The physics of line-driven winds of hot massive stars
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Introduction

1.1 Massive stars in the universe

A starry night in the Chilean desert is one of the most beautiful views a person can see in her or his life. One is overwhelmed by the immensity of our galaxy (see Figure 1.1), and is intrigued by the presence of two of its satellites, the Large and Small Magellanic Cloud.

Galaxies are comprised of stars and clouds of gas. Stars that appear equally bright to the naked eye may either be nearby objects that are relatively dim or distant objects that are very luminous. The intrinsically brightest stars are the topic of this thesis. Their luminosities can be more than a million times that of our Sun, which is considered a nominal star. These stars are also the most massive ones, some of them starting their lives with perhaps more than a hundred times the mass of our Sun. Although spectacular objects, massive stars are rare. Depending on the adopted lower mass limit – usually eight solar masses – only some hundred thousands of such objects may exist in our galaxy, that overall contains approximately $10^{11}$ stars.

Why are we urged to understand these massive and luminous objects if they only comprise such a very small fraction of the stellar population? One compelling reason is that they are so extreme. They have short lifetimes – measured in millions of years rather than billions – and end their lives in a supernova explosion or gamma-ray burst, that can be seen throughout the universe. For the major part of their existence, their surface layers are extremely hot. Therefore, the many photons they emit are sufficiently energetic to heat-up, ionize, or facilitate chemical reactions in the gaseous material or microscopically small solid particles in their surroundings, called the interstellar medium.

Moreover their supernova explosions send shock waves through the interstellar medium, possibly triggering new epochs of star formation (e.g. Tenorio-Tagle & Bodenheimer 1988; Oey & Massey 1995). The material that is ejected in this explosion is enriched with chemical species produced in the star by nuclear fusion in its cen-
1. Introduction

Figure 1.1: The Milky Way above Paranal in the Chilean Atacama desert where the most advanced European optical telescope, the Very Large Telescope (VLT) of the European Southern Observatory (ESO), was built. Courtesy: S. Deiries/ESO

ter but also elements with an atomic number higher than iron produced by neutron capture in the explosion. In this way, the ambient medium is enriched with these new elements. As a consequence, later generations of stars will be composed of a chemical mixture that contains a larger fraction of, for instance, metals.

It is not only through explosions that massive stars inject material into the interstellar medium. They do this — in a much milder way — during their entire lives, by powering a more or less spherical outflow of ionized gas. These outflows are called stellar winds. They create large bubbles around the stars by sweeping up the interstellar gas that is encountered (see Figure 1.2). Through these stellar winds, massive stars lose mass. This may severely affect their course of evolution — i.e. the way in which they change their physical state over time —, as well as the properties of their supernova explosions, and the nature of the compact object — a neutron star or black hole — that is left behind.

Beyond stellar physics, another reason to study these massive objects comes from considerations pertinent to the early universe. The mass distribution of the first generation of stars formed in our universe, some 400 million years after the Big Bang, is thought to be different from the present-day mass distribution. At these early times, massive stars dominated, with perhaps a sizable fraction of stars exceeding hundreds of solar masses (Abel et al. 2002; Bromm et al. 2002; Nakamura & Umemura 2002; Bromm & Larson 2004; Loeb et al. 2008). It is particularly interesting to ponder on the question of how much mass stars of the first generation might have lost through stellar winds, prior to their supernova explosions. If the time integrated mass loss is
small, or even negligible, they may have left black holes with masses of $\sim 10^2 M_\odot$, that may have been pivotal in creating the first galaxies. If such first galaxies collided, these black holes might have merged and may be identified as the building blocks of the supermassive black holes detected in the centers of galaxies today (Kawakatu et al. 2005).

So, did these First Stars have stellar winds? If so, are the properties of these winds different from those of the massive stars of today? If they are not, it is extremely unlikely that massive black holes have been produced in the way described above, as the winds of massive stars in our galaxy are so powerful that these may strip 80–90 percent of the initial mass of such a star prior to its supernova explosion (Maeder & Meynet 1994).

The physics of stellar winds is the central theme of this thesis. A state-of-the-art method is presented that allows to determine the wind properties – notably the rate of mass loss and the terminal velocity at which this material is expelled from the star – of hot massive stars, given their global properties (for instance mass, luminosity, surface temperature) and surface chemical composition (for instance a metal-poor or a metal-rich mixture). In this first chapter, we will introduce stellar winds and present an overview of the studies presented in this thesis. We start by recapping some aspects of the evolution of massive stars (Sect. 1.2). Then, we briefly summarize some observed properties of massive star winds (Sect. 1.3). The driving mechanism of the winds of hot massive stars is described in Sect. 1.4. Finally, Sect. 1.5 provides an overview of the individual chapters of this thesis.

