The Art of Modelling Stars in the 21^{st} Century
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Interaction of massive stars with their surroundings

Gerhard Hensler

Institute of Astronomy, University of Vienna, Tuerkenschanzstr. 17, 1180 Vienna, Austria
email: hensler@astro.univie.ac.at

Abstract. Due to their short lifetimes but their enormous energy release in all stages of their lives massive stars are the major engines for the comic matter circuit. They affect not only their close environment but are also responsible to drive mass flows on galactic scales. Recent 2D models of radiation-driven and wind-blown HII regions are summarized which explore the impact of massive stars to the interstellar medium but find surprisingly small energy transfer efficiencies while an observable Carbon self-enrichment in the Wolf-Rayet phase is detected in the warm ionized gas. Finally, the focus is set on state-of-the-art modelling of HII regions and its present weaknesses with respect to uncertainties and simplifications but on a perspective of the requested art of their modelling in the 21^{st} century.

Keywords. Stars: supergiants, (ISM:)HII regions, ISM: kinematics and hydrodynamics, galaxies: evolution

1. Introduction

Massive stars play a crucial role in the evolution of galaxies, as they are the primary source of metals, and they dominate the turbulent energy input into the interstellar medium (ISM) by their massive and fast stellar winds, by the ultraviolet radiation, and by supernova explosions. The radiation field of these stars, at first, photo-dissociates the ambient molecular gas and forms a so-called photo-dissociation region (PDR) of neutral hydrogen. Subsequently, the Lyman continuum photons of the star ionize the HI gas and produce a HII region that expands into the neutral ambient medium.

As these stars have short lifetimes of only a few million years, HII regions indicate the sites of star formation (SF) and are targets to measure the current SF rate in a galaxy. Furthermore, the emission line spectrum produced by the ionized gas allows the accurate determination of the current chemical composition of the gas in a galaxy. Although the physical processes of the line excitation are quite well understood and accurate atomic data are available, so that the spectral analysis of HII regions (see e.g. Stasińska 1979, Evans & Dopita 1987) serves as an essential tool to study the evolution of galaxies, their reliability as diagnostic tool have also to be studied with particular emphasis e.g. to temperature fluctuations (Peimbert 1967, Stasińska 2002) and line excitations.

The simple concept of a uniform medium in ionization equilibrium with the radiation from a massive star (the Strömgren sphere) is successful in describing several global features of HII regions and allows to model the emission line spectrum to a first-order reliability. Since it has long been realized that HII regions are also excerting complex dynamics to the ISM, dynamical modelling of HII regions caused purely by the energy deposit of the stellar radiation field has therefore been started already long ago (see e.g Yorke 1986 and references therein) providing a first insight into the formation of dynamical structures. In addition, also an expanding stellar wind bubble (SWB) with a

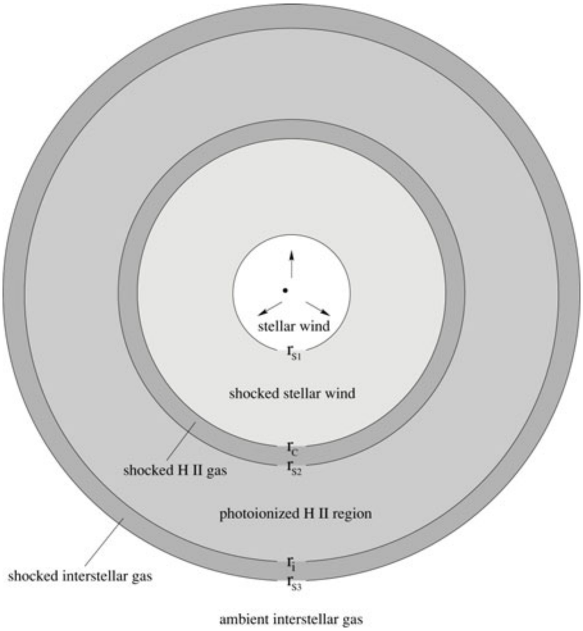

Figure 1. Schematic structure of a SWB as derived by Weaver *et al.* (1977): rs1 marks the position of the reverse shock, rc the contact discontinuity, rs2 the forward shock of the stellar wind bubble, ri the ionization front, and rs3 the forward shock of the HII region expansion.

constant wind power but neglecting its dynamics can be analytically described for the adiabatic phase as the self-similar evolution by Sedov.

