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Abstract. We present a practical, efficient semi-analytic formalism for computing steady-state X-ray emission from radiative shocks from colliding stellar winds in relatively close (orbital period up to order tens of days), massive-star, binary systems. Our simplified approach idealizes the individual wind flows as smooth and steady, ignoring the intrinsic instabilities and associated structure thought to occur in such flows. By also suppressing thin-shell instabilities for wind-collision radiative shocks, our steady-state approach avoids the extensive structure and mixing that has thus far precluded reliable computation of X-ray emission spectra from time-dependent hydrodynamical simulations of close-binary, wind-collision systems; but in ignoring the unknown physical level of such mixing, the luminosity and hardness of X-ray spectra derived here represent upper limits to what is possible for a given set of wind and binary parameters.

1. Introduction

Massive, hot, luminous stars – those of spectral type OB and WR – have strong, high-speed, radiatively driven stellar winds. In the many binary systems consisting of two massive stars, collision of the individual stellar winds leads to the formation of strong shock fronts, in which the kinetic energy of the high-speed (> 1000 km/s) wind flows is converted into a high-temperature (> 10 MK) gas capable of emitting moderately hard X-rays (> 1 keV). Efforts to develop dynamical simulations of colliding-wind X-ray emission have been quite successful for the adiabatic shocks characteristic of the relatively low densities at interaction fronts of wide-binary systems (Stevens, Blondin, & Pollock 1992, Pittard et al. 2002); but such numerical simulations encounter severe difficulties in resolving the extensive structure of unstable radiative shocks (e.g., Myasnikov, Zhekov, & Belov 1998, Walder & Folini 2000) that occur at the higher interaction-densities of close binaries (Stevens et al. 1992, Pittard 1998).
The principal goal of this paper is to address this latter shortcoming. By applying detailed planar shock emission calculations within simplified, steady-state models for the wind-interaction front geometry, we derive X-ray emission spectra for close-binary systems with a range of wind and stellar parameters. In this relatively short publication we shall focus on describing the basic ideas behind our method (section 2), skipping the mathematical formalism. A more detailed description of the method can be found in Antokhin, Owocki, & Brown (2004). We illustrate the results for a sample close binary model, providing both a full X-ray light curve, as well as detailed spectra at selected orbital phases (section 3). We conclude with a summary of the advantages and limitations of our approach, and outline its potential application for interpreting detailed X-ray observations from close, massive-star binary systems (section 4).

2. The Method

In hydrodynamical simulations of colliding winds in close binaries, the inherent instability of the resulting radiative shocks leads to extensive variability and structure, inducing extensive mixing between hot and cool material. The associated reduction in hot material can substantially reduce the hardness of the associated radiative emission. Unfortunately, the physically appropriate degree of mixing is difficult to predict a priori. Because of numerical diffusion, and the inherently limited resolution of the spatial grid, the level of mixing in simulation models may likely overestimate what occurs in actual colliding-wind systems. Given this uncertainty regarding the importance of mixing, and the computational expense of running numerical simulation models, analyses of observed X-ray spectra from colliding-wind systems have often defaulted to applying generic plasma emission codes assuming one or more discrete temperatures.

Our method aims to provide an intermediate alternative that accounts for the detailed form of the wind collision shock, but within a relatively simple, smooth, steady-state model that ignores any mixing. Under the further idealization that the wind density is high enough to make the shock purely radiative, the model also ignores losses associated with adiabatic expansion of the post-shock gas. By thus assuming that the entire energy dissipated in the shock is radiated away at temperatures ranging up to the immediate post-shock value, the derived spectra should represent an upper limit to the level and hardness of the radiation within the bandpass of orbiting X-ray telescopes like Chandra and XMM. Because of this assumption of thin, radiative shocks, our approach only applies to dense winds in relatively close binary systems.

In addition to this suppression of unresolvable structure and mixing, a key advantage of our approach stems from its separation of the small-scale shock-emission calculation from the model for the large-scale, geometric form of the wind-wind interaction front. In our idealization of laminar, steady, radiative shocks, the post-shock, radiative-cooling layer is presumed to be geometrically thin compared to any competing scale, for example the binary separation. Moreover, the timescale for shock-heated material to cool is likewise presumed to be small compared to the time required for the flow to advect along a substantial arc of the curved front. This justifies neglect of the adiabatic cooling from wind expansion, which would effectively couple the internal evolution of the shock to
the global wind structure. It also implies that nearly all of the incoming kinetic energy from the wind flow normal to the front is locally converted into radiative emission in the post-shock region. This allows an “on-the-spot” treatment of the radiative emission at each location along the front.

In this approach, the contact surface, which separates the distinct material from each wind, and which lies within the interaction front, acts effectively as a fixed barrier or wall that stops the normal component of the incoming wind flow. In the idealization that the interaction region between the initial wind shock and this contact-surface wall is geometrically thin, this incoming wind can moreover be treated as locally planar, i.e. neglecting the global divergence associated with the spherical wind expansion.