### 1.2 The evolution of massive stars

Most stars are in hydrostatic equilibrium. They obey a well defined relation between their mass $M$ and luminosity $L$. Roughly, $L \propto M^\alpha$, where $1 < \alpha < 3$ (Kippenhahn & Weigert 1990). As the lifetime of a star $\tau$ is expected to be proportional to $M/L$ this implies that $\tau \propto 1/M^{\alpha-1}$. It implies that, given a lifetime of 10 billion years for the Sun, a $100 M_\odot$ star may live only on the order of a few million years.

During most of their life, massive stars produce their energy by thermonuclear burning of hydrogen to helium in their centers, where temperature and pressure are sufficiently high to overcome the strong repelling Coulomb forces between protons. The chain of reactions relevant for massive stars, in which eventually four protons are merged into one helium nucleus, involves catalyst species. These are carbon, nitrogen, and oxygen. Therefore, the chain of reactions is referred to as the CNO-cycle. This phase in the star’s evolution encompasses about 90 percent of the total lifetime and lasts until all hydrogen is converted into helium in the stellar core. It is referred to as the main sequence phase of evolution, after which the star experiences a short contraction phase until hydrogen burning ignites in a shell around the helium
Introduction

core. As a result the star expands and cools at the surface. The post main-sequence evolution of massive stars is complex and may involve many phases such as the blue supergiant, red supergiant, and the Wolf-Rayet phase. The evolutionary path the star follows, depends on many factors: e.g. its metal content, its mass, its rotational velocity, whether it is magnetic or not, and whether it is a single star or part of a multiple system.

In idealized circumstances, the initial conditions of the evolution completely determine the path the star takes. If the star does not form together with a companion, its mass, angular momentum and chemical composition fully specify what will happen to the star over time. The mass is a dominant parameter determining the total lifetime. Stars more massive than eight solar masses can prevent the carbon/oxygen core that develops after the main sequence has ended to become degenerate. This brings them on track to a supernova explosion. Lower mass stars, that do form degenerate cores, eject their outer layers and fade out as white dwarfs.

Rotation plays a more subtle role in the life of stars, at least at first sight. Through rotation the star may “feel” a slightly lower mass than it actually has, as the centrifugal forces associated with rotation help to balance gravity. Rotation, especially rapid rotation, induces internal mixing (see e.g. Maeder & Meynet 1996; Heger et al. 2000). Material from (close to) the core is dredged up to the surface – causing a change in

Figure 1.2: The M1-67 nebula surrounding WR 124: a Wolf-Rayet star, a massive star in a late evolutionary stage. The nebula with a diameter of about 2.3 parsec, is the result of the interaction of the stellar wind and material ejected in outbursts with the interstellar medium (Grosdidier et al. 1998; van der Sluys & Lamers 2003). The gas that we see here is ejected over at least tens of thousands of years. Courtesy: NASA, HST.
the chemical patterns as, for instance, products of CNO-cycle burning appear. Material from outside the core is dredged down into the core, delivering hydrogen, and prolonging the main sequence lifetime.

Interestingly, if the star is rotating with a significant fraction of its break-up velocity, i.e. the velocity at which the centrifugal force balances gravity at the stellar surface, the star may mix so efficiently that it becomes (quasi) chemically homogeneous (Maeder 1987; Langer 1991). Such stars evolve unlike normal (slowly or modestly rotating) stars, in that they do not inflate towards blue- or red supergiants. Rather they remain hot and compact. Massive stars in our galaxy may never experience such homogeneous evolution, because their stellar winds appear to be too strong. These winds not only carry away mass, but also angular momentum. In other words, galactic massive stars may spin down quite efficiently already in their main sequence stage. As we shall see below, stars with a chemical composition that is poor in metals have weaker winds (see e.g. Kudritzki et al. 1987; Kudritzki 2002; Vink & de Koter 2005). Such stars, if born rotating rapidly, may experience homogeneous evolution.

The chemically homogeneous evolving metal-poor stars have been proposed to be progenitors of long-duration gamma-ray bursts. These are very strong flashes of gamma-ray radiation. The current consensus is that long gamma-ray bursts may occur when a rapidly spinning massive star explodes as a supernova (see e.g. Hjorth et al. 2003). Studies of the progenitors of gamma-ray bursts have been done by e.g. Hirschi et al. (2005); Yoon et al. (2006); Woosley & Heger (2006); Hirschi (2007).

