Simulating Binary Systems at the Onset of the Common Envelope Phase

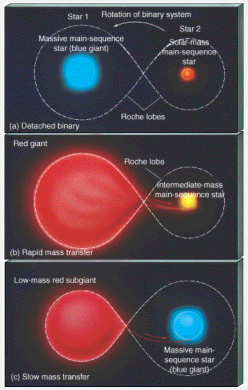
Ali Pourmand[1], Natalia Ivanova[1]
[1]Department of Physics, University of Alberta, Edmonton, T6G 2E7, Alberta, Canada

Introduction

Binary stellar systems are composed of two stars that are gravitationally bound together. The effective acceleration felt by the two stars includes not only the gravitational pull of the two stars, but also the centrifugal force due to the orbit. This makes their evolution deviate from singular stars.

This deviation becomes non-negligible when one of the two stars expands sooner than the other one, such that it fills its Roche Lobe (see figure below). At this stage mass transfer (MT) may start, which if unstable could result in a common envelope (CE) phase; a stage of the binary stellar evolution which could result in the creation of exotic astrophysical objects such as binary neutron stars or the merging of two stars.

Codes such as MESA are able to perform stellar evolution effectively (assuming spherical symmetry), however they do not include the gravitational field of binary stars, which is needed to properly simulate the properties of the system at the onset of the common envelope phase. However it is a challenge to incorporate the gravitational field of a binary system into a one-dimensional (1D) code, since it isn't spherically symmetric.



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Objectives

1. To propose an effective method to simulate binary stars up to the common envelope stage with 1D stellar evolution codes
2. To compare the outcome of binary stellar evolution using our new method with what was the previously predicted behavior of binary stars at the common envelope stage; using the code MESA

Methods

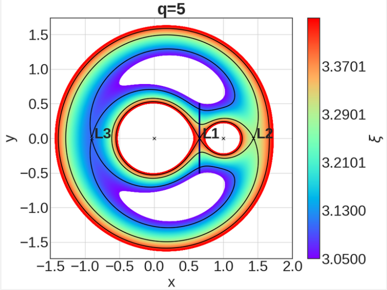
Numerical Integration of the Properties on Equipotential Shells

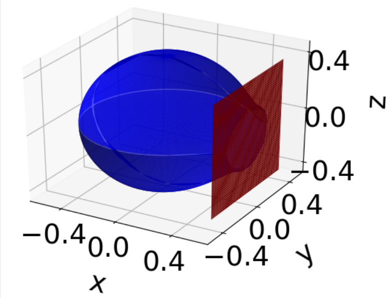
In order to simulate the effective acceleration of binary stars in 1D, whose equipotential slices are depicted for a sample mass ratio in the left figure; we need to somehow define a "radius" to ascribe to these systems. To that goal, we use the concept of volume-equivalent radii of each equipotential shell; which is obtained by equating the enclosed volume in each shell with the equation of the volume of a sphere. We set an ad hoc limit for the enclosed volumes of each shell; which is the plane passing L1, and is perpendicular to the orbit (we call it the L1 plane; it can be seen in the figure on the right).

Then, we obtain an effective acceleration , by taking the average of this quantity on each equipotential surface. We have calculated and tabulated these two properties for 109 mass ratios ranging from q=1e-6 to q=1e+5, each table including properties of 600 shells.

Incorporating into MESA

In order to use these tables to simulate binary stars in MESA, we modify MESA to use the values in our tables for effective acceleration instead of the gravitational field of a singular star. This procedure requires two different interpolations, one between mass ratios (since it might not be what it precisely is in our tables), and radii (our tables are composed of volume-equivalent radii).





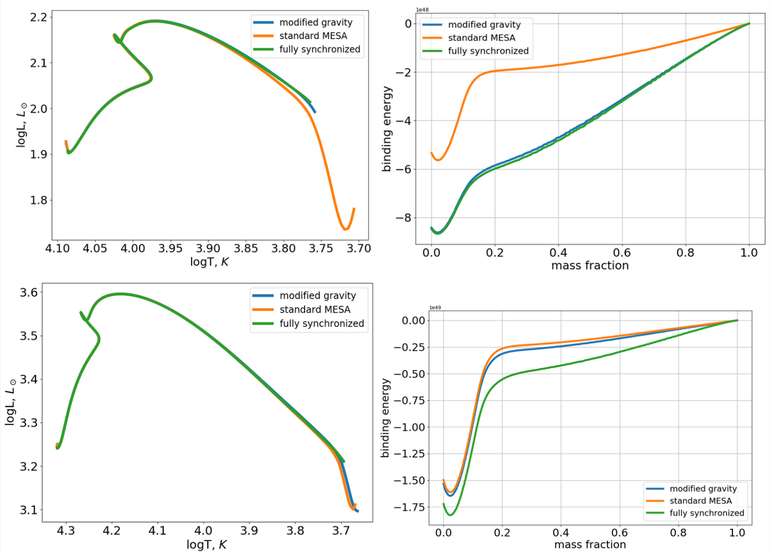
Results

We have evolved a grid of stars up to the point that the donor star fills its Roche Lobe, using 3 different methods for each:

1. with our subroutine that has modified MESA's standard gravity
2. MESA's standard package for evolving binary stars (excluding tidal evolution)
3. MESA's binary package including the effects of tidal synchronization

Here, we have shown the results of our simulations with two different plots for two different initial conditions for the binary system; the plots on the left column depict the HR diagram which shows the evolutionary tracks of the star, and the plots on the right are depicting the binding energies of the star when the Roche Lobe radius is filled, as a function of mass fraction. The properties of the two stars are listed below:

- 1st row: donor star with 3 solar masses, companion star with 0.3 solar masses, and initial orbital separation of 17.3 solar radii.
- 2nd row: donor star with 7 solar masses, companion star with 0.7 solar masses, and initial orbital separation of 95.13 solar radii.



Analysis

- The evolutionary tracks behave as expected; at the beginning of their evolution, the three methods are more or less following the same path, which could be expected since the gravitational field of binary stars doesn't deviate much from a singular star when it hasn't expanded enough to become comparable to the Roche Lobe. However, the final point, (on the right) of the three methods are spread out, in some cases very significantly from each other.
- As could be seen, for both cases binding energy distribution with our method matches neither method 2 nor method 3. Since this quantity is important in determining the outcome of the CE phase, this result is significant in determining whether the two stars will merge or not.

Conclusion

We conclude that in order to simulate stars in binary systems up to the common envelope phase, one cannot neglect the effects of the effective acceleration caused by the companion star and centrifugal force. Our results show that the HR track and stellar interiors could deviate notably from what MESA's standard package already does.

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