Massive Stars Across Redshifts in the Era of JWST and Large Surveys
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Tidal shear energy dissipation and stellar structure

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Abstract. Asynchronous rotation in binary stars induces a localized differential rotation structure which, in the presence of viscous turbulence, can inject energy into the outer stellar layers. This paper explores the effect of such energy injection in a $162\,M_\odot$ star early in its evolutionary lifetime. We find that in response to the injected energy, the radius, luminosity and mass-loss rate increase, compared to a standard model. We also find that the computed turbulent viscosity values imply synchronization timescales for the inner layers that exceed the main sequence lifetime. Hence, binary stars on the main sequence may not be in true corotation even if their outer layers appear to be rotating synchronously, and they may appear more luminous and have larger mass-loss rates than their analogous single-star counterparts.

Keywords. Massive binaries, Binary evolution, Tidal interactions, Asynchronous rotation

1. Shear energy dissipation and stellar structure

Binary stars whose rotation angular velocity differs from the instantaneous orbital angular velocity undergo oscillatory motions that induce differential rotation (Koenigsberger *et al.* 2021). In the presence of viscous turbulence, a fraction of the energy involved in the shearing motions can be converted into heat. This is an ingredient generally neglected in stellar structure calculations. In this paper we present results of an experiment to determine the effect on its structure of injecting heat into the outer layers of a massive star.

The Modules for Experiments in Stellar Astrophysics (MESA) spherically symmetric stellar evolution code (version 12778, Paxton *et al.* 2015) was used to evolve a binary system with ZAMS masses $186{+}186\,M_\odot$, initial orbital period $P_0 = 2.8$ d and SMC metallicity up to an age of 0.729 Myr, at which time an estimate of the internal tidal shear energy dissipation rate at several depths was injected. At this age, partway through the main sequence, the stellar mass is $162.5\,M_\odot$, the radius is $17.66\,R_\odot$, and the orbital period is 3.48 d.

The energy dissipation rate $\dot{E}(r, \theta, \phi)$ was calculated in a 3D grid with the TIDESnvv code† (Moreno *et al.* 2011; Koenigsberger & Estrella-Trujillo 2024), assuming a polytrope with index 2.7, which approximates the internal structure of the MESA model

† TIDESnvv is available at https://zenodo.org/records/10799022

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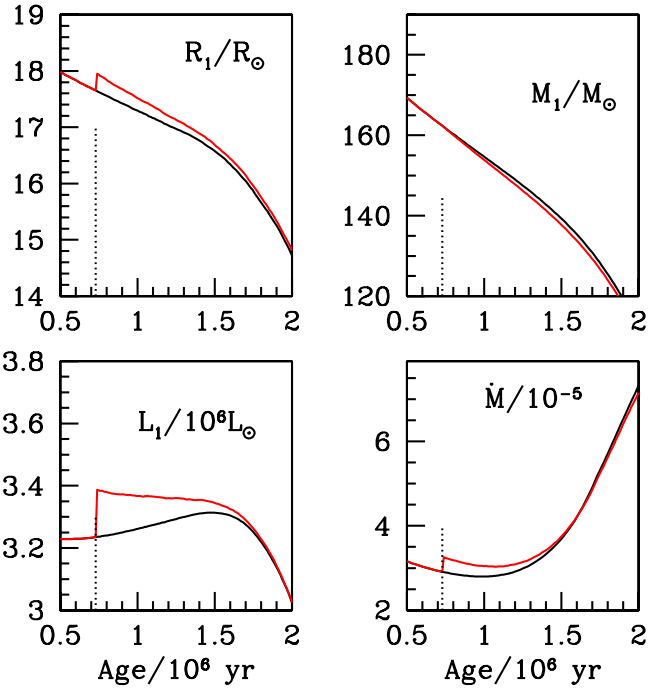


Figure 1. Evolution of radius, luminosity, mass-loss rate, and mass as function of age for the tidally-heated model (red) and the standard model.

at 0.729 Myr. The perturbed star was assumed to be initially rotating with a uniform, supersynchronous rotation rate $\omega_{\rm rot}$ such that $\omega_{\rm rot}/\Omega_{\rm orb} = 1.4$, where $\Omega_{\rm orb}$ is the orbital angular velocity at periastron. The TIDESnvv calculation was performed for 10 layers, with radii as listed in column 1 of Table 1. The total $\dot{E}$ value in each layer was averaged over the orbital cycle, interpolated to the MESA radial grid, and activated when the model reached an age of 0.729 Myr.