An example of the behavior of a rapidly rotating metal-poor magnetic star of $40 \, M_\odot$ in the Hertzsprung-Russell diagram – a plot of luminosity versus effective temperature – is shown by the grey curve in Fig. 1.3 (Yoon et al. 2006). This star remains hot during the course of its evolution since it evolves chemically homogeneous. In that same figure the evolution of a rapidly rotating $85 \, M_\odot$ metal-poor star without internal magnetic fields is also presented (Hirschi 2007). This star becomes a cool supergiant, and spins down.

The third parameter controlling the evolution of stars is its chemical composition. Metal poor stars start their main sequence life being hotter than metal rich stars. The most important effect, however, is through the coupling between chemical composition and mass loss: both empirical and theoretical results show that the higher the metal content, the stronger the stellar wind (see e.g. Puls et al. 1996; Vink et al. 2001; Mokiem et al. 2007).

The mechanism that drives the wind is based on the absorption and scattering of photons in atomic transitions; the more complex atoms contribute stronger to the force, so the larger their abundance the higher the mass-loss rate. This rate scales in many cases with the metal content to the power $\sim 0.7$ (Vink et al. 2001; Krtička 2006; Mokiem et al. 2007). In other words, a massive star with a metal content ten
times lower than the Sun will lose mass at a rate 5 times lower than a star with the same properties but a solar chemical composition.

The effect of mass loss on the evolution of a massive star is twofold: the star becomes less massive and therefore the rate at which it burns nuclear fuel is affected, and the rotating star will spin down since the wind takes away angular momentum. During its life, a massive star in our galaxy may lose a significant fraction of its initial mass through its stellar wind, and almost all of its initial angular momentum. The mass-loss history of a star may also strongly impact the properties of its supernova explosion and the compact remnant it leaves behind.

Beside the effect of stellar winds, massive stars may also lose mass in eruptive processes (see e.g. Humphreys & Davidson 1994). These eruptive processes are not very well understood but tend to occur when the star becomes unstable by reaching either its critical rotation velocity, the so-called Eddington limit, i.e. when gravity is overcome by radiation forces at the surface, or a combination of both when the star reaches its $\Omega-\Gamma$-limit (Maeder & Meynet 2000). Whether or not such eruptions depend on the metal content is unknown.

In the early universe, stars were very metal poor or practically metal free. The very first generation of stars or First Stars were formed from gas clouds containing almost only hydrogen and helium. Early on in their evolution, they may have produced small amounts of carbon, nitrogen and oxygen in their cores. These stars most likely do not
1.3 Observational properties of stellar winds

have a sufficient metal content to drive a stellar wind (Krtička & Kubát 2006). They may not lose any mass or angular momentum during their main sequence evolution if they do not suffer from major eruptive mass-loss events. In the later stages of their evolution, the (primary) carbon, nitrogen and oxygen produced at the center may surface due to internal mixing processes (Marigo et al. 2001, 2003; Yoon et al. 2006; Hirschi 2007). This happens in rapid rotators but also in slow rotators it could be the case (due to dredge up during the red supergiant phase). As a consequence the sum of the carbon, nitrogen and oxygen surface abundance may become higher than the total solar metal abundance. Will these enriched stars suffer from strong stellar winds? Their total metal content may be high but carbon, nitrogen and oxygen have a different atomic structure than elements like iron that are present in massive stars in our galaxy. Iron-like atoms are very efficient in driving a wind, more so than carbon, nitrogen and oxygen (Vink et al. 1999; Puls et al. 2000). The study of the wind properties of these CNO enriched very metal-poor stars is one of the subjects addressed in this thesis.

1.3 Observational properties of stellar winds

Hot massive stars reveal that they lose mass in several ways. For a detailed description of these signatures we refer to e.g. Lamers & Cassinelli (1999) or Kudritzki & Puls (2000), here we give a short overview. First, profiles of resonance lines of metal species such as carbon, nitrogen, oxygen, silicon and magnesium, located in the ultraviolet part of the spectrum, show shapes indicating a more or less spherical outflow of matter. These P Cygni lines probe up to about 10 stellar radii from the surface and are the most sensitive mass-loss rate ($\dot{M}$) diagnostics, allowing to measure rates as low as $10^{-9} \, M_\odot \text{yr}^{-1}$. Second, recombination lines of hydrogen and helium in the optical and near-infrared parts of the spectrum are signatures of out-flowing gas close to the star (within $\sim 2$ stellar radii). The hydrogen lines can probe mass-loss rates as low as $10^{-7} \, M_\odot \text{yr}^{-1}$. Finally, continuum emission at infra-red or radio wavelengths provides a measure of the wind density, hence the mass-loss rate (Panagia & Felli 1975; Wright & Barlow 1975). Notably radio emission may originate from up to 30-100 stellar radii. As radio-fluxes tend to be weak for hot massive stars, only galactic objects can be studied in this way. The rates that can be measured probe the range of several times $10^{-7} \, M_\odot \text{yr}^{-1}$ and up.

