Bulletin de la Société Royale des Sciences de Liège, Vol. 80, 2011, p. 165 - 169

Mass loss in 2D Rotating Stellar Models

Catherine Lovekin[1]* and Robert G. Deupree[2]

[1] LESIA, Observatoire de Paris
5 Place Jules Janssen, 92195 Meudon, France
[2] Institute for Computational Astrophysics, Saint Mary's University
923 Robie St, Halifax, NS B3H 3C3, Canada

Abstract: Radiatively driven mass loss is an important factor in the evolution of massive stars. The mass-loss rates depend on a number of stellar parameters, including the effective temperature and luminosity. Massive stars are also often rapidly rotating, which affects their structure and evolution. In sufficiently rapidly rotating stars, both the effective temperature and radius vary significantly as a function of latitude, and hence mass loss rates can vary appreciably between the poles and the equator. In this work, we discuss the addition of mass loss to a 2D stellar evolution code (ROTORC) and compare evolution sequences with and without mass loss.

1 Introduction

Many massive stars start their lives as rapid rotators, and some remain rapidly rotating throughout their main sequence evolution. This will influence their structure and the course of their evolution. As a result of centrifugal forces, rapidly rotating stars become flattened, and the temperature, and hence the flux, varies as a function of co-latitude (von Zeipel 1924). Very massive OB stars are luminous enough to lose mass in a radiatively driven wind (Lucy & Solomon 1970; Castor, Abbott & Klein 1975). The amount of mass lost can be significant, as is the effect on the stellar evolution, as radiatively driven winds remove both mass and angular momentum from the surface of the star. The rate at which mass is lost is dependent on the temperature and the radius, so as these vary across the surface of a star, the mass loss rate can also be expected to vary (see, e.g. Owocki, Cranmer & Gayley 1998; Dwarkadas & Owocki 2002).

Rotation also changes the shape of the stellar surface, increasing the radius of the equator relative to the polar radius. This is thought to be the origin behind the $\Omega\Gamma$ limit, as described by Maeder & Meynet (2000). In stars sufficiently close to the Eddington limit, the critical velocity is reduced, such that

$$v_{crit} = v_{crit,1}(\frac{3}{2})^{1.25}(1-\Gamma)^{1/2}$$

when $\Gamma > 0.639$, and $v_{crit,1} = (2GM/3R_p)^{1/2}$ (Maeder & Meynet 2000). This is not expected to have a large effect on the total mass loss, but see the discussion in Section 3.

*Current Address: Los Alamos National Laboratory, P.O. Box 1663, T-2, MS-B283, Los Alamos, NM 87545

The variation in the mass-loss rate over the surface of the star will also affect the angular momentum loss. As the angular momentum depends on the distance from the rotation axis, variation in the mass-loss rates over the surface of the star will change the amount of angular momentum lost compared to spherically symmetric (1D) models of mass loss. Since rotation is also an important factor in determining the evolution of a star, changing the amount of angular momentum lost will influence the evolution. The change in angular momentum loss and the distribution of mass loss from a rotating star can be expected to affect the evolution of the star. In this work, we investigate these effects and attempt to determine their significance.

To determine the actual importance of these 2D effects on the evolution of rotating massive stars, we have added radiatively driven mass loss to a 2D stellar evolution code. We discuss the method used to model the mass loss, and the effects of 2D mass loss on both the structure and evolution of the models.

2 Models

We calculate mass loss-rates for 2D stellar structure models calculated using `ROTORC` (Deupree 1990, Deupree 1995). This code solves the equations for conservation of mass, energy and three components of momentum along with Poisson's equation on a two dimensional grid, defined by the angular coordinate (co-latitude) and the fractional surface equatorial radius. The equatorial radius is determined by requiring the integral of the density over the volume to produce the correct mass of the model. The surface is assumed to be an equipotential with the value set by the equatorial radius. Calculating the surface in this way, allows us to determine the surface location in rotating stars without assuming von Zeipel's law (von Zeipel 1924) holds.

The models discussed here use 581 radial and 10 surface zones. The mass loss rate is calculated locally for each of the 10 surface zones using the local effective temperature and a local luminosity in each zone. The local luminosity is calculated using the local flux, and corresponds to the luminosity in a spherically symmetric star with the local effective temperature and radius. The mass-loss rates are calculated using the prescription of Vink et al. (2001), which also depend on the mass and metallicity of the star. All of the models discussed here are 20 $M_\odot$ with solar metallicity. Once the mass loss rate in each zone has been calculated, the total mass lost from that zone is calculated by weighting the mass loss rate by the area of the zone. We have also included an option to calculate the mass loss using the overall effective temperature, calculated as the effective temperature of a sphere with the same luminosity, and luminosity of the model, which gives us a pseudo-1D mass loss calculation. In this case, the mass lost is divided evenly among the angular zones.

Regardless of the mass-loss prescription, once the mass-loss rates and the total mass loss has been calculated, the mass is removed from successive surface layers until the required amount of mass loss has been reached. The surface of the star is redefined to this new location, and the model is then allowed to relax to an equilibrium configuration, in which the surface is once again an equipotential and the model is in thermal and hydrostatic equilibrium, before the evolution continues.

