Interacting Stellar Winds: Theoretical Overview

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Abstract. I review the theoretical understanding of various kinds of interactions that occur in the massive, high-speed stellar winds from hot, luminous stars, including:
- internal collision of varying-speed flow streams arising from both small-scale intrinsic wind instabilities and large-scale surface variations;
- wind-wind collisions in high-mass binary systems;
- external collision with circumstellar environs, including a previous epoch wind, a supernova explosion, or the interstellar medium.

Given the generally supersonic nature of the relative flows, strong shocks are a common feature of all types of interaction, but these exhibit various types of instability that can lead to complex structure in the interaction region. Moreover, large-scale geometry and observational signatures are influenced by a variety of specific factors, including rotation, binarity, radiative forces, magnetic fields, and interstellar environment.

1. Introduction

Massive, luminous stars are understood to lose a substantial fraction of their initial mass, first through a strong, high-speed, nearly steady outflow called a stellar wind, then through even stronger but slower, episodic outbursts identified with Luminous Blue Variables (LBVs), and finally in the catastrophic, high-speed explosion of a supernova (SN). The material in these outflows can interact in a variety of ways, and on a variety of spatial and temporal scales, leading to vividly complex nebulae, as well as to more subtle signatures in spatially unresolved spectra from the radio to gamma-ray domains. To set the stage for the observational and theoretical discussions to follow at this conference, I provide here a general overview of theoretical issues for understanding and interpreting the various kinds of wind interactions occuring near massive stars.

2. Internal Structure within Wind Outflows

First, it should be emphasized that, even in nearly steady, stellar-wind outflows from single stars, high-speed flow interactions are apparently quite pervasive on a wide range of spatial and temporal scales. Direct evidence for relatively large-scale structure comes from the explicit variability seen in the P Cygni line-profiles formed in the winds from many O and B stars, for example the semi-regular occurrence of “Discrete Absorption Components” (DACs) (Lamers
et al. 1982; Kaper et al. 1999; Prinja et al. 1998) or the more regular “Periodic Absorption Modulations” (PAMs) (Fullerton et al. 1997). (See left panel of Figure 1.) The fact that these variations have an amplitude sufficient to be detectable even at the relatively low signal-to-noise ($\approx 20$) characteristic of IUE implies that the associated wind disturbances must have quite a large spatial scale, large enough to occult a substantial fraction of the stellar disk. For DACs the slow apparent outward acceleration and clear net increase in material absorption suggest some sort of “mass ejection” triggered by a disturbance, perhaps related to magnetic activity, on the stellar surface. For PAMs, the more regular, period recurrence and the existence of decreases as well as increases in absorption suggest instead a surface modulation of the wind mass flux, perhaps associated with non-radial pulsation. 2D hydrodynamical simulations by Cranmer and Owocki (1996) have shown how bright spots on a rotating stellar surface can lead to spiral stream structure analogous to “Corotating Interaction Regions” first identified in the solar wind, and how these can induce signatures in UV wind lines that have many of the properties of both DACs and PAMs (Owocki, Cranmer, and Fullerton 1995). Thus far, there have only been limited theoretical efforts to model directly the dynamical effect of magnetic fields.
(e.g. Babel and Montmerle 1997) or pulsations (Cranmer 1996) on a radiatively driven wind outflow.

There is also strong indirect evidence for smaller-scale, turbulent structure in OB star winds. The effective backscattering needed to produce the nearly black troughs observed in saturated P Cygni line-profiles suggests a highly non-monotonic velocity field (Lucy 1982). And the near constancy (variation < 1% and spectral softness ($E = 0.1 - 1$ keV) of ubiquitous X-ray emission seems to imply extended emission by a large number ($N > (1/0.01)^2 = 10^4$) of internal wind shocks (Bergheofer et al. 1996) The wind driving by line scattering of the star’s continuum radiation is intrinsically highly unstable to velocity perturbations near and below the Sobolev length $L \equiv v_{th}/(dv/dr)$ (Lucy and Solomon 1970; Owocki and Rybicki 1985), and numerical simulations have shown this leads naturally to a strong compressive turbulence characterized by a highly nonmonotonic velocity field, multiple shocks, and extensive clumpiness in material density (Owocki, Castor, and Rybicki 1988; Feldmeier 1994). Such models can quite readily reproduce the UV line black troughs, but have not yet been successful in explaining key properties like the scaling of the X-ray emission with bolometric luminosity $L_x \sim 10^{-7}L_{bol}$ (Feldmeier et al. 1997).

In Wolf-Rayet (WR) stars the much higher signal-to-noise of the optical emission lines used to diagnose wind properties makes it possible to directly detect relatively small-scale variations, and even to test how well these may agree with hierarchical scaling laws expected for compressible turbulence (Lépine and
Moffat 1999). Moreover, the slow rate of net migration of fluctuations from line center to wing indicates that the associated wind structure undergoes a remarkably slow acceleration, extending over a spatial scale, $\beta R_* \approx 20 - 50 R_\odot$, that is many times the core stellar radius, $R_* \approx 2 - 5 R_\odot$. Considering the inverse-radius-squared decline of the radiative flux, maintaining such an extended acceleration with radiative driving requires the effective mass-absorption opacity $\kappa = \sigma/m$ to increase with radius. One way this can occur is if optically thick clumps expand as they propagate outward; for example, if the clump cross section increases as $\sigma \sim r^2$, then the radiative acceleration could be maintained constant as long as the blob remains optically thick. (See Figure 2.)