In the hot region immediately behind the initial adiabatic shock, the velocity (density) is decreased (increased) by a maximum factor of four (for the assumed case of a monatomic gas with ratio of specific heats $\gamma = 5/3$); but then within a nearly isobaric cooling layer, the gas is gradually slowed to an effective stop as cooled, dense material piles up against the fixed wall. We apply an extensive atomic database to compute the spectral emission and associated cooling, and integrate this throughout the layer from the shock to the wall. The resulting code for computing the cumulative shock emission spectrum constitutes one key component for the study here.

The second component regards the model for the interaction front. The overall geometric form of this front is derived from integration of a first order, ordinary differential equation that accounts for the ram-pressure balance associated with the relative momentum flux of the two winds. This approach builds on previous analyses (see, e.g. Huang & Weigert 1982, Usov 1992, Canto, Raga, & Wilkin 1996), but uses simple “beta” velocity-laws to take into account the possibility that, in such close-binary systems, the wind speeds may have not yet reached their terminal values at the interaction front. In this study we neglect orbital motion and associated inertial forces, as in close binaries with fast stellar winds the deflection of the interaction front in the region producing X-rays is relatively small.

In practice, we first apply our planar shock emission code to tabulate the detailed emitted energy spectrum as a function of just a single parameter representing the shock strength, namely the post-shock temperature (which depends on the square of the normal component of the incoming flow velocity at a given point on the contact surface). The overall level of emission is then adjusted according to the local density. The local emission from both wind shocks at each differential patch is then accumulated to provide a global model for the wind-wind X-ray emission.

It is important to take into account the absorption of the X-rays, particularly by cooler (or “warm”) material, for which there is a substantial bound-free opacity. Such cool/warm material can include both the ambient stellar winds, as well as the radiatively cooled material of the shocked interface itself. For both these sources, we generally adopt an energy-dependent opacity appropriate for “warm” material. This is then multiplied by an integral column depth from the X-ray source at each front location, thus giving the total optical depth to an observer in some direction.
3. Simulated Models

Let us first review some of the general intrinsic properties of the associated wind-collision models. The left panel in Fig. 1 illustrates the contact surfaces for different values of the wind momentum ratio $\eta$. The kinetic energy of the two winds provides the energy for the shock emission, and so sets the total luminosity of the emission. The hardness of the emitted spectra, on the other hand, is set by the velocity component normal to the front, which defines the specific energy and thus the immediate post-shock temperature. It is therefore instructive to examine how the specific and total kinetic energy associated with the front-normal wind component depends on the position along the contact surface.

![Figure 1](image-url)

Figure 1. Left: A few examples of contact surfaces. The labels show the values of $\eta$ at the shock apex $y = 0$, with velocities taken from the wind velocity laws. The parameters of the models are: the distance between the components $D = 60 R_\odot$, $r_{*1} = r_{*2} = 10 R_\odot$, $V_{1,\infty} = V_{2,\infty} = 2000 \text{ km/s}$, $\beta_1 = \beta_2 = 1$, $\dot{M}_1 = 1.0 \cdot 10^{-6} \, M_\odot/\text{year}$, $\dot{M}_2 = 1.0, 0.5, 0.4, 0.3, 0.26 \cdot 10^{-6} \, M_\odot/\text{year}$ for the models 1 - 5 respectively. Top right: The immediate post-shock temperature versus $y$. Bottom right: The kinetic energy of the winds (primary wind – solid line; secondary wind – dashed line) entering a given circular strip ($dy = 0.01 \cdot D$) on the contact surface per second, plotted versus the immediate post-shock temperature of the strip.

For model 3, the top right panel of Fig. 1 plots the immediate post-shock temperatures of the two winds as a function of the $y$-coordinate. As expected, the highest temperatures (thus the hardest spectra) occur near $y \approx 0$, where the normal components of the wind velocities are maximal. The bottom right panel shows the kinetic energy carried per second through a circular strip of the interaction front, again for the two winds, as a function of the immediate post-shock temperature. The maxima of these functions roughly give the energy at which the bulk of X-ray emission is emitted.

Due to the lack of space, we present the simulated X-ray spectra and a light curve only for model 1 from Fig. 1, again referring the reader to Antokhin et al. (2004). The additional orbital parameters defining the model are: orbital
inclination \( i = 90^\circ \), eccentricity \( e = 0 \), \( \omega = 270^\circ \). Solar abundances for the material of both winds were assumed. This model represents the simple case of a circular orbit system with identical stars and winds. In this case, phase zero is an eclipse phase, with the component number 2 being in front.