3 Mass-Loss Rates

We compared the mass loss rates calculated using the 2D mass loss rates, based on the local effective temperature and local luminosity in each zone to the pseudo-1D calculation, based on the overall effective temperature and luminosity of the star. In both cases, the total amount of mass lost is the same. This is consistent with the results of Maeder & Meynet (2000), which indicate that rotation is not expected to have a significant effect on the total mass loss. However, while the amount of mass

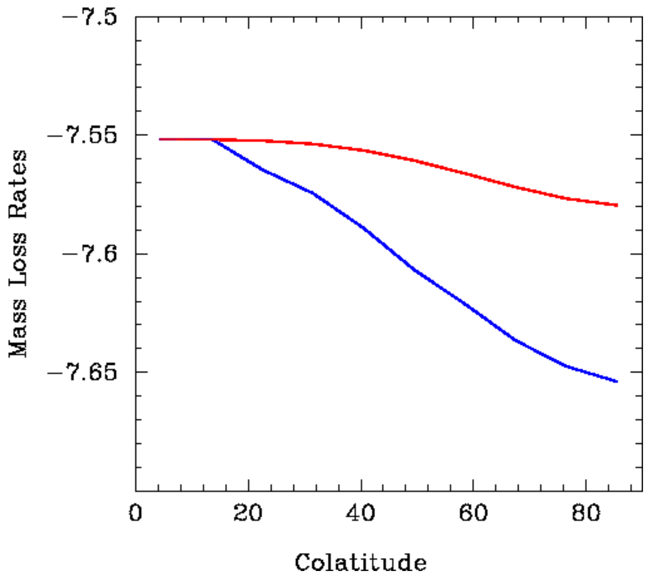

Figure 1: Calculated mass-loss rates for a 20 $M_\odot$ rotating at 275 $km\,s^{-1}$ for the 2D case (blue) and the CAK predictions (red). The mass loss rates in the 2D calculation decrease towards the equator much more rapidly than the CAK predictions.

lost in both calculations is the same, the distribution of mass loss is not. The 2D calculation, using the local temperature and luminosity, has a much higher mass-loss rate at the pole than the 1D case, while the mass loss rate at the equator is lower. Our fully 2D calculations will allow us to calculate the evolutionary effects of the mass loss distribution and perhaps better understand the $\Omega\Gamma$ limit. Unlike previous calculations, we do not need to assume a Roche potential or a specific gravity darkening law when calculating the stellar structure.

Scaling laws for calculating the mass loss as a function of angle for 1D models exist, and have been used extensively. Using the Castor, Abbott & Klein (1975) (CAK) mass-loss rates and assuming a von Zeipel (1924) gravity darkening law, it can be shown that the mass loss rate as a function of angle is

$$\frac{\dot{m}(\theta)}{\dot{m}_o} = 1 - \Omega \sin^2 \theta$$

where $\Omega = V^2_{rot,eq} R_{eq}/GM$ (Owocki, Cranmer & Gayley 1998). A comparison of our fully 2D calculation using the Vink et al. (2001) mass loss rates and the CAK predictions based on this formula is shown in Figure 1. The CAK mass loss rates are normalized to be the same as the Vink et al. (2001) mass loss rates at the pole. As shown in Figure 1, our calculated mass loss rates are considerably lower at the equator than the CAK predictions. Work is in progress to determine how much of this difference arises from the models, and how much arises from the different mass loss rates.

4 Structure

We have compared the interior structure of models that have had mass removed by both the 2D calculation and the pseudo 1D calculation. As discussed above, the type of calculation does not affect the total amount of mass removed, merely the distribution of this mass. We have found that even one mass loss event, corresponding to $\sim 10^{-4} - 10^{-5}$ $M_\odot$ is sufficient to affect the interior structure. A comparison of the 1D and 2D mass loss rates shows small differences throughout the star. In general, the density of the 1D model is larger than the 2D model, while the internal temperature is lower. After a single mass loss event, the differences are too small to have a significant effect on the star, but may accumulate over the course of the main sequence evolution. As discussed below, the radius of the 1D model does not increase as rapidly as the other model, which would correspond to a larger density given the same rate of mass loss.

Changing the surface distribution of the mass loss also affects the surface structure, as might be expected. We compared mass loss in a model with an initial equatorial radius of 5.992 $R_\odot$. After a 2D mass-loss event, the equatorial radius was 5.997 $R_\odot$, while after a 1D mass-loss event the equatorial radius was 5.991 $R_\odot$. The surface shape was also affected. In both cases, the polar radius remained the same fraction of the equatorial radius, at 0.969 R_{eq}. Both models had slightly smaller radii at some intermediate latitudes, but the 1D model shrank at more latitudes than the 2D model. This is again consistent with the finding that the radius of the 1D model does not increase as rapidly as the 2D model, as discussed in the next section. The model under consideration here is rotating at only 200 $\mathrm{km\,s^{-1}}$, which gives $\Omega/\Omega_{crit} \sim 0.3$, and the temperature difference between pole and equator is only about 1000 K. Presumably, as this difference increases in more rapidly rotating models, the differences between 1 and 2D mass loss will also increase.

