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A unified heuristic X-ray production model for thick and thin winds from single nonmagnetic hot stars

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Abstract

Observations of X-rays from WR6 and other dense winds require the presence of mechanisms that can produce hot gas at much larger radii than in lower density OB winds. But does this require some new mechanism in Wolf–Rayet winds, or could it simply be that the same hot-gas production is made more visible by denser winds? This article explores the latter perspective, and suggests a unified approach to the X-ray heating in all single nonmagnetic hot stars, as a kind of benchmark for observational testing. The results produce an X-ray generation efficiency that peaks as winds just become optically thick to X-ray reabsorption, but can still maintain detectable efficiencies at the large radii necessary in optically thick WR winds. A key element of the model is that fast terminal speeds serve to rapidly advect the gas being shocked out to large radii where some of the X-ray emission can emerge, even as X-rays emitted deeper down are copiously reabsorbed. An essential requirement is that the turbulence lengthscale increases with the wind acceleration lengthscale, as the latter is seen to be stretched out in Wolf–Rayet winds. Radiative efficiency is maintained at large radii by the high densities in the wind, allowing X-ray heating in an extended spatial "tail" of the normal OB-type emission to become observable. Hence in this scenario, the observation of dense winds serves as a complementary means of spatially resolving the nature of X-ray heating in nonmagnetic single hot-star winds.

Keywords: Methods: analytical; X-rays; Stars: mass loss; Stars: winds; Outflows; Stars: Wolf–Rayet

1. Introduction

Recent X-ray observations (Oskinova et al., 2012; Huenemoerder et al., 2015) of WR6 have demonstrated that the sources of X-rays in this wind are well outside the acceleration zone where the line-driven instability is expected to be active (Gayley and Owocki, 1995). A question that can be asked is whether or not this requires a fundamentally different process for generating these X-rays, than is active in less dense winds like those from O stars. Models of WR6 suggest that its wind is highly optically thick across the X-ray domain (Hamann et al., 2006), so we would not expect to be able to see X-rays from the acceleration zone. Thus we may find it surprising that WR6 is an X-ray source at all, and we may wonder if it possible for a similar mechanism that is responsible for X-rays in single nonmagnetic OB stars to also operate in WR winds, or if that is precluded by the observations. The similar mechanism would involve compressible turbulence stirred up in the acceleration zone by the line-driven instability (e.g., Dessart and Owocki, 2005a; Krticka et al., 2009) or some other instability inducing local variations in windspeed. The resulting dispersion in the windspeed would then need to survive to large enough radii to be responsible for strong shocks there.

Thus, the approach taken here is to examine general properties of X-ray generation in thick winds from the perspective that thick-wind X-ray generation is simply the

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extension of similar processes in thin winds, but where the thicker winds reveal a different aspect of those processes due to their higher X-ray emissivity at larger radii, coupled with copious X-ray reabsorption at smaller radii. The purpose is to explore the plausibility of unifying the mechanisms in nonmagnetic single stars throughout OB and Wolf–Rayet stars into a single idealized picture, and test that picture for any significant deviations from observations. As will be seen below, no clear contradictions with observations are seen using this picture if certain requirements are met, and several potentially elucidating features of thick winds, in contrast with thin ones, are encountered.

2. Self-similar shock structure

The approach here for unifying OB and WR wind X-ray generation is to assume that all these winds exhibit at radii well outside their acceleration zones a kind of two-phase structure, with clumpy slow wind moving at the prevailing terminal speed, and faster low-density streams filling the space between the clumps. This general type of structure, initiated by the line-driven instability, can be seen in one dimension in simulations like Feldmeier et al. (1997) and Runacres and Owocki (2002), and in higher dimensions in Dessart and Owocki (2005a). The way these winds will be unified here into a scale-free picture is by rescaling the radius by assuming the existence of a correlation length L between the fast streams and slow clumps, embedded in the frame of the wind, such that the average time for fast wind to run into slow clumps is $t_s \cong L/\Delta v$, where Δv is the characteristic speed excess in the fast streams. The L distance scale parameter is the fundamental adjustable parameter in this model, and although heuristic at this point, it is intended to express a physical meaning, rather than represent a purely arbitrary parametrization of some kind of hot-gas filling factor.

