ but it is too deep within the star to effectively damp tides.

Using the details given in Hurley, Tout & Pols (2002) and de Mink et al (2009), we have estimated the circularization timescale of the binary to be a few thousand years, similar to the time of the interaction in our model. The two timescales are similar in order of magnitude, but because both are uncertain we conclude it is unlikely that complete orbit circularization is possible. In comparison we find that for initially tighter binaries mass-transfer occurs on the main-sequence via RLOF only over a timescale of $>0.1$ Myrs. Therefore there would be plenty of time for complete circularization to occur.

One detail to consider in Table 1 are the ratios of surface carbon, oxygen and helium abundances by number from our models. De Marcho et al (2000) derived the abundance ratios for $\gamma^2$ Velorum from different model atmosphere codes. They found that [C/He] took values of 0.15 to 0.06 and [O/He] took values of 0.03 to 0.01 respectively. The binaries in Table 1 agree with these inferred compositions. However looking at the models in detail when we match the [C/He] ratio we underestimate [O/He] by a factor of 3 indicating the rotation may play some role in the evolution of the primary star during the WR phase.

2.3 Modelling the secondary

Modelling the secondary is not an easy task. If the two stars have interacted in some way it is difficult to know exactly what effect this would have had on the secondary (Cantiello et al. 2007; Stancliffe & Eldridge 2009). Here we restrict ourselves to study the effect of rotation on the secondary alone. We see from Table 1 that there is a wide range of initial masses possible for the secondary. Some possible progenitors accrete a large amount of mass to reach that observed today. These stars with lower initial mass, $M_2 = 20$ and $28M_\odot$, are less evolved at the time of mass-transfer and thus have lower luminosity and/or higher surface temperature at the time when the primary star matches the observations.

Here we concentrate on the secondary star from our favoured model with an initial mass of $31.5M_\odot$ which accretes very little mass. We find that this star has the same mass as observed for the secondary at the same time as the primary is a WC star with a mass of $9M_\odot$ and fulfills our criterion outlined in Section 2.2. However as shown in Figure 1 a basic model only just agrees with the observed luminosity and radius and $\gamma^2$ Velorum would need to be closer than 300 parsecs. This disagrees with the distances measured by North et al. (2007) and Millour et al (2007). If we consider that the star can only be more distant than we have assumed as indicated by Millour et al (2007) and thus more luminous it suggests that our basic model cannot reproduce the observed secondary radius. In Figure 2 we see that the basic model agrees with the luminosity and mass simultaneously but only at the very end of its main-sequence lifetime. Using Figure 3 we estimate an age from the basic secondary model of $5.6^{+0.9}_{-1.3}$ Myrs.

Rotation is a complicated physical process in stars and our code does not currently include it. The general effect of rotation is to induce mixing in a star that increases the time spent on the main-sequence by mixing processed material to the surface of the star and new hydrogen into the core. To simulate this effect we have included an arbitrary small amount of extra-mixing through the radiative zone of our model. We see in Figure 1 that with this mixing the star achieves a higher luminosity at a given radius and eventually agrees with the observed luminosity and radius of the secondary. Comparing to models that do include rotation (Meynet & Maeder 2005) the evolution is similar to that provided by reasonable rotation velocities around 200 km s$^{-1}$.

We see in Figure 2 that the model with enhanced mixing also agrees with the observed mass and luminosity of the secondary and is in the middle of its main-sequence evolution. Figure 3 allows us to estimate the age of the secondary star to $5.4^{+0.9}_{-1.3}$ Myrs. This is consistent with the range of ages we determined for the age of the WC star and binary system above.

3 DISCUSSION AND CONCLUSIONS

We have used three different methods to estimate the ages of $\gamma^2$-Velorum. These were estimating the age of a $9M_\odot$ WC star, modelling the binary orbit and components simul-
John J. Eldridge

Figure 1. The luminosity-radius relationship for two different stellar models with initial masses of 31.5\(M_\odot\). The black line indicates our normal stellar model while the red dash-dotted line is for a stellar model where a small amount of mixing is allowed within the radiative zones, simulating the effect of rotation on the evolution. The dashed line indicates the parameters of the secondary in the \(\gamma\)-Velorum binary with the grey shaded region indicating the error in the luminosity due to the uncertain distance.

Figure 2. Similar to Figure 1 but the relationship between stellar mass and luminosity of our stellar models.

taneously and considering the age of the best fitting initial secondary mass with and without enhanced mixing. We find that the age must be older than 3.5 Myrs and by combining different ages we estimate that it is 5.5 \(\pm\) 1 Myrs. The 2 Myrs difference is because North et al. (2007) used single-star non-rotating isochrones to determine a lower limit for the secondary star age. This work demonstrates the necessity for publicly available grids of binary star models to be created. The use of single-star models can give misleading results that lead to incorrect conclusions.

Our age estimate is in better agreement with ages derived for the surrounding lower-mass stars from Jeffries et al. (2009). It suggests that all the stars in the Vela OB2 association formed at a similar time.

The older age estimate may also help explain the non-detection of 1.8 MeV photon emission from \(\gamma^2\) Velorum. This emission is due to the radioactive decay of \(^{26}\text{Al}\) formed during core hydrogen burning by proton capture on \(^{25}\text{Mg}\). \(^{26}\text{Al}\) has a half-life of 0.75 Myrs and \(\gamma^2\) Velorum is predicted by Mowlavi & Meynet (2006) to have detectable emission. Currently no such emission has been detected. We suggest there are two factors reducing the amount of \(^{26}\text{Al}\) below the detectable abundance. First in our models of \(\gamma^2\) Velorum we find the time difference between the end of core hydrogen burning and our age estimate is 0.85 Myrs thus less than half of \(^{26}\text{Al}\) created remains. Second the lower initial mass of the WR star may mean less \(^{26}\text{Al}\) is created during the main-sequence as predicted for the 60\(M_\odot\) star by Mowlavi & Meynet (2006).

The fact that the binary is still eccentric does not rule out a binary mass-transfer event. Our binary models indicate that some post main-sequence (Case B) mass-transfer events occur so rapidly that the tides formed in the mostly radiative envelope are unable to circularise the orbit. On the other hand, WR binaries with periods below 30 days experiences Case A mass-transfer on the main-sequence and the tides do have time to circularise the orbit. This places a limit on the circularization timescale of tides in radiative envelopes to a few thousand years, the time required for the hydrogen envelope to be removed in a mass-transfer event.

Our major remaining uncertainty is the evolution of the secondary. We find that it is possible to explain its current evolutionary state if initially it was a 31.5\(M_\odot\) star with a rotation rate of \(\approx 200\text{km s}^{-1}\). Less massive stars that accrete a large amount of mass never match the radius and luminosity of the secondary when the primary star is a WC star of 9\(M_\odot\). Future study of this system may provide more clues to the effect of rotational mixing and of mass-transfer on the secondary stars in binary systems.

Figure 3. Similar to Figure 1 but the relationship between age and luminosity of our stellar models.
4 ACKNOWLEDGEMENTS

JJE would like to thank the referee Georges Meynet for helpful comments that lead to a vastly improved paper and the editor for finding some typos. JJE is currently supported by the IoA’s STFC Theory Rolling Grant. And thanks Rob Jeffries for useful discussion and Julie Wang for proof-reading.

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