5 Evolution

To date, we have evolved models through the first 15 time steps of an evolution sequence, or approximately 1.5 Myr. Mass-loss events were calculated after the fifth and tenth time steps. We have found that relative to a rotating model with no mass loss, the effective temperature increases and the total luminosity decreases, as shown in Figure 2. The temperature difference is largest immediately after the mass loss event, and remains larger than that of a non rotating model. The differences in luminosity are smaller, but also smoother than the temperature differences. Interestingly, the temperature difference is larger in the pseudo-1D case, while the luminosity difference is slightly larger in the 2D case.

The origin of these differences is probably in the change in equatorial radius of each of these models. In all three models (1D, 2D, no mass loss) the equatorial radius increases and the surface rotational velocity decreases as the star evolves. Of the three models considered here, it is actually the model with no loss that expands and spins down the fastest. Although no angular momentum is removed by mass loss in this model, no mass is removed from any point on the star either. In the pseudo-1D case, a significant amount of mass is lost from the equator, taking angular momentum with it. The larger mass loss and angular momentum loss effectively shrink the equatorial radius in this model, such that the radius grows more slowly than in the other models, and the model spins down the least.

In effect, the temperature differences shown in Figure 2 are somewhat deceptive, as it is actually the pseudo-1D model that changes the least in temperature. What appears as a relatively large temperature difference is actually a result of the faster increase in radius, and hence faster decrease in temperature, of the model that does not lose mass. In the 2D model, less mass and angular momentum are lost from the equator than in the pseudo-1D case, and the model is intermediate between the other two cases. After only 1.5 Myr, the differences are small, but increase with time, and can be expected to accumulate over the course of the main-sequence evolution.

6 Conclusions

Preliminary results indicate that a full 2D calculation of mass loss using the local effective temperature and luminosity can significantly affect the distribution of mass loss in rotating main sequence stars. More mass is lost from the pole than predicted by 1D models, while less mass is lost at the

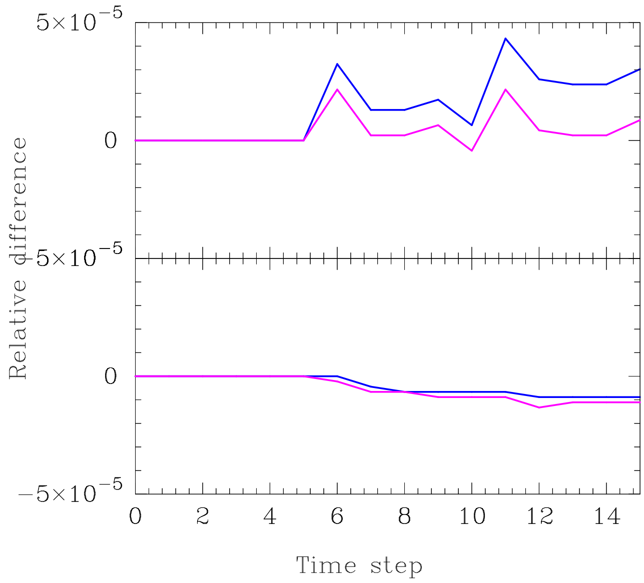

Figure 2: The effective temperature (top) and luminosity (bottom) relative to a model which is rotating but not losing mass. The differences are normalized by the effective temperture and luminosity of the non-rotating model. Shown are the differences for pseudo 1D (blue) and 2D (purple) mass loss.

equator. This change in the distribution of mass loss will affect the angular momentum loss, the surface temperature and luminosity, and even the interior structure of the star. After a single mass-loss event, these effects are small, but can be expected to accumulate over the course of the main sequence evolution.

Acknowledgements

This work was supported by the French National Research Agency (ANR) and the National Science and Engineering Research Council of Canada (NSERC). Computational facilities were provided through ACENet, which is funded by the Canada Foundation for Innovation (CFI) and agencies of the Atlantic Canadian provinces.

References

Castor, J.I., Abbott, D.C. & Klein, R.I. 1975. *ApJ*, 195, 157
Deupree, R.G. 1990. *ApJ*, 357, 175
Deupree, R.G. 1995. *ApJ*, 439, 357
Dwarkadas, V.V. & Owocki, S.P. 2002. *ApJ*, 581, 1337
Lucy, L.B. & Solomon, P.M. 1970. *ApJ* 159, 879
Maeder, A. & Meynet, G. 2000. *A&A*, 361,159
Owocki, S.P., Cranmer, S.R. & Gayley, K.G. 1998. *ApSS*, 260, 149
Vink, J.S., de Koter, A. & Lamers, H.J.G.L.M. 2001. *A&A*, 369, 574
von Zeipel, H. 1924. *MNRAS*, 84, 665