A Short Review of Radiatively Driven Stellar Winds for Luminous Stars

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Key concepts: *Stellar winds, mass loss rate, terminal flow speed, line-driven radiation, Monte-Carlo method, Eddington parameter, Wolf-Rayet Stars*

1 Introduction

Stellar winds are the continuous outflow of protons, electrons, or heavy elements at supersonic speeds from the outer layers of stars [6]. Projecting from stars indefinitely, stellar winds are a source of mass, energy, and momentum to the interstellar medium [1]. Understanding stellar winds requires studying the balances of hydrostatic equilibrium, where the inward force of gravity battles (and loses to) outward forces of pressure and radiation. This interaction helps astronomers determine two important parameters to study stellar winds: mass loss rate and terminal flow speed. Mass loss rate ($\dot{M}$), as the name suggests, the is rate at which stars expel theirs masses in the form of these winds. Terminal flow speed (v_∞) is the maximum velocity the particles will experience at large distances from the star. Typically, terminal flow speed is proportional to the escape velocity of the star [6]. Stellar wind strength depends heavily on the luminosity of the star, and thus can be split into three categories: (1) Low mass stars, (2) cool giants and supergiants, and (3) hot, massive, and luminous stars.

Most stars, like our Sun, don't have high enough luminosities to produce notable stellar winds like the ones to be discussed later. This makes their observation difficult. Nonetheless, these low-mass stars generate their winds via the gas-pressure expansion of the corona [8]. Because their winds are so weak, they will only expel about .01% of their initial by the end of their lives [6].

"Cool" giants and supergiants refer to massive stars that don't have the characteristic high luminosity that certain giants such as Wolf-Rayet or Luminous Blue Variable (LBV) stars have. These stars have a weaker gravitational pull on their surfaces and thus experience a higher mass loss rate, though with a slower terminal flow speed [6]. At the end of the star's life, pulsations increase mass loss rate until the star is below the Chandrasekhar limit of 1.4 $M_\odot$. Note Chandrasekhar mass is largest mass a star can have to remain a white dwarf. Larger stars (8-40$M_\odot$) will continue losing mass at a rapid rate through the hypergiant phase until they become supernovae[6].

Hot, massive, and luminous stars release their stellar winds due to radiation, and thus will be the main focus of this paper. These stars, which are typically of spectral type O and B, burn extremely hot, with surface temperatures between 10,000 and 100,000K. At these temperatures, the momentum of the light scattering off particles in the stellar atmosphere is enough to overcome the force of gravity and drive winds

[6]. Among hot, massive, and luminous stars are Luminous Blue Variables (LBV) and Wolf-Rayet (WR) stars, each of which having their own properties that describe and drive their wind.

2 Mass, Momentum, and the Monte-Carlo Method

In the standard model case (see section 3.1), the mass loss rate ($\dot{M}$) can be found from the equation of continuity.

$$\dot{M} = 4\pi r^2 \rho(r) v(r) = constant \tag{1}$$

Here, ρ is the density of the star, and v is the velocity of the wind. It then follows that momentum is

$$v\frac{dv}{dr} = -\frac{GM}{r^2} - \frac{1}{\rho}\frac{dP}{dr} + g_{rad} \tag{2}$$

where g_{rad} is the wind acceleration due to radiation and P is pressure as a function of radius. When g_{rad} exceeds gravity in the outer layers of the star, winds appear.

The Monte-Carlo method can be used to observationally determine the rate of mass loss. The Monte-Carlo method involves using repeating random sampling to obtain numerical results [4]. Vink et al. used the relation

$$\Delta E_{tot} = \frac{1}{2}\dot{M}(v_\infty^2 + v_{esc}^2) \tag{3}$$

to develop a mass loss rate formula for O and B class stars. Using linear regression and the Monte-Carlo approach, they determined:

$$\dot{M} \propto L^{2.2} M^{-1.3} T_{eff} \left(\frac{v_\infty}{v_{esc}}\right)^2 \tag{4}$$

Here, it is shown that luminosity has a higher effect on mass loss rate than mass itself [10].

3 Line-Driven Winds of Hot Stars

The magnitude of a star's mass loss rate can cause certain spectral bands to become opaque in the atmosphere. Radiative processes in these atmospheres include free electron (or Thompson) scattering, free-free absorption/emission by electrons near ions, bound-free absorption, free-bound emission, and bound-bound (line) scattering/absorption/emission by atoms or molecules [5]. Among these, bound-bound (line) driven radiation is the leading cause of mass outflow. Both the properties of line radiation and the environment in the atmospheres of hot stars drastically magnify the outflow of winds [7].