In order to approach reality of how a radiation-driven and wind-blown SWB around a massive star interacts with its surroundings one has to take the kinetic energy of the wind and its dissipation into account and has to consider the ionization of the neutral environmental gas where it still exists. Analytically, this can be allowed for in spherical symmetry under the simplifying assumptions of a point source of constant strong wind that interacts with a homogeneous ambient ISM as derived by Weaver *et al.* (1977). This leads to a clear stratification of the surrounding bubble (see fig. 1) from inside out: freely expanding stellar wind, reverse shock, shocked stellar wind, contact discontinuity, SWB forward shock, photo-ionized HII region, ionization front, forward-shocked ambient gas.

Although the analytical and semi-analytical solutions for the evolution of SWBs have been improved over the years as well as the numerical simulations have been done with increasing complexity, like e.g. 2D calculations of SWBs (see e.g. by Różyczka 1985 and a series of papers) and/or combined 1D radiation-hydrodynamical models of HII regions coupled with the dynamical SWB (for references see Freyer *et al.* 2003) a variety of physical effects remains to be included in order to achieve a better agreement of models and observations e.g. with regard to the evolution of the hot phase in bubbles (MacLow 2000, Chu 2000).

2. SWB Models

To improve the insight into the evolution of radiation-driven + wind-blown bubbles around massive stars, we have performed a series of radiation-hydrodynamical simulations with a 2D cylindrical-symmetric nested-grid scheme for stars of masses 15 $M_\odot$ (Kroeger

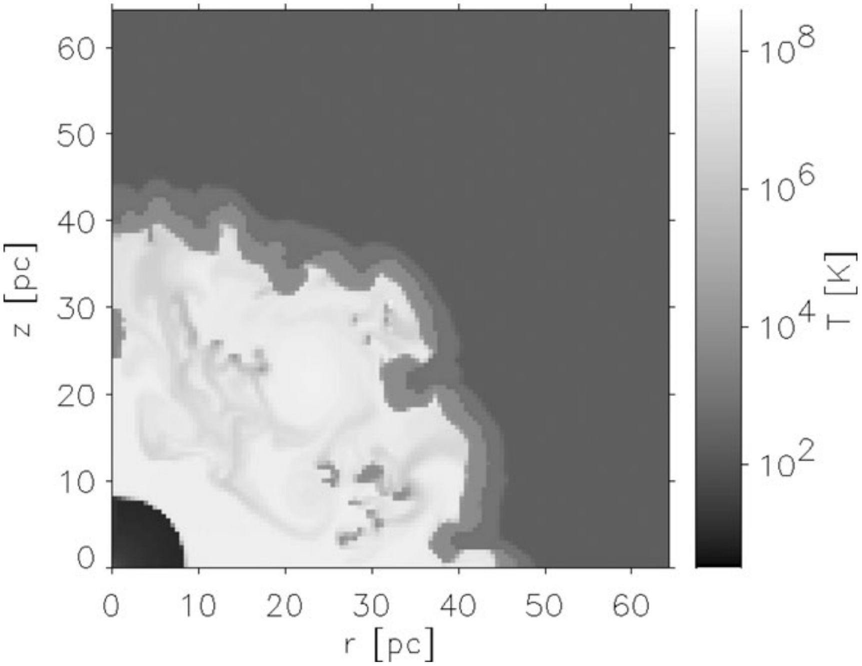

Figure 2. Temperature distriution of stellar wind bubble + HII region surrounding a 60 $M_\odot$ star at an age of 3.3 Myr (Freyer *et al.* 2003).

et al. in prep.), 35 $M_\odot$ (Freyer *et al.* 2006), 60 $M_\odot$ (Freyer *et al.* 2003), and 85 $M_\odot$ (Kroeger *et al.* 2007). The main issues of these models can be summarized as follows:

1) The HII regions formed around the SWBs have complex structures mainly affected by dynamical processes, like e.g. shell instabilities, vortices, mixing effects, etc. (see fig. 2)

2) The stronger the wind the higher the compresssion of the SWB-surrounding HII region (Hensler *et al.* 2008), what means that the HII rgion does not increase according to the larger ionizing flux.