The best way to obtain an estimate of the terminal wind velocity is by measuring the location of the blue-edge of the absorption trough in saturated P Cygni profiles (see Figure 1.4). The blue-shifted region is caused by absorption of continuum photons in the gas in front of the stellar disk that is moving towards us. Though a simple measurement, a presence of turbulence in the outflow and photospheric absorption lines near the blue-edge may introduce a sizable uncertainty in the measurement of
1. Introduction

![Figure 1.4: P Cygni line profile of the triply ionized carbon doublet at $\lambda\lambda$ 1548.2 Å - 1550.77 Å. Material that is moving toward (away from) the observer causes a blue-shift (red-shift) in the wavelength. The absorption is due to material in front of the stellar disk. The emission is symmetric around the rest wavelength(s) of the doublet line. These type of profiles are characteristic for a radial outflow of gas. The sharp absorption lines are produced by the interstellar medium and mark the rest wavelengths of the triply ionized carbon doublet. Courtesy of the International Ultraviolet Explorer (IUE).](image)

the terminal velocity, perhaps reaching 30 percent for specific types of stars. Typical values for the wind terminal velocity, $v_{\infty}$, that have been deduced from these line profiles range between 400 km/s and 3300 km/s for stars hotter than 21 000 K and in between a 100 km/s and 1500 km/s for stars in the temperature range between 10 000 K and 21 000 K (Kudritzki & Puls 2000 based on Prinja et al. 1990; Howarth et al. 1997; Prinja & Massa 1998).

Deriving mass-loss rates for massive stars is a more complicated task. As mentioned above, there are several techniques that can be used depending on the strength of the stellar winds. In Figure 1.5, the logarithm of the empirically derived modified wind momentum – the product of the square root of the star’s radius divided by the solar radius ($R_*/R_\odot$), the terminal wind velocity and the mass-loss rate – $D_{\text{mom}} = \sqrt{R_*/R_\odot} \times M_{\infty}$, is plotted against the logarithm of the luminosity of the star. $D_{\text{mom}}$ is for practical purposes a measure of the mass-loss rate since $v_{\infty}$ varies only within a factor 3 and $\sqrt{R_*/R_\odot}$ within a factor 2 for the range of stars investigated in this figure. Considering $D_{\text{mom}}$ rather than $\dot{M}$ has the advantage that it is (almost) independent of stellar mass and that also central stars of Planetary Nebulae and A supergiants, that also lose mass through the same mechanism, can be included in the comparison. The black dots are mass-loss rates determined from fitting the H$\alpha$ line profile and the grey dots correspond to mass-loss rate estimates that strongly rely on ultraviolet resonance lines. One notes that there is a steep jump – of about a factor 100 – in the mass-loss rate at $10^{5.2}$ times the solar luminosity, illustrated by the red
1.3 Observational properties of stellar winds

Figure 1.5: The modified wind momentum $\sqrt{R_*/R_\odot} Mv_\infty$ as a function of stellar luminosity for galactic stars using the data of Mokiem et al. (2007) and references there in. Black symbols refer to mass-loss estimates based on the fitting of the Hα-profile; grey symbols are mass-loss estimates from ultraviolet resonance lines. Note that the Hα estimates at $L < 10^{5.2} L_\odot$ are upper limits. A steep jump – of about 2 dex – can be seen at a luminosity of $10^{5.2} L_\odot$. The black line corresponds to the empirical wind-momentum luminosity relation with rates not corrected for clumping, the black dashed line corresponds to the one corrected for clumping and the grey dotted line is obtained by fitting to the modified wind momentum obtained from ultraviolet resonance lines. The red lines, to guide the eye, overplot the black line in the high luminosity regime ($\log L/L_\odot > 5.2$) and the grey line in the low luminosity regime. The plot is based on a figure from Mokiem et al. (2007).
1. Introduction

line. For stars to the left of this point the Hα line profile becomes too weak to use as a reliable mass-loss diagnostics and therefore the ultraviolet resonance lines have to be used.

