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Review

Moving inhomogeneous envelopes of stars

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ABSTRACT

Massive stars are extremely luminous and drive strong winds, blowing a large part of their matter into the galactic environment before they finally explode as a supernova. Quantitative knowledge of massive star feedback is required to understand our Universe as we see it. Traditionally, massive stars have been studied under the assumption that their winds are homogeneous and stationary, largely relying on the Sobolev approximation. However, observations with the newest instruments, together with progress in model calculations, ultimately dictate a cardinal change of this paradigm: stellar winds are highly inhomogeneous. Hence, we are now advancing to a new stage in our understanding of stellar winds. Using the foundations laid by V.V. Sobolev and his school, we now update and further develop the stellar spectral analysis techniques. New sophisticated 3-D models of radiation transfer in inhomogeneous expanding media elucidate the physics of stellar winds and improve classical empiric mass-loss rate diagnostics. Applications of these new techniques to multiwavelength observations of massive stars yield consistent and robust stellar wind parameters.

Contents

1. Introduction 101
2. Empirical diagnostics of mass-loss 101
    2.1. Resonance lines 101
    2.2. Stellar atmosphere model PoWR 102
    2.3. Optically thin recombination lines: Hα. 102
3. Stellar wind clumping 102
4. P V AND THE DISCORDANCE OF MASS-LOSS RATES DIAGNOSTICS 103
5. Microclumping. 103
6. Macroclumping 104
    6.1. Gray opacity. 104
    6.2. Continuum opacity 104
    6.3. Line opacity 106

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7. Radiative transfer using realistic 3-D Monte-Carlo wind models 107
8. What are the true empirical mass-loss rates of massive stars? 109
References 110

1. Introduction

The initial mass of a star on the zero-age main sequence largely determines its fate. Stars born with masses exceeding $\sim 10\,M_\odot$ end their lives in a core-collapse event, e.g. a supernova (SN) explosion, and leave a neutron star or a black hole as remnant [40]. Such massive stars are luminous, with bolometric luminosities exceeding $L_{\rm bol} \gtrsim 10^4\,L_\odot$. On the main sequence, massive stars have spectral types earlier than B2V. These bright stars live very fast, the most massive of them die within just ~ 10 Myr. Albeit we see many massive stars by naked eye in the night sky (e.g. the Orion Belt consists of massive stars), these stars are actually very rare and constitute only $\sim 0.4\%$ of all stars in our Milky Way.

Despite their small number, massive stars have enormous impact on the galactic ecology. Their strong ionizing radiation and stellar winds, as well as their final demise in SN explosions, largely determine the physical conditions in the interstellar medium (ISM) and influence the formation of new generations of stars and planets. Thus, massive stars are among the key players in the cosmic evolution.

The atmospheres of hot massive stars are usually transparent in the continuum but opaque in many spectral lines. Because the stars are hot, a large fraction of their bolometric luminosity is emitted at ultraviolet (UV) wavelengths. The radiation leaves the star in radial direction. A photon in a spectral line ν_0 may be absorbed by an ion and re-emitted in any direction, transferring its momentum to the ion. The ion would be accelerated. Because of the Doppler effect, the wavelength of the spectral line will shift, and will be able to scatter light with wavelengths other than ν_0. Hence, the photons within a broad wavelength range will be "swept up", by the same spectral line. The Coulomb coupling between particles ensures the collective motion, and a stellar wind develops. Such radiatively driven stellar winds [12, CAK] are ubiquitous in hot non-degenerate stars.

The amount of mass removed from the star by its wind is determined by the mass-loss rate, $\dot{M}$. Theory predicts that for O-stars the mass-loss rates are in the range $\dot{M}_{\rm CAK} \approx (10^{-7}-10^{-5})\ M_\odot\ {\rm yr}^{-1}$ depending on the fundamental stellar parameters $T_{\rm eff}$, $L_{\rm bol}$, and $\log g$ [87,116]. Hence, during stellar life time, a significant fraction of mass is removed by the stellar wind. Thus, the mass-loss rate is a crucial factor of stellar evolution.

2. Empirical diagnostics of mass-loss

To check and validate theoretical predictions, robust empirical estimators of mass-loss rates shall be employed. These diagnostics usually rely on a spectroscopic analysis. Below we briefly consider some common examples of such analyses.

2.1. Resonance lines

For hot stars, the resonance lines of most important ions are located in the UV part of the electromagnetic spectrum. When formed in a wind, these lines show P Cygni-type profiles (see e.g. [53]).

The resonance line of an ion is produced by photon scattering, therefore the line strength is a linear function of the density, which is related to the expansion velocity $v(r)$ by the continuity equation

$$\rho(r) = \frac{\dot{M}}{4\pi\ v(r) r^2}. \qquad (1)$$

The radial dependence of the wind velocity is usually prescribed by the "β-velocity law", $v(r) = v_\infty (1-1/r)^\beta$.

The line strength, the terminal wind velocity, v_∞, and the parameter β can be measured from the observed spectral line. Hence, in principle, by modeling a resonance line of an ion, the product of its ionization fraction and mass-loss rate could be empirically obtained. To model a spectral line, an adequate theory of line formation is required.

Line formation in a moving stellar envelope was studied by Sobolev [106]. It was shown that if the thermal motions in the atmosphere can be neglected compared to the macroscopic velocity, the radiative transfer problem can be significantly simplified (see review by Grinin [28]). This is now known as the *Sobolev approximation.*

The Sobolev approximation is well justified in stellar winds, and was extensively used for their analysis. At least two different solution techniques that relied on the Sobolev approximation were developed [11,60]. An atlas of theoretical P Cygni profiles was computed [13] and used to estimate mass-loss rates from the first available UV spectra of O stars (e.g. [14]).

With time the limitations of the Sobolev approximation became clear. For instance, within Doppler-shifts of a few tens of kilometers per second around the line center, the profiles computed in Sobolev approximation are inaccurate, especially because of the high turbulence present in stellar winds [33] and/or non-monotonic wind velocities [61,62].

These shortcomings were overcome by Hamann [33], who compared line profiles computed with a comoving frame approach [72,32] with those computed using Sobolev approximation. It was shown that the error in the Sobolev approximation arises mainly from the treatment of the formal integral and, to a lesser extent, from the approximated source function. Based on this suggestions, Lamers [54] developed the "Sobolev with Exact Integration" (SEI) method. In this method, the source function is calculated in the Sobolev approximation, but the equation of transfer is integrated exactly. As a result, the model provides significantly better fits to the observed lines [29], consequently allowing for more precise mass-loss rate determinations [55].