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Modeling X-ray emission line profiles from massive star winds – A review

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Abstract

The *Chandra* and *XMM-Newton* X-ray telescopes have led to numerous advances in the study and understanding of astrophysical X-ray sources. Particularly important has been the much increased spectral resolution of modern X-ray instrumentation. Wind-broadened emission lines have been spectroscopically resolved for many massive stars. This contribution reviews approaches to the modeling of X-ray emission line profile shapes from single stars, including smooth winds, winds with clumping, optically thin versus thick lines, and the effect of a radius-dependent photoabsorption coefficient.

Keywords: X-rays; Massive stars; Stellar winds; Line profile modeling; Stellar mass loss

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1. Introduction

Massive stars have long been known to be X-ray sources (Cassinelli and Olson, 1979; Harnden et al., 1979; Long and White, 1980; Cassinelli et al., 1981). Early X-ray studies of massive stars (i.e., non-degenerate OB stars) were limited to pass-band fluxes or low-resolution spectra (e.g., Berghöfer et al., 1997). Recent instrumentation with *Chandra* and *XMM-Newton* have since permitted observations of resolved broad-emission lines from several massive stars, which have represented a major forward step in studies of the X-ray properties of massive stars (Kahn et al., 2001, e.g.,; Waldron et al., 2001; Cassinelli et al., 2001; Skinner et al., 2001; Oskinova et al., 2006; Waldron and Cassinelli, 2007; Güdel and Nazé, 2009; Oskinova et al., 2012; Leutenegger et al., 2013; Cohen et al., 2014a,b).

Winds of massive stars typically have wind terminal speeds of order 10^3 km s^{-1}. Shocks involving speeds at this level easily produce peak temperatures at several MK. At such temperatures a thermal plasma will cool primarily via emission lines (Cox and Tucker, 1969; Raymond and Smith, 1977). There are many scenarios that can lead to strong shocks in massive star winds. Some massive stars are in binary systems, and the winds of the two stars can collide to produce relatively hard and luminous X-ray emission. Another scenario involves stellar magnetism. In some massive stars, the stellar magnetic field is strong enough to deflect or even channel a portion of the wind flow. The channeling can lead to head-on collisions of counter-moving streams of plasma, leading to strong shocks and a significant X-ray luminosity. The calculation of line profile shapes for colliding wind binaries and magnetically channeled winds is not reviewed in this contribution. A review of X-ray emission from colliding winds appears in Rauw et al. (2015); and the influence of stellar magnetism for X-ray emission from massive stars is reviewed in ud-Doula and Nazé (2015) and Nazé (2014).

This review focuses on approaches for modeling X-ray emission line profile shapes for single massive stars.

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Modeling of the line shape is important for extracting information about the source, such as the mass-loss rate of the wind. This paper emphasizes line profile calculations; results derived from model fitting to observed X-ray spectra of massive stars are reviewed by Oskinova (2016).

For single massive stars, the leading culprit for the production of multi-million degree gas is found in the same mechanism that propels their fast winds, namely the line-driving force (Lucy and Solomon, 1970; Castor et al., 1975; Pauldrach et al., 1986; Müller and Vink, 2008). This force is subject to the line deshadowing instability (LDI) that results in the formation of wind shocks (Milne, 1926; Lucy and White, 1980; Owocki et al., 1988). As a result, a highly structured, supersonic wind flow develops (e.g., Dessart and Owocki, 2003), with a distribution of wind shocks capable of emitting X-rays at observed temperatures (Feldmeier et al., 1997a). Modeling of the line shapes has grown more complex to match the observations. This is exciting because the data have pushed the line modeling to include greater physical realism.