For stars more luminous than $10^{5.2}L_\odot$, the theoretical predictions as done by Vink et al. (2000) and the empirical mass-loss rates (Mokiem et al. 2007) seem to be in (reasonably) good agreement. We will come back to this point later. However, for objects less bright than $10^{5.2}L_\odot$ there is a serious discrepancy between the predictions and observations, which is referred to in literature as the weak-wind problem (Martins et al. 2005b; Puls et al. 2008; Marcolino et al. 2009). What could be the cause of this discrepancy? On the observational side, at this luminosity the mass-loss diagnostic changes: for mass-loss rates above $10^{-7}M_\odot\text{yr}^{-1}$ the Hα line diagnostic method is sensitive enough to provide mass-loss rates, whilst below this value one has to resort to the ultraviolet spectral range. Here the P Cygni-line diagnostics is more sensitive, but potentially also less reliable because of the uncertainties in ionization fraction (see e.g. Lamers & Leitherer 1993). On the theoretical side, the predictions have been derived subject to a set of assumptions. Some of the most stringent assumptions are: the stellar wind is a homogeneous medium, it is spherically symmetric, and time independent. Here, we want to discuss the assumption that a stellar wind is a homogeneous outflow.

There are several reasons that indicate that a stellar wind is not a continuous flow of gas but consists of an ensemble of fluid parcels of different densities and velocities. On the observational side: moving subpeaks in emission line profiles have been detected (see e.g. Eversberg et al. 1998), structure can be seen on large scales (see e.g. Kaper et al. 1996), and the linear polarization of the light from a wind can be variable (see e.g. Davies et al. 2007). From theory, it is predicted that the winds should be clumpy. The force accelerating the gas away from the stellar surface is unstable and therefore perturbations are expected (Lucy & Solomon 1970; Owocki et al. 1988).

These inhomogeneities are important since the mass-loss rates derived from Hα-profiles are affected by them, i.e. these mass-loss rates should be reduced if one accounts for clumping (Hillier 1991; Moffat & Robert 1994). In general clumping affects stellar wind diagnostics that are sensitive to the density squared, e.g. the Hα-profile, but not diagnostics that depend linearly on the density, e.g. P Cygni lines. We previously mentioned that there is a small discrepancy between the empirical mass-loss rates and the theoretical predictions for stars more luminous than $10^{5.2}L_\odot$: the empirical rates are higher. If one corrects only these empirical mass-loss rates for clumping, theory and observations agree already for only a modest clumpiness (Repolust et al. 2004; Mokiem et al. 2007).

However, relaxing on the assumption that the wind is a homogeneous outflow may also have an impact on the theoretical predictions of the mass-loss rate. In chapter 2 of this thesis, we account for effects caused by inhomogeneities in the flow. We
1.4 Theory of line-driven stellar winds

The atmospheres of most hot massive stars are not in hydrodynamic equilibrium. Gravity is overcome by radiation and gas pressure forces. As a consequence gas streams outward (Lucy & Solomon 1970). The processes between the gas and the photons, causing the radiation forces, can be divided in two categories: “continuum” processes and “line interactions”. The gas in the atmosphere of the star is highly ionized and consists mostly of free electrons, fully ionized hydrogen, ionized helium, and multiply ionized species of more complex atoms. The continuum processes are interactions between photons and free electrons or ions of the following types: a photon interacts with a free electron, or an ion. In the latter case it can even further ionize it if it has sufficient energy. The strength of the continuum radiation force depends on the density of the gas and the number of photons. The contribution of this type of interactions to the total radiation force can be important deep in the wind, but it does not play a very important role once the strong acceleration due to line interaction has started in layers further out.

In case of a line interaction, a photon is absorbed in an atomic transition. A photon can be absorbed in such a transition only if its energy is equal to the energy needed to bring a bound electron to a higher energy level. The new state of the ion has a very short life time. The electron falls back to its original energy level, and a photon is re-emitted. In this process, energy and momentum are transferred from the radiation field to the absorbing ion or vice versa. These absorbing ions share the momentum and energy gained in this manner with the other gas particles, dragging them along.\footnote{In some cases this mechanism is not very effective but we do not consider this here.}

The number of photons with the proper energy for the transition is limited in a medium with constant velocity. If the gas is accelerating, the ions are able to absorb photons that are Doppler shifted with respect to the photons absorbed in the layers below. This means that while the gas is moving out, it remains able to intercept an unattenuated flux at the right Doppler-shifted frequency, causing it to be accelerated even more. So, interestingly, an accelerating flow boosts a further acceleration. The radiation force associated with this process is called line force. It is the main force that drives the kind of stellar winds investigated here, the so called line-driven winds.

The important variables that determine the strength of this force are the stellar flux of photons at each frequency, the abundance of the various atoms, their excitation and ionization state, and the number of transitions the configurations have. Some ions...
1. Introduction

are more efficient in absorbing photons than others. This efficiency is *grosso modo* determined by the product of the atom abundance, the ionization fraction, and the number of different transitions. Although hydrogen and helium are the most abundant species by far, they do not dominate the line force. Hydrogen is almost fully ionized. The fraction of neutral hydrogen times its abundance is almost equal to the number abundance of more complex atoms in their dominant ionization stage. So, these roughly cancel out. Therefore, the number of transitions is important. A complex ion can have many thousands of transitions in the region of the flux maximum of the star, many more than hydrogen which only has several tens. Therefore, the complex ions are the main contributors to the line force.