3.1 Standard Model

The standard model provides the most seamless route to understanding radiatively driven stellar winds. Under the standard model we assume a one-dimensional environment where the wind is stationary, homogeneous (no shocks or clumps), and spherically symmetric. These conditions hold as long as rotation and magnetic fields are neglected.

3.1.1 Standard Model for Radiative Line Acceleration

Of all atomic transitions light experiences in the atmospheres of stars, line scattering produces by far the most acceleration. Line scattering—also known as bound-bound emission—occurs when an electron moves from one energy state to another in an atom or ion, releasing light as discrete spectral lines in the process [3]. Stellar winds are generally rich in He, N, C, and O, and thus emission lines come from the ionization stages of these elements [6]. Line scattering is much more prominent in driving winds because of its resonant nature and because the Doppler effect allows photons and matter to interact at many more frequencies (See section 3.2).

Given a single spectral line of frequency ν and optical depth τ being illuminated by photons, the wind acceleration caused by that line can be approximated with Sobolev Theory as long as opacity and the velocity gradient do not change significantly over a Sobolev length denoted as $L_{Sob} = \frac{v_{th}}{\frac{dv}{dr}}$, where $v_{th}$is the thermal velocity of the particles (see section 3.2 for formula) [9]. Using Sobolev Theory, the acceleration of winds at a single spectral line is:

$$g^{line}_{rad,i} = \frac{L_\nu}{4\pi r^2 c^2}\frac{dv}{dr}\frac{1}{\rho}(1 - e^{-\tau}) \tag{5}$$

Here, L_ν is the luminosity of the star at the spectral line frequency and τ is the radial line optical depth. Repeating this process for all lines contributing to wind acceleration is a long and arduous process, however, one can sum over all contributing line using the CAK model by Castor et al. The CAK model defines line-strength distribution functions, which describe the dependence of the number of lines at their frequency and line strengths [1].

3.2 Doppler Shift and Resonance

Doppler shift in the case of radiatively driven stellar winds is a change in frequency/wavelength of light due to the motion of ions in stellar atmospheres. The motion of these ions is produced thermally and is described by:

$$v_{th} = \sqrt{\frac{kT}{m_i}} \tag{6}$$

where k is the Boltzmann constant, T is temperature of the star's atmosphere, and m_i

is the atomic mass of the ion. This random thermal motion widens the "width" of line radiation (See section 3.1.1), thus causing stronger radiative acceleration. The broadened line is denoted as:

$$\Delta\lambda = \lambda_0 \frac{v_{th}}{c} \tag{7}$$

Note with (6) and (7) that the higher the temperature ($L \propto T^4$), the more thermal velocity, therefore the wider the line width, and therefore the higher acceleration/stronger wind.

Another phenomena that amplifies the strength of line emissions as a source of acceleration is resonances. Resonances occur when the surrounding environment of an object vibrates at the same frequency as that object. In this case, spectral lines resonate with continuum photons from the star/stellar atmosphere. This greatly increases the probability of specific transitions occurring between two energy levels (jargon: increased cross section) in line emission [2].

4 Special Cases

Previous sections focused on O and B stars with high luminosities, but even these spectral types have stars that push the limits of radiative stellar winds. The most extreme stars approach the Eddington limit, or the maximum luminosities stars can have before their radiative forces blow off the outer layers [7]. The Eddington limit is reached when the Eddington parameter (Γ_e) is 1.

$$\Gamma_e = \frac{\kappa_e L}{4\pi G M c} \tag{8}$$

The Monte-Carlo method described in section 2 is correct for stars that are not near the Eddington limit ($\Gamma_e < .5$), but must be updated for more extreme stars such as Wolf-Rayet stars, Luminous Blue Variables, or stars with initial masses $>100 M_\odot$. Recalling equation (4) and using the Monte-Carlo approach, mass loss rate become proportional to $M^{-1.8}$ instead of the normal $M^{-1.3}$ for O and B spectral type stars. Therefore, as these extreme stars start to lose mass, the rate of mass loss increases, and a positive feedback loop is created.

4.1 Wolf-Rayet Stars

Wolf-Rayet (WR) stars are characterized to be large, luminous, and evolved—having a curious deficiency in hydrogen. Typically they burn helium and other heavier elements such as carbon, nitrogen, and oxygen in their cores [7]. The mass loss rate of WR stars is so high that the "photosphere" lies within the wind itself. This makes studying their radiation more difficult as their opacities are so high [6]. Nonetheless, there appears to be a link between the metallicities of WR stars and the strength of their radiatively-driven winds, where the higher the metallicity, the stronger the winds [7].

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