Fig. 2 plots the light-curve of this model in the energy range 0.5–10.0 keV. Note that, as to be expected for this highly symmetric system, the light-curve shows dual symmetry about phases corresponding to both quadrature (0.25, 0.75) and alignment (0, 0.5) of the stars to the line of sight. The minimum of the luminosity occurs at the alignment phases 0.0 and 0.5, when the brightest emitting region between the stars is subject to the greatest attenuation by stellar occultation and wind absorption. As orbital phase increases to 0.25, the line of sight to this bright region passes through less dense parts of the stellar wind, with little or no stellar occultation, and the brightness increases. The narrow, deep dip very near phase 0.25 is due to the absorption from the geometrically thin layer of cooled gas at the interaction front. In real systems any such dip is likely to be broader and more shallow, due to the finite extension of the cooling front, which may be additionally broadened by various front instabilities (Stevens et al. 1992, Vishniac 1994, Walder & Folini 2000).

The right panel of Fig. 2 compares the spectra of the model at phases 0.0 (minimum \( L_x \)) and 0.2 (maximum \( L_x \)). For comparison, the intrinsic unabsorbed spectra are also shown (the higher intensity functions on the plots). The decrease of the wind absorption in the soft part of the spectra towards phase 0.2 is evident. Note that the lower intensity of the hard part of the spectrum at phase 0.0 is not due to larger wind absorption, but mainly results from the stellar occultation of the part of the interaction front near the system axis, which is the main source of the hard X-rays.

4. Concluding Outlook

The approach described above provides a tractable, efficient way to derive X-ray emission spectra from the radiative shocks characteristic of wind-wind collisions in close, massive-star binaries. But to maintain perspective, let us summarize some of the key approximations and limitations of the present implementation.
1. In neglecting an unknown physical level of mixing that may occur in radiative shocks, as well as adiabatic expansion, the derived spectra only define upper limits for the X-ray brightness and hardness for a given system.

2. The assumption of 2D axisymmetry for the interaction front ignores the role of orbital motion in deflecting the larger scale front into a 3D spiral form.

3. The treatment of absorption assumes a fixed, warm-medium opacity, and does not account self-consistently for the effect of X-ray radiation in ionizing both wind and compressed front material.

4. The wind models assume fixed, kinematic velocity laws, and so ignore effects like radiative inhibition (Stevens and Pollock 1994) or braking (Gayley, Owocki, & Cranmer 1997) that depend on the dynamical role of the stellar radiation fields.

Future development may reduce these limitations. But even in the current configuration, the formalism developed here represents a substantial advance over previous approaches for interpreting X-ray emission from radiative shocks in colliding-wind systems. A principal result of the initial sample model computed here regards the broad, distinctive form of the emitted X-ray spectra. Because of the range of formation temperatures – both within a given shock cooling layer, and cumulatively over the differing shock strengths of the interaction front – the cumulative spectrum simply cannot be well fit by the usual single- or even two-temperature thermal emission models of standard X-ray analysis packages like XSPEC (Antokhin et al. 2004).

The method here is moreover quite computationally efficient, allowing an iterative application to fit a specific observation set for a given system. This demonstrates a clear potential for further application to numerous recent and upcoming X-ray observations of close binaries of massive stars by both XMM-Newton and Chandra.

References
Discussion

Andy Pollock: The success or otherwise of your model presumably depends on the smallness of the cooling length in your picture, which has to be much less than the binary separation or something like that. Is that guaranteed to happen? And second question: Are the luminosities you get out still a couple of orders of magnitude too high compared with observations?

Igor Antokhin: For the first question: Yes, of course we assume, as I said, that these cooling layers are thin and that dictates the limitations of this model. You can apply it only to close binary systems. Actually we have a paper on this work which is due to be published in the second number of the August issue of The Astrophysical Journal and we have some estimates there for the periods and for the parameters of the system, where you can apply this model. So, that’s true. As for the luminosities, as I said, in our approximation the definition of our X-ray luminosity is just equal to the kinetic luminosity of both winds. You don’t see the whole luminosity because you absorb your X-ray radiation in the winds. And I didn’t show you any comparison with any real data, although I have some. But it’s very preliminary and I don’t want to confuse you. What I can say is that, for instance, for the 5-day, circular-orbit O+O binary which we saw yesterday in Hugues’ presentation, HD 152248, it’s an ideal case in which to apply this model. So for that particular case, what I have is that our internal intrinsic X-ray luminosity is $10^{35}$ ergs/s. And the observed X-ray luminosity in this binary is a few times $10^{32}$ ergs/s. What we get after we account for the absorption in the winds is $10^{33}$ ergs/s. So we are still about one order of magnitude above the observed values, but it’s not surprising in the limitation of our model. Of course, you always have some mixing. This is what I call this efficiency factor; you have to introduce it somehow.

Stan Owocki: I just want to add to what Igor just said that for this system, radiation inhibition is probably going to be important and will lower the luminosity. That system would be a very good test of the radiative inhibition model.

Igor Antokhin: Yes, that’s another thing.