In order for a hot massive star to power a line-driven wind the radiation force – that will be described below – must overcome gravity. Whether or not this can be achieved, as well as the manner in which the flow is accelerated and the rate of mass loss in which this results, depend on the star’s physical properties. The main goal of theoretical research into stellar winds is to understand the physics of this problem.

In this thesis different methods for predicting wind properties are applied. In chapter 2 a Monte Carlo method contrived by Abbott & Lucy (1985) and advanced and refined by de Koter et al. (1997) is used. Interestingly, it does not rely on a solution of the equation of motion of the stellar wind – often referred to as the wind equation. The detailed information on microscopic physics available in these simulations are the core element of two improved treatments of the wind problem presented in chapter 3. One of these, termed best-β method, follows the work of Müller & Vink (2008), the other, termed hydrodynamical method, is new. The latter method provides a consistent solution of the wind equation. The results presented in chapters 4 and 5 rely on the best-β method, which we show to provide solutions that agree well with those of the numerical method but is computationally faster.

The basis for the Monte Carlo method is that for the derivation of the mass-loss rate for a specific set of model parameters, one relies on an iteration procedure between the structure of the atmosphere and the radiation field (computed using the code *isa-wind*; de Koter et al. 1993), and the line force determined using a Monte Carlo simulation (computed using the code *mc-wind*; de Koter et al. 1997; Vink et al. 1999). The structure of the atmosphere is determined using an input mass-loss rate. In the Monte Carlo code, it is derived how much mass per unit time can be accelerated by the radiation field of the *isa-wind* atmosphere out of the star’s gravitational potential using global energy conservation. These two codes are iterated until the line force can drive the input mass-loss rate of the model atmosphere. In this case, the energy needed to accelerate the wind out of the star’s gravitational field up to the terminal flow velocity of the wind equals the energy the gas absorbed from the photons, allowing for global energy conservation and not for local dynamical consistency. So indeed, the equation of motion remains unsolved.
1.4 Theory of line-driven stellar winds

1.4.1 The wind equation

The outflow of a line-driven stellar wind is governed by the forces at play. Assuming spherical symmetry this can be described by the following equation:

$$\frac{dv}{dr} = -\frac{GM}{r^2} + g_{\text{rad}} - \frac{1}{\rho} \frac{dp}{dr},$$

(1.1)

where $r$ is the distance from the center of the star, $v(r)$ is the velocity, $g_{\text{rad}}(r)$ the radiation force per unit mass, $p(r)$ the pressure, $\rho(r)$ the density, $G$ is Newton’s gravitational constant, and $M$ the stellar mass. Using mass continuity, $M = 4\pi r^2 \rho v$, and the equation of state of the gas, we can rewrite the pressure term as:

$$\frac{1}{\rho} \frac{dp}{dr} = -\frac{a^2}{v} \frac{dv}{dr} - \frac{2a^2}{r} + \frac{k}{m} \frac{dT}{dr},$$

(1.2)

where $T(r)$ is the temperature at radius $r$, $k$ is Boltzmann’s constant, $m$ the mean particle mass and $a(r)$ the local sound speed, given by:

$$a = \sqrt{\frac{kT}{m}}.$$

(1.3)

The radiation force consist of a continuum radiation force $g_{\text{con}}$, and a line force $g_{\text{line}}$. If we take the continuum radiation force to be equal to the electron scattering force only, and assume the flow to be isothermal, we may write the wind equation in a fairly simple form:

$$a_o \left( \frac{v}{a_o} - \frac{a_o}{v} \right) \frac{dv}{dr} = -\frac{R_* v_{\text{esc}}^2}{2r^2} + \frac{2a^2}{r} + g_{\text{line}},$$