Figure 1 shows the equatorial radius R_1, total luminosity L_1, mass-loss rate $\dot{M}_1$ and total mass M_1 as a function of time of the heated model, compared to the standard model. A sharp jump in R_1, L_1, and $\dot{M}_1$ is observed in the heated model as the stellar structure adjusts to the extra energy in its outer layers, and these parameters remain high during the next ~ 1 Myr. The mass-loss rate increases because it depends directly on the luminosity (Vink *et al.* 2001; Brott *et al.* 2011). As a consequence of the larger mass-loss rate, the total mass of the star is reduced with respect to the standard model. Thus, we conclude that heat injection in a MESA massive-star binary model causes an increase in mass-loss rate, equatorial radius and luminosity with respect to a standard model.

2. Implications and conclusions

TIDESnvv computes a turbulent viscosity $\nu_t = \lambda \ell_t \Delta u_l$ at each timestep of the calculation using the instantaneous velocity of each volume element relative to its neighboring elements Δu_l and the element characteristic size ℓ. ν_t is a crucial ingredient in the calculation of synchronization timescales $\tau_{\rm sync}$.

The average ν_t value in each layer of our model is listed in column 2 of Table 1 and the resulting values of $\tau_{\rm sync}$, calculated using the expression given by Zahn (2008), in column 4 of this table. Whereas the surface layers synchronize with the orbital motion on short timescales, the timescales for the inner layers exceed the main sequence lifetime.

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Table 1. Results from the TIDESnvv calculation.

$r_{\rm layer}$ $R_\odot$	$\langle\nu\rangle$ cm^2/s	$t_{\rm diss}$ yrs	$\tau_{\rm sync}$ yrs	$\langle\dot{E}\rangle$ erg/s/layer
7.59	8.4×10^{13}	105.3	1.2×10^{9}	1.9×10^{35}
8.65	1.5×10^{14}	79.3	2.9×10^{8}	1.8×10^{36}
9.71	1.9×10^{14}	77.0	1.0×10^{8}	6.6×10^{36}
10.77	2.2×10^{14}	79.8	4.6×10^{7}	1.5×10^{37}
11.83	2.3×10^{14}	94.4	2.5×10^{7}	2.5×10^{37}
12.89	3.5×10^{14}	72.8	9.8×10^{6}	3.5×10^{37}
13.95	7.8×10^{14}	38.3	2.7×10^{6}	6.4×10^{37}
15.01	2.9×10^{15}	11.9	4.7×10^{5}	3.4×10^{38}
16.07	1.0×10^{16}	4.0	9.1×10^{4}	2.2×10^{39}
17.13	2.6×10^{16}	1.7	2.4×10^{4}	1.3×10^{39}

Notes: $r_{\rm layer}$ is the midpoint of each layer modeled. $\langle\nu\rangle$ is the turbulent viscosity average over the layer and over an orbital cycle, and is computed as $\nu=\lambda\ell_t\Delta u_l$, where λ is the fraction of local kinetic energy converted into heat, ℓ_t is the characteristic length, here taken to be the width of the layers, and Δu_t is the relative velocity of volume elements with respect to their neighbors. $\langle\dot{E}\rangle$ is the tidal shear energy dissipation rate in each layer, averaged over orbital cycle, assuming $\lambda=1$ (see Koenigsberger & Estrella-Trujillo 2024, for details). The synchronization timescale for each layer is $\frac{1}{\tau_{\rm sync}}=\frac{1}{t_{\rm diss}}\frac{(\Omega-\omega)}{\Omega}q^2\frac{Mr^2}{I}\left(\frac{r}{a}\right)^6$, where $t_{\rm diss}=r^2/\langle\nu\rangle$, I is the moment of inertial and a is the orbital separation (Zahn 2008).

Hence, the tidal perturbations due to asynchronous rotation persist throughout most of the lifetime of the star.

Our values of $\tau_{\rm sync}$ are lower limits because in the calculation for this experiment we set $\lambda=1$. This proportionality factor $\lambda\in[0,1]$ represents the fraction of kinetic energy that is dissipated and converted into heat, and in general, $\lambda<1$. A smaller ν_t implies longer synchronization times. Thus, from an observational standpoint, the surface equatorial velocity may be in corotation but deeper layers may not be. As a consequence, the entire stellar structure may differ from that of a single-star model and several modes of stellar oscillations may be active.

There are several caveats to our results. Tidal perturbations are aspherical, with the largest amplitudes generally occurring around the equatorial latitudes. However, MESA calculates the 1D, spherically symmetric stellar structure, so we have adopted the average tidal shear energy dissipation over an entire shell for input into MESA. In reality, the actual values in the equator are significantly larger that in the poles, an effect that has unknown consequences on the stellar structure. Also, our turbulent viscosities are estimated using a simplistic formulation and a refinement is required. Finally, it is not clear how tidal perturbations interact with surface convective layers, a phenomenon that requires further investigation.

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