3) Finger-like and spiky structures of different densities and temperatures are formed in the photo-ionized region (Freyer *et al.* 2003).

4) The regions contributing to the HII region emission line spectrum are not solely limited to the photo-ionized shell around the SWB but also form from photo-evaporated gas at the trailing surface of the SWB shock front (Hensler *et al.* 2008; and see fig. 2).

5) Because dispersion of this cooler photo-evaporated gas into the hot SWB leads to mixing also the stellar material expelled by the wind has to emerge partly in the HII region spectra.

6) As a consequence the metal-enrichment of the wind in the Wolf-Rayet stage which is generally assumed to remain only in the hot SWB for a long time affects the observationally discernible abundance of the HII gas. By these models Kroeger *et al.* (2006) could prove for the first time that the metal release by Wolf-Rayet stars can be mixed within short timescales from the hot SWB into the warm ionized gas and should become observationally accessible. As the extreme case for the 85 $M_\odot$ star we found a 22% enhancement of Carbon, but neglible amouts for N and O.

Since the occurrence of a WR phase is strongly metal dependent, the enrichment with C should also depend on the average metallicity. This would mean that any radial gradient of C abundance of HII regions in galactic disks is steeper than that of O. And indeed, Esteban *et al.* (2005) found $d[\log(C/O)]/dr = -0.058 \pm 0.018$ dex kpc^{-1} for the Galactic disk.

7) As expected from the distribution of HII gas the radially projected Hα brightness shows a decrease to the center and a slight brightening to the limb but not as strong as expected according to the increase of the line-of-sight with impact parameter (Freyer *et al.* 2003). This effect depends on the bubble age and evolves from central brightning to a moderate central trough. It also demonstrates both: the neglection of heat conduction and the homogeneous initial density do not allow a sufficient brightning of heat conductive interfaces so that, secondly, only the photo-evaporated backflow can contribute to the Hα luminosity in present models. In reality, condensations which become embedded into the hot SWB are exposed to heat conduction.

8) The sweep-up of the slow red supergiant wind by the fast Wolf-Rayet wind produces remarkable morphological structures and emission signatures which agree well with observed X-ray luminosity and temperature as well as with the limb brightening of the radially projected X-ray intensity profile (for details see Freyer *et al.* 2006).

9) Connected to 1) the higher compression of the pushed HII region leads to a stronger recombination and, by this, a higher energy loss by means of collisionaly excited line emission. This means that the energy transfer efficiencies ϵ's for both radiative as well as kinetic energies remain much lower than analytically derived (more than one order of magnitude) and amount to only a few per mil (Hensler 2007). There is almost no dependence on the stellar mass what contrasts expectations because the energy impact by Lyman continuum photons and by wind luminosity increase with stellar mass. Vice versa, since the gas compression is stronger by a more energetic wind also the energy loss by radiation is more efficient.

3. Caveats and Required Developments for the Art of Modelling in the 21st Century

Nonetheless, words of caution and unfortunately of discouragement have to be expressed here with respect to various aspects:

At first, the stellar evolutionary models are not yet unique but depend on the authors. In order to get a quantifiable comparison of the models by García-Segura *et al.* (1996a, 1996b) with our 2D radiation-hydrodynamical simulations (Freyer *et al.* 2003, 2006) for the 35 and 60 M$_\odot$ studies we used the same stellar parameters. Since no stellar parameters were available from the same group for the 15 and 85 M$_\odot$ models we had to make use of the Geneva models (Schaller *et al.* 1992). A comparison of the age-dependent parameters between the Langer and the Geneva 60 M$_\odot$ models (fig. 3) has revealed enormous differences in the energetics by almost one order of magnitude as well as that the Wolf-Rayet and Luminous Blue Variable stages occur in contrary sequence, respectively (Kroeger 2006).