(1.4)

where $a_o$ is the isothermal sound speed at the effective temperature of the star and $v_{\text{esc}}$ is the effective escape velocity, i.e.:

$$v_{\text{esc}} = \sqrt{\frac{2GM(1 - \Gamma_e)}{R_*}},$$

(1.5)

where $\Gamma_e$ is the electron scattering force divided by the gravitational force. Equation (1.4) is a critical point equation. We discuss this aspect later and for now focus on the line force. The fairly simple form of the wind equation is deceitful due to the nature of this force. As already alluded to, it is a function of the acceleration (in this case we mean $dv/dr$ and not, as commonly used, $dv/dt$), the number density of the ions and the flux at each frequency. It also depends on the specific characteristics of each atomic transition. The problem faced can be expressed in a simple way: the force driving and determining the structure of the flow itself depends in a complex way on this structure.
The Monte Carlo method to study the line force relies on a model atmospheric structure to determine the amount of momentum and energy transferred from the radiation field to the gas, enabling the determination of the radiation forces. Given the structure of the wind, we can determine the probability of photons of all frequencies to be absorbed by the gas. We use this to determine the point of interaction and the nature of this interaction for photons emitted with a random frequency in a random direction at the inner boundary of the model, having a random probability to be absorbed at a specific location. The location where the photon is absorbed, is determined based on the physical properties of the medium the photon travels through, i.e. it is based on the distance a photon of the given frequency can travel on average before it is absorbed.

At the point of interaction the photons are re-emitted and the amounts of energy and momentum transferred are calculated. They are followed until they either back scatter through the inner boundary or escape through the outer boundary. Knowing the nature of each interaction, i.e which particle was involved and the amounts of energy and momentum transferred, we have a very powerful tool to study the radiation force. It equals (Abbott & Lucy 1985):

\[ g_{\text{rad}} = -\frac{1}{M} \frac{dL}{dr}, \tag{1.6} \]

where \( dL \) is the amount of energy lost by the radiation field in a layer of thickness \( dr \).

We want to use this radiation force to solve the wind equation. In Figure 1.6, the black plus-symbols show a typical output line force from a Monte Carlo simulation.
as a function of the distance $r$ from the center of the star. One notes that the line force shows a considerable amount of scatter as it has been determined in a statistical manner. Therefore, it is not very suitable to use as an input to solve the wind equation. We opt to formulate a fit function that describes the line force as a function of radial distance and captures the general behavior of the output Monte Carlo force following Müller & Vink (2008). This approach is distinct from the theory by Castor, Abbott and Klein (Castor et al. 1975, CAK), where $g_{\text{line}}$ is a function of the velocity gradient and radial distance. To be clear, in our representation $dv/dr$ also plays an important role, though this is not explicit in $g_{\text{line}}$. Our $g_{\text{line}}$ function should fulfill several requirements; i) $g_{\text{line}}$ must be approximately zero at the stellar surface; ii) $g_{\text{line}}$ should always be positive or zero as the flux of radiation from the photosphere is streaming outwards; iii) $g_{\text{line}}$ is required to decrease as $1/r^2$ for large radial distance from the central star, and iv) $g_{\text{line}}$ has an absolute maximum somewhere in the range between the stellar surface and the outer edge of the wind. The last requirement follows from properties i-iii above. The following function fulfills these requirements:

$$g_{\text{line}} = \begin{cases} 0 & \text{if } r < r_0, \\ g_o (1 - r_0/r)^\gamma/r^2 & \text{if } r \geq r_0, \end{cases}$$

(1.7)

where $g_o$, $r_o$, and $\gamma$ are fit parameters to the Monte Carlo line force. Figure 1.6 displays a comparison of the fit function and the Monte Carlo line force. We used this function to solve the wind equation numerically. The solutions produce trans-sonic velocity laws that pass through the critical point. The critical point is defined as the location where both sides of equation (1.4) are zero. Using the above parametrization of the force this coincides with the sonic point, the location where the flow reaches the local sound speed.

The sonic point is an important point in the outflow. It is the point where gravity is almost exactly equal to the radiation force. Since the main force driving the flow depends on the acceleration, it is critical to initiate the flow. The more complex an ion, the more efficient the mechanism of line acceleration will work for small values of the velocity. The ensemble of transitions provided by iron-group elements, is more effective in driving the flow at the base of the wind.

If the metal content of the star is very low, or it does not produce a sufficient amount of photons, the radiation and pressure forces alone may be not strong enough to start a wind.

This principle is applied throughout this thesis. In chapter 3, we present the method developed to solve the wind equation and we apply it to galactic stars. In chapter 4, we investigate the mass-loss behavior of very luminous and very massive stars up to 300 times the mass of the Sun. In chapter 5, we apply this method to investigate the mass-loss behavior of carbon-nitrogen-oxygen enriched metal-poor stars.
1.5 Summary: a guide to this thesis

To conclude we give a brief overview of the main conclusions of the scientific chapters in this thesis:

