Chapter 9
Mass Loss

So far we have always assumed that stars have constant total mass. This is, however, not at all the case. The Sun is losing mass via the solar wind at a rate of about $10^{-14}\,M_\odot/\text{year}$. While this mass loss is so slow that it can savely be ignored, other stars may have mass loss rates of up to $10^{-8}\,M_\odot/\text{year}$ or even beyond. The highest mass loss rates for single stars are known for very massive stars ($M \gtrsim 50\,M_\odot$) and for stars of intermediate mass (around $5\,M_\odot$) in a very late stage of their evolution. In addition, stars in binary systems can lose (and gain) mass at any rate due to the gravitational interaction between the two components. Mass loss can therefore range from being totally irrelevant for the evolution of a star up to reducing the mass by up to 50 % or more.

For completeness, we add that the nuclear processes, which provide the overwhelming part of the radiation lost from the stellar surface, imply a conversion of matter to energy and therefore lead to a reduction of the stellar mass, too. For the Sun, this is of the same order as the solar wind, and can therefore be safely ignored. This is also true for all other stars either because this effect is very small, anyhow, or because stellar wind mass loss is much larger.

Evidence for mass loss and estimates of its size come from the direct detection of circumstellar matter and from spectral signatures, such as Doppler shifts and spectral line shapes. Wind velocities can range from a few to a few thousand km/s.

Physically, stellar winds result in many cases from the interaction of the photons emitted from the photosphere with atoms, molecules, or dust grains in the atmosphere. It is therefore a complicated radiation-hydrodynamics problem, which, in addition, may depend on chemical processes, too. An example for the latter are winds from very cool stars, which depend on the coupling of radiation to dust grains. Their formation is a complicated chemical process depending strongly on temperature and density in the stellar atmosphere, which may be subject to regular variations due to stellar pulsations. High mass loss rates are often associated with pulsations in extended stellar envelopes. In some cases, solid physical models exist, which describe the mechanisms for stellar winds. This is particularly true for winds from hot stars (so-called *radiation-driven winds*) and for *dust-driven winds* of cool stars with carbon-rich chemistry. For the observational evidence and for

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introductions to stellar wind theories, we refer the reader to the reviews "Winds from hot stars" by Kudritzki and Puls (2000), "Mass loss from cool stars" by Willson (2000), and "Dust driven winds" by Sedlmayer and Dominik (1994).

Since a full theoretical model for any stellar wind is not available, and would not be reasonable to be used in modelling stellar evolution, and since most information about stellar mass loss still results from observations, empirical mass loss formulations are used in the models. They have all been obtained from observations of some class of stars, and therefore differ from each other. Therefore, different mass loss formulae have to be used for different type of stars. None of them is very accurate, but in most cases, it suffices to have the correct order of magnitude of mass loss and its dependence on the global properties of the star. We now introduce a few such empirical mass loss formulations, which are widely used in stellar evolution calculations.

The most famous mass loss formula of all is that of Reimers (1975), obtained from red giants with heavy element abundances similar to those in the Sun. Reimers showed that the dependence of the mass loss rate on basic stellar parameters can be expressed by the simple fitting formula

$$\dot{M}_{\mathrm{R}} = -4 \times 10^{-13} \eta \frac{L}{gR} \cdot \frac{g_\odot R_\odot}{L_\odot}. \tag{9.1}$$

The unit of $\dot{M}$ is $M_\odot$/year. This formula reflects the intuitive expection that mass loss increases with luminosity L, and decreases with a deeper gravitational potential well $gR = GM/R$. The parameter η was introduced later to use Reimers' formula for other types of stars, too. It usually varies between 0.2 and 1.0 and is lower for metal-poor stars, indicating a weaker coupling of the photons to the gas if fewer heavy elements are present.

Reimers' formula has no strong theoretical justification, but seems to be a useful estimate for the order of magnitude of mass loss from cool stars. It has been modified from time to time to take into account a more detailed dependence on stellar parameters. One of the latest of such modifications, which is fitting better to recent mass loss determinations, is that of Schröder and Cuntz (2005), which is

$$\dot{M}_{\mathrm{SC}} = -8 \times 10^{-14} \frac{LR}{M} \frac{M_\odot}{L_\odot R_\odot} \left(\frac{T_{\mathrm{eff}}}{4,000\,\mathrm{K}} \right)^{3.5} \left(1 + \frac{g}{4,300 g_\odot} \right). \tag{9.2}$$

For very cool and luminous stars on the *asymptotic giant branch*, which experience an almost catastrophic mass loss event with mass loss rates up to $10^{-4} M_\odot$/year, a simple and useful formula has been derived by Blöcker (1995), based on observations and dust-driven wind theories. There are more sophisticated theoretical or empirical mass loss functions (see Sect. 34.6), but Blöcker's is in most cases sufficient for an estimate:

$$\dot{M}_{\mathrm{B}} = -4.83 \times 10^{-9} \dot{M}_{\mathrm{R}} (M_\star / M_\odot)^{-2.1} (L/L_\odot)^{2.7} \tag{9.3}$$

There are two variants of this formula, in which for $M_\star$ either the initial or the present mass of the star is used. Since (9.3) is only a rough estimate of the actual mass loss, this is acceptable.

Finally, we add a formula fitting empirical mass loss rates for hot stars of spectral type O and B, obtained by Lamers (1981):

$$\dot{M}_\mathrm{L} = -1.48 \times 10^{-5} \left(\frac{L}{1,000 L_\odot} \right)^{1.42} \left(\frac{R}{30 R_\odot} \right)^{0.61} \left(\frac{30 M_\odot}{M} \right)^{0.99} \tag{9.4}$$

A more physical discussion of mass loss from hot stars can be found in the mentioned review by Kudritzki and Puls (2000).

Obviously, all these formulae contain, in some form or other, the basic dependence on M, R, and L by Reimers. Sometimes a dependence on chemical composition is added. It is generally assumed that $\dot{M} \sim X_\mathrm{res}^{1/2}$, where X_res denotes the mass fraction of all elements other than hydrogen and helium.

Equations (9.1)–(9.4) already indicate that the main effect of mass loss is simply to reduce the total mass of a star. This has to be taken into account in stellar modelling and will be discussed in Sect. 12.5.