Section 2 provides an overview of the evolution of X-ray emission line profile calculations. Section 2.1 begins with a description of the emissive process for the production of X-rays from single massive-star winds, followed by a description of the properties of spherical stellar winds in Section 2.2. Then 2.3 details expressions to calculate line profile shapes for smooth winds. A review of the exospheric approximation is given in Section 2.4 to illustrate basic scalings, followed by 2.5 that compares effects for thin versus thick lines. The special case of a constant expansion wind is handled in 2.6. The topic of clumping is covered in 2.7. Using a linear (or, homologous) velocity law, a selection of illustrative profile calculations are provided in Section 2.8. A summary and conclusions are given in Section 3. Appendix A details the derivation of profile shapes for constant spherical expansion with a power-law volume filling factor. Appendix B presents a derivation for the photoabsorbing optical depth in the case that the absorbing coefficient is a power law in the wind velocity.

2. Modeling of stellar wind X-ray emission line profiles

2.1. The line emissivity

X-ray line profile shape modeling begins by specifying the source geometry and the emissivity process. For geometry the winds are assumed to be spherically symmetric in time average. This assumption can accommodate the inclusion of stochastic structure in the wind, normally referred to as “clumping”.

The X-ray emission from single and non-magnetic massive star winds is normally attributed to embedded wind shocks. This “hot plasma” component at millions of Kelvin is a thermal plasma that emits a spectrum dominated by lines of highly ionized metals (e.g., Cox and Tucker, 1969; Raymond and Smith, 1977). The bulk of the line photons arises from collisional excitation followed by radiative decay. Consequently, the line emissivity is a density-squared process. In addition, wind shocks are expected to display a range of temperatures as the post-shock gas undergoes cooling (e.g., Feldmeier et al., 1997b; Cassinelli et al., 2008; Krtička et al., 2009; Gayley et al., 2014).

The volume emissivity for a line is denoted as j_l [erg s^{-1} cm^{-3}] and is given by

$$j_l(T, E_l) = \Lambda_l(T, E_l)\,(n_{\rm i}\, n_{\rm e})_X, \tag{1}$$

where the “l” subscript identifies a particular line, $\Lambda_l(T, E_l)$ [erg s^{-1} cm^{-3}] is the cooling function for a line at energy E_l, and $n_{\rm i}$ and $n_{\rm e}$ are number densities for the ions and electrons in the X-ray emitting gas (hence the “X” subscript). Here Λ_l is frequency (or energy, or wavelength) integrated over the line profile; its value depends on the temperature, T, of the plasma. Note that another form of the emissivity is the volume emissivity per unit solid angle, η_l. For isotropic emission one has that $j_l = 4\pi\eta_l$.

For an optically thin plasma in which there is no line transfer and no photoabsorption of the X-rays, the line luminosity generated in a differential volume element is

$$dL_l(T, E_l) = j_l(T, E_l)\,dV \tag{2}$$

$$= \Lambda_l(T, E_l)\,(n_{\rm i}\, n_{\rm e})_X\,dV \tag{3}$$

$$= \Lambda_l(T, E_l)\,dEM_X, \tag{4}$$

where EM_X is the emission measure of the X-ray emitting gas.

The total luminosity generated from a multi-temperature plasma in a particular line becomes

$$L_l = \int \Lambda_l(T, E_l)\,\frac{dEM_X}{dT}\,dT, \tag{5}$$

where dEM_X/dT signifies the differential emission measure and represents the relative amounts of plasma at different temperatures.

Although Eq. (5) is correct, the integration over differential emission measure is not normally how line profile shapes are modeled. Instead, most approaches for the line modeling tend to start with Eq. (3). The properties of the stellar wind density and temperature distribution are specified. Taking account of the wind velocity distribution, the contribution by a differential volume element to the line profile depends on the volume’s Doppler shift with respect to the observer.

2.2. The stellar wind model

For a spherically symmetric wind, the density of the gas, ρ, is determined by the continuity equation

$$\rho(r) = \frac{\dot{M}}{4\pi r^2\, v(r)}, \tag{6}$$

where $\dot{M}$ is the mass-loss rate, r is the radius in the wind, and $v(r)$ is the wind speed. The wind speed starts with a low initial value of v_0 at the wind base, that is frequently