Secondly, as presented by George Meynet (this conference) the role of stellar rotation was until recently totally underestimated, mainly, because of a lack of model insights. In principle, the radiation-driven stellar wind is smaller at the equator of a rotating star with respect to the poles due to van Zeippel's theorem, while in contrast the centrifugal-driven amount should increase. In addition, the radial and azimuthal redistribution of fresh fuel and already burned material in the stellar interior is uncertain as long as at least 2D stellar evolutionary models are lacking.

Hirschi *et al.* (2004, 2005) showed that taking stellar rotation into account in the Geneva stellar evolution code increases the yields for heavy elements by a factor of

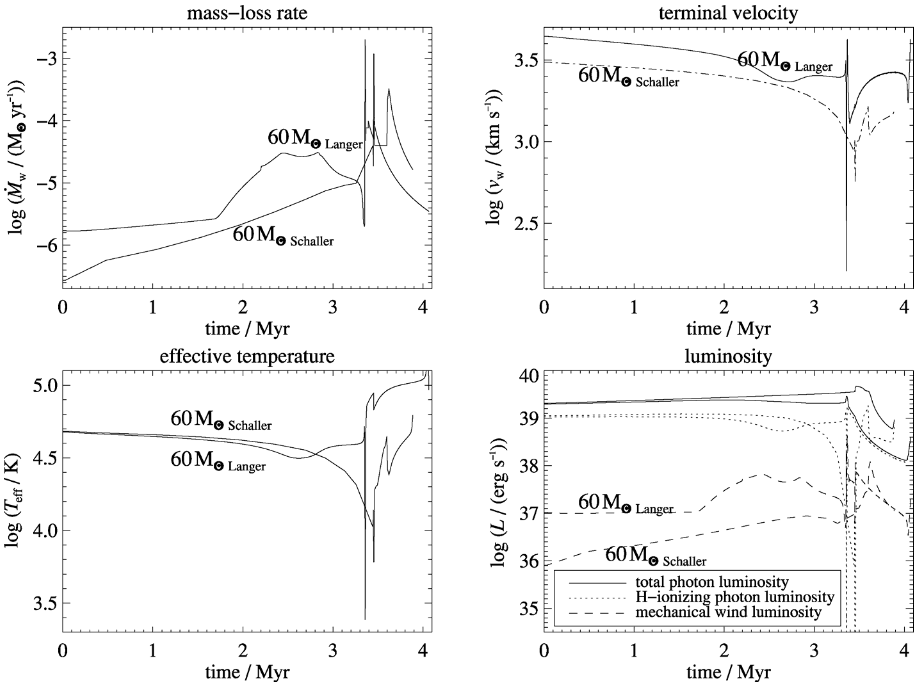

Figure 3. Comparison of the 60 $\mathrm{M}_{\odot}$ star parameters from evolutionary models by Langer García-Segura *et al.* 1996a and Schaller *et al.* (1992) (see line notation). Notice that in the lower-left figure total luminosity by Schaller *et al.* is represented by the upper curve. (from Kroeger 2006)

$1.5 - 2.5$ for stars between 15 and 30 $\mathrm{M}_{\odot}$. For the more massive stars rotation raises the yields of ^{4}He and other H-burning products like ^{14}N, but the yields of He-burning products like ^{12}C are smaller. Additionally, for stars with $M \gtrsim 60\ \mathrm{M}_{\odot}$, the evolution differs from that of non-rotating stars by the following manner: Rotating stars enter the WR regime already in the course of their main-sequence. Nevertheless, the WR phase has to be treated in the context of fully self-consistent evolutionary models with meridional circulations.