In chapter 2 we investigate the effect of inhomogeneities on the wind properties of massive stars. The wind is envisioned to consist of clumps in which the density is high. The inter-clump medium is assumed to be void. On the one hand, due to the high clump density relative to the density under the assumption of a smooth medium, the excitation and ionization state of the gas are affected; the gas tends to recombine. On the other hand, photons emitted by the star have a probability to escape relatively easily ‘in-between the clumps’ or to become trapped in optically thick clumps. This behavior is called porosity. The processes mentioned compete in their effect on the mass-loss rate and terminal wind velocity. We adopt several prescriptions for the behavior of clumping as a function of distance and for the length-scale of the clumps. We show that in the case of small geometric clumps and small clumping factors, the energy transferred from the radiation field to the gas is barely affected, allowing to easily reconcile the empirical mass-loss rates of very luminous stars with the theoretical ones accounting for only a small amount of clumping. In the case of geometrically large clumps and large clumping factors, the wind energy can drop by as much as a factor 100. In these cases the mass-loss rates become too small to reconcile the empirical mass-loss rates with theoretical ones. In principle, such low mass-loss rates might provide a solution to the weak-wind problem – discussed in Sect. 1.3. This is however not likely, unless a mechanism can be identified that causes extreme structure to develop in the winds of stars with \( L < 10^{5.2}L_\odot \) that have \( M \lesssim 10^{-7}M_\odot\text{yr}^{-1} \) (weak winds) that is not active in denser winds.

In chapter 3 we present two methods to solve for the mass-loss rate and velocity profile of hot massive stars, and we apply this to dwarf, giant and supergiant O-type stars. An important finding is that we can not drive stellar winds for dwarf stars that are less luminous than \( 10^{5.2} L_\odot \). This coincides with the luminosity at which the weak-wind problem – discussed in Sect. 1.3 – occurs. We propose that in this regime the line force is too weak to accelerate the wind through the sonic point. As such relatively low luminosity stars do have (weak) winds, there must be an extra force that plays a role in driving the wind. For stars more luminous than \( 10^{5.2} L_\odot \) we find mass-loss rates that are in good agreement with previous estimates, notably the mass-loss recipe of Vink et al. (2000). Our derived terminal velocities are about 35 % to 45% higher than the mean of the observed values. This may be related to the presence of clumping in the outer wind and/or other physical processes not taken into account in our simulation.
1.5 Summary: a guide to this thesis

The wind properties of stars in the range of 40–300 $M_{\odot}$ that approach their Eddington limit are investigated in chapter 4. We find a very well behaved relation between mass loss and the basic parameters mass and electron scattering Eddington factor $\Gamma_e$. The latter is a measure of the proximity of stars to their Eddington limit. We find an upturn in the mass loss versus $\Gamma_e$-dependence, exactly at the point where the model winds become optically thick. This is also the point where the wind efficiency numbers surpass the single-scattering limit (of $\eta = M v_{\infty} c / L = 1$), reaching $\eta \approx 2.5$ close to the Eddington limit. This suggests a natural transition from common O-type stars to Wolf-Rayet characteristics where the wind becomes optically thick. This ‘transitional behavior’ is also found in terms of the parameter describing the rate of acceleration of the flow (so-called $\beta$), which increases from the canonical value of 0.9 in normal O stars to values as high as 1.5, as well as in the spectral morphology of the characteristic He II line at 4686 Å.

In chapter 5 the winds of metal-poor stars that have their surfaces enriched by primary CNO are studied. So far, mass-loss estimates for such stars have been based on the assumption that the metal content implied by carbon, nitrogen and oxygen $Z_{\text{CNO}}$ can be substituted for the metallicity, $Z$, as intended in mass-loss rate recipes using a mixture of elements that is scaled to the solar composition. We find that CNO driven winds feature much lower mass-loss rates than scaled solar metallicity winds if $Z_{\text{CNO}} = Z$. The reason is that carbon, nitrogen and oxygen have simpler atomic structures than iron; consequently, iron has many more atomic transitions and drives the wind more efficiently near the sonic point. We find that driving CNO winds for stars hotter than 50 000 K is not possible, as the lines of the ions that are dominant at these temperatures do not provide sufficient driving. The mass-loss behavior of cooler stars is very complex, but can be summarized quite homogeneously by normalizing to rates implied by the mass-loss prescription of Vink et al. (2001). The latter is frequently used in stellar evolution codes. We further conclude that the winds of massive very metal-poor stars ($Z \lesssim 10^{-4}$), whether they are primary CNO enriched or not, are so weak that they do not significantly impact the total mass and/or angular momentum loss during their evolution. If other mass-loss mechanisms, such as $\eta$-Carinae type mass eruptions, do not occur for such objects, their supernova explosions are expected to be responsible for the major part of the early cosmological nucleosynthetic chemical enrichment, and may have left black holes with masses of $\sim 10^2 M_{\odot}$. 