Another advantage of the physical nature of the length L is that it also corresponds to what has been called the porosity length in more formal clumping models (e.g., Sundqvist et al., 2012). It is expected here that this length may be roughly characterized by the size of the acceleration region in which the instability is active, on the grounds that the length scale on which bulk kinetic energy is pumped into the wind may also characterize the length scale on which turbulent energy is added by the instability. Thus we might expect $L \sim \beta R_*$, for β an order-unity parameter that controls the size of the acceleration region.

For OB stars, $\beta \sim 1$ is common, but there is evidence that WR winds have larger β, such that βR_* is in the range 10–20 $R_{/odot}$ (Lepine and Moffat, 1999; Dessart and Owocki, 2005b). This implies large values of $\beta \lesssim 10$ if $R_* \sim 2 - -3R_\odot$, as inferred for WN4 stars like EZ CMa (Hamann et al., 2006). The details of the appropriate value of L will be left to future analysis, though it will be important for this model that it can be many stellar radii in WR winds, perhaps traced to their extended wind acceleration lengths. The approach here is to assume the L parameter has been supplied, and then define a rescaled radius by $z = r/L$, such that dz counts the fraction of a porosity length, which is the natural scale for tracking the shock physics. Even more importantly, the probability of the fast gas passing into a shock in scaled distance dz is dz/z_s, where $z_s = v_\infty/\Delta v$ because the probability per time is $\Delta v/L$ by the definition of L, and the advected distance per time is dr/v_∞ outside the acceleration region (which is the domain of the shock dissipation under consideration). Since it is assumed that the input shock structute initiates over the acceleration zone, the model used here assumes the wind is already clumped and already at v_∞ throughout the domain where the shock dissipation is being tracked.

The assumption of a self-similar shock structure is then imposed by the expectation that at any scaled radius z, the mass fraction involved in fast streams is a universal function $y(z)$, which thus obeys the simple probabilistic relation

$$\frac{dy}{dz} = -\frac{y(z)}{z_s}. \quad (1)$$

This admits the simple solution

$$y(z) \propto e^{-z/z_s}, \quad (2)$$

in analogy to the well-known solution to the radiative transfer equation, where z_s is the "mean free path" in r/L units for shocking the fast streams. The range of the fast gas, for given Δv, is then described by $z \sim z_s$, which corresponds to the physical distance that the turbulent gas is advected in the time it takes to "catch up with" its clumpy slower targets over the distance L in the clumpy wind frame. Higher L, or higher v_∞, will tend to extend this advected distance, allowing hot gas to be created at potentially large enough radii to emerge through the photosphere of X-ray reabsorption.

3. The emergent X-rays

The goal is to use the fast-gas fraction to infer the shock rate, and then the emergent X-ray flux, by noting that the emergent X-ray flux per unit radius, dL_x/dr, must obey the proportionality

$$\frac{dL_x}{dr} \propto y(z)\frac{\Delta v}{v_\infty L} e^{-\bar{\tau}_x} F_{ad} F_{mix}, \quad (3)$$

where

$$e^{-\bar{\tau}_x} = \frac{1}{2}\int_0^\pi d\theta \sin\theta \; e^{-z_1\theta/z\sin\theta} \quad (4)$$

accounts for X-ray reabsorption (MacFarlane et al., 1991) given that z_1 is the z value where the radial optical depth is unity, and F_{ad} and F_{mix} account for lost X-rays due to adiabatic cooling and mixing of hot and cool gas, respectively. We now turn to an estimation of these correction factors.