Already in non-rotating models for metallicities less than solar two effects reduce the heavy element release by WR stars: First, the lower the metallicity the more massive a star has to be to evolve through the WR stages. Therefore, the number of WR stars decreases with decreasing metallicity. Schaller *et al.* (1992) found that with metallicity $Z = 0.001$ the minimal initial H-ZAMS mass for a WR star is $> 80\ \mathrm{M}_{\odot}$. At $Z = 0.02$ the minimal initial mass is $> 25\ \mathrm{M}_{\odot}$. Second, the lower the metallicity the shorter are the WR lifetimes, and not all WR stages are reached. At solar metallicity WR stars enter all three WR stages (WNL, WNE, WC), whereas at $Z = 0.001$ only the WNL phase is reached (Schaller *et al.* 1992). The WR lifetime of an 85 $\mathrm{M}_{\odot}$ star, e.g., is $t_{WR} = 0.204 \times 10^{5}$ yr at $Z = 0.001$ and $t_{WR} = 4.008 \times 10^{5}$ yr at $Z = 0.02$ (Schaller *et al.* 1992).

At third, the quiescent SF as a self-regulated process is a widely accepted concept. The stellar feedback can adapt both signs, positive as a triggering mechanism in a self-propagating manner like in superbubble shells vs. negative as self-regulation. Primarily the correlation between the surface density of disk galaxies' HI gas and the vertically integrated SF rate derived from the Hα flux (Kennicutt 1998) serves as the best proof of a SF self-regulation. Such self-regulation is a plausible process due to the energy release mainly by massive stars as demonstrated by Köppen *et al.* (1995), whereas its level of the SF rate is determined by the deposit of the released energy to the ISM. While the windless i.e. purely photo-ionizing models and analytical results e.g. by Lasker (1967) reach about one percent for the energy transfer efficiency ϵ (see e.g. Freyer *et al.* 2003), the radiation-dirven + wind-blown models by us fall short by more than one order of magnitude even to below 0.1 percent.

As a further aspect, the two-dimensionality of the numerical treatment must be overcome to 3D in order to allow for a proper description of turbulent eddies and small-scale inhomogeneities. In addition this requires also a change in the spatial resolution of the numerical code: the nested-grid strategy has to be changed to a flexible mesh adaptivity (adaptive mesh refinement: AMR). This approach was already developed by Rijkhorst *et al.* (2006) for the publicly available and widely used AMR code FLASH.

Last but not least, massive stars are born in OB associations with separations such low that their wind-driven HII regions should overlap. For observations these colliding SWBs should produce a higher X-ray luminosity than expected from individual massive SWBs. Recent X-ray observations of hot gas even in the Orion complex (Guedel *et al.* (2007)) support this expectation. The modelling of such star-forming regions is highly complex, necessarily 3D, and requires inherently AMR. Only those explorations will enable us to answer the problem of timescales and energetics necessary for the observed gas evacuation of star clusters (Baumgardt & Kroupa 2008).

As one recognizes we are still in the natal phase of understanding and modelling structure and evolution of massive stars and their influence on the ambient ISM. Much before the end of this 21^{st} century revolutionary observational results and numerical models will enlighten our present-day ignorance.

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Discussion

LANGER: To what extent do you need many different stellar evolution input models for your bubble models; it looked as if the energy transfer efficiencies in the 4 very different cases you tried were very similar.

HENSLER: That is correct. From our models the energy transfer efficiency seems not to depend on the stellar mass although the power of radiative and wind releases do. This can be understood, because the stronger stellar wind at larger masses lead to stronger compression of surrounding gas, and, by this, to stronger cooling by collisional excitated emission. Different evolutionary models, however, affect other issues. We explored e.g. that differences in the kinetic energies of the stellar wind (see fig. 3) change the dynamical structure of the 60 $M_\odot$ model in the sense that the fingure-like structures (see Freyer *et al.* 2003) are less pronounced for Schaller *et al.* (2002) parameters. In addition, differences in stellar evolutionary models also change the LBV-WR sequence and the element release and they have stronger effects on the chemical evolution and the self-enrichment of HII regions.