UCSB, MESA SCHOOL 2012

# Stellar Rotation I

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## 1 Test Suite: 15M_Dynamo

Run the calculation from the test suite `/mesa/star/test_suite/15M_Dynamo`. You can find a useful description of what MESA is doing in Jared Brook's tutorial in the tutorial section of the MESA forum: `http://mesastar.org/documentation/tutorials/15m_dynamo`

- Reproduce Fig. 3 in the tutorial (Surface Rotation)
- Look/reproduce Fig.4,5,6. What are the important mixing processes?
- In Fig. 6 examine the angular velocity profile at the end of the run. Can you explain its behavior in the different parts of the star?

## 2 The evolution of a rotating massive star

Here we want to study the evolution of a rotating massive star from the zero age main sequence till late evolutionary phases. In principle MESA is able to evolve massive stars till the end of Silicon burning. However, to avoid running too long calculations, during the LAB we will only try to evolve the star till central carbon exhaustion. Remaining phases of evolution can be calculated outside of LAB time. **Q: Why does computational time increase substantially for late burning phases?**
It is probably smart to check beforehand what kind of variables you want to save during the calculations. Useful output is saved in the `LOGS/star.log` and `LOGS/log**.data` files, but some of the variables you need might not be listed in your `log_columns.list` and `profile_columns.list` so you might wanna add them. A good starting point would

be to copy these two files from the `15M_dynamo` test suite case, where they should include most of the quantities we're interested in. If you use this `log_columns.list` be sure to comment out the lines `burning_regions = 80` and `mixing_regions = 40` in order to avoid dumping a LOT of information you do not need for this exercise.
For reference the full list of available options can be found in:

```
mesa/data/star_data/log_columns.list
mesa/data/star_data/profile_columns.list
```

### Rotating Zero Age Main Sequence

1. Create a $15M_\odot$, Z=0.02, ZAMS star and save a model. Again, if you have trouble doing this, you can find some usefule examples in `mesa/star/test_suite/`. A good starting point is having a look at the test suite `massive_prems_to_late`.

   One vital skill is knowing how to tell MESA when to stop via inlist parameters (hint: grep "when to stop"). This has the advantage of letting you save a model of particular physical interest without knowing a priori what model number it will be.

2. Make the star rotating with a (typical) initial rotation of 200 $\mathrm{km\,s^{-1}}$. To do this set the following in the `&star_job` section of your inlist:

   ```
   change_rotation_flag = .true.
   new_rotation_flag = .true.
   set_surf_rotation_v_step_limit = 10
   new_surface_rotation_v = 200.0 ! km/sec
   ```

Run your calculation for just 10 timesteps setting `max_model_number = 10` in your `&controls` section of the inlist. You'll need to delete the `model_number` line in your saved `.mod` file for MESA to start counting from zero again. **Q: What is MESA doing when we set a value for `new_surface_rotation_v`? Hint: `grep` is your best friend and the real MESA manual.** It is now interesting to look at the internal rotational profile of your rotating ZAMS star. **Q: What is the initial rotational law? Do you think this is realistic?** Also it is interesting to compare the imposed rotational rate with the critical rotation rate. **Q: How is defined and what is the physical meaning of the critical rotation rate?** Finally, take a look at the different diffusion coefficients responsible for transporting angular momentum inside the star. **Q: Which mixing processes dominate?** For a more physical picture we'll want to include a scheme for mass loss via stellar winds on the RGB and beyond in `&controls` , for example:

```
RGB_wind_scheme = 'Dutch'
AGB_wind_scheme = 'Dutch'
RGB_to_AGB_wind_switch = 1d-4
Dutch_wind_eta = 0.8
```

Now we are ready to evolve our rotating star! Below the evolutionary phases you want to go through and some important checks you want to make to test what MESA is doing.

Main Sequence (Core H-burning)

- Burning timescale
- Evolution of surface rotation. Compare to critical velocity.
- Evolution of surface abundances: **Q: Is the N-enrichment compatible with results from other codes? And with massive stars observations? Take a look at Heger et al. 2000 (e.g. Fig. 5) and Potter et al. 2012 (e.g. Fig. 6) to draw your conclusions.**
- Internal diffusion coefficients MS (40% central H mass fraction)
- Internal j-profile MS (40% central H mass fraction)
- Internal j-profile TAMS (1% central H mass fraction)

Core He-burning

- Burning timescale
- Evolution of surface rotation. Compare to critical velocity.
- Omega profile at He-exhaustion (1% He mass fraction). Core-Envelope coupling?
- Internal j-profile He-exhaustion (1% He mass fraction)

Carbon burning *(Note: time and RAM permitting! If the previous phases of evolution took more than around 30 minutes to compute then you'll want to save this for homework. Typically laptops with less than 8GB of RAM would fall into this category.)*

- Burning timescale
- Omega profile at C-exhaustion ($T_c = 1.2 \times 10^9$). Core-Envelope coupling?
- Internal j-profile C-exhaustion ($T_c = 1.2 \times 10^9$)

Beyond carbon burning At home, try and evolve a model up to Si-depletion (ready for core-collapse!).

- Burning timescale
- Omega profiles at O, Si exhaustion. Core-envelope coupling?
- Internal j-profiles at O, Si exhaustion

### 2.1 Evolution including Tayler-Spruit dynamo

It is now interesting to look at the evolution of total angular momentum as function of time. Then, you might want to plot together the j-profiles calculated for the different phases, to look at how the internal angular momentum content has evolved with time. You want to compare your results with Fig. 2 in Heger et al. (2005).

### 2.2 Evolution without the Tayler-Spruit dynamo

The jury is still out regarding the Tayler-Spruit dynamo mechanism, so you might want to check what differences it makes including it or not in your calculations. The control parameters you want to add/modify in your inlist are:

```
! set to 0 for non-magnetic
         D_ST_factor = 1.0
         nu_ST_factor = 1.0
```

where the first parameter multiplies the diffusion coefficient for angular momentum transport resulting from Tayler-Spruit dynamo (internal magnetic torque), while the second multiplies the diffusion coefficient for chemicals (magnetic mixing). **Q: Is there any difference between the MS timescale for the models with and without Tayler-Spruit B? Why?** Plot your angular momentum profiles at different evolutionary stages. Again, you want to compare your results with Fig. 2 in Heger et al. (2005).

### 2.3 (*Optional*) Convergence Study

Never trust your results until you've checked how sensitive they are to your resolution. The controls you wanna have a look at are: `varcontrol_target` and `mesh_delta_coeff`. From `mesa/star/public/star_defaults.dek`:

```
varcontrol_target = 1d-4
! this is the target value for relative variation in the structure from one
! model to the next. The default timestep adjustment is to increase or reduce
! the timestep depending on whether the actual variation was smaller or
! greater than this value.
mesh_delta_coeff = 1
! a value > 1 increases the max allowed deltas and decreases the number of
! grid points. And a value < 1 does the opposite.
! e.g., you'll roughly double the number of grid points if you cut
! mesh_delta_coeff in half. Don't expect it to exactly double the number.
```

Rerun your ZAMS model down to $X_c = 0.01$. Fill in the following table, which asks how some basic quantities depend on $C$, a parameter multiplying both default values of `varcontrol_target` and `mesh_delta_coeff`.

| C | Zones | Steps | Computation time (s) | $t_{\rm MS}$ (Myr) | Other... |
|---|---|---|---|---|---|
| 3 | | | | | |
| 2 | | | | | |
| 1 | | | | | |
| 0.5 | | | | | |
| ⋮ | | | | | |

Table 2.1: Below which value of $C$ you think your results converge?