3. Colliding Winds in High-Mass Binaries

3.1. Interaction geometry: bow-fronts vs. pinwheel spirals

The winds in high-mass binary systems undergo violent collisions in which much of the directed wind speed $v > 1000 \text{ km/s}$ of one or both winds is dissipated in very strong shocks. The scale and overall geometry of the interaction front depends both on orbital parameters, like the separation and eccentricity, and on wind parameters, like the flow speeds and mass loss rates. Quite generally, the stellar orbital speeds ($< 100 \text{ km/s}$) are much less than the wind speeds ($> 1000 \text{ km/s}$), and so over the scale of the orbital separation the interaction can be approximately modeled as a 2D conical structure, symmetric about the axis of separation from two nearly stationary sources. For stars of separation $D$, and with wind momenta $\dot{M} v$ in a ratio $P > 1$ of the stronger to weaker wind, the stagnation along the axis of separation is near a radius $r_{\text{stag}} = D/(\sqrt{P} + 1)$ from the weaker-wind star. The interaction front takes a bowed, conical form wrapped around the star with the weaker wind, with opening angle decreasing with increasing wind momentum asymmetry $P$.

Over a larger scale – roughly on the order of the wind transit distance $v \tau$ over an orbital period $\tau$ – the interaction front becomes deflected into a spiral or “pinwheel” form, as recently resolved directly in infrared observations of dust emission in WR 104 and WR98a (Tuthill et al. 1999; Monnier et al. 1999). While the spiral form is expected, the apparent formation of dust is a puzzle, since this is generally thought to require a much higher density and lower temperature than is expected in wind collision fronts.

By contrast, simple models of wind collision shocks generally predict a stronger, harder X-ray emission than is commonly observed from colliding wind binaries. One explanation is that the strongest X-ray emission from the region of direct wind collision between the stars is attenuated by absorption in the two winds. Another factor may be the mixing of hot X-ray emitting gas with cooler material within the generally unstable cooling regions behind the strong shocks (Walder and Folini 1998; Pittard 2000).

3.2. Radiative Braking

Another potential factor in reducing X-ray emission in some colliding wind binaries is the slowing of an incoming wind by the radiation field of the impacted star, which thus reduces the wind-wind shock strength. Analyses by Gayley,
Figure 3. (a) Wind-wind momentum fluxes vs. distance along the line of centers in an O+O star binary system. (b) Momentum fluxes vs. distance in a WR+O binary, illustrating the balance between the WR-wind and the O-star light.

Owocki, and Cranmer (1997) suggest that such “Radiative Braking” can have an important influence on the overall collision front geometry in many close to medium separation binaries with a substantial asymmetry in wind momentum ratio, $P \gg 1$. This includes several WR+O systems, wherein the WR and O stars have similar luminosities and similar wind speeds, but the WR star has a substantially larger mass loss rate. Indeed, in the close WR+O systems V444 Cygni, the WR wind is so much stronger that, if there were no radiative braking, it should completely overwhelm the O-wind and impact directly onto the O-star surface, a situation that appears contrary to observed light curves of UV wind lines (Cherapaschuk et al. 1995). On the other hand, if we consider instead the ratio $P_{WR/\nu} \equiv (\dot{M}v)_WR/(L_O/c)$ of WR wind momentum to that of the O-star radiation, then momentum balance can now occur near a “braking radius” $r_b = D/(1 + \sqrt{P_{WR/\nu}})$, if there is sufficient opacity in the WR wind to intercept the O-star light. (See Figure 3.)

Figure 4 shows results of 2-D radiation hydrodynamical simulations for V444 Cygni that include the effects of radiative braking via line-scattering of the O-star radiation by WR wind material, computing the line-acceleration through the standard CAK formalism using distinct assumptions about the CAK opacity normalization constant $k$. A key result is that radiative braking is only effective when the WR wind is assumed to have the enhanced line opacity that would be needed to drive its stronger mass-loss rate from the WR star in the first place (Figure 4b). If WR wind opacity is only equal to that of the weaker O-star wind, then radiative braking is too weak to hold off the WR wind from direct impact onto the O-star surface (Figure 4a). This suggests that observational constraints on the overall geometry of the wind interaction front in WR+O binaries – for example its separation from the stellar surface, or the opening angle of the bow-
Figure 4. Left: 2D simulations of radiative braking in the colliding winds in V444 Cygni when the WR is assumed to have CAK line-opacity normalization of (a) $k_{WR} = k_O = 0.15$ or (b) $k_{WR} = 0.8$. Right: Classification of specific binary systems, with shaded triangle region representing the estimated parameter domain for radiative braking.

...could provide new clues on the nature of line-opacity needed to drive the enhanced mass loss of WR winds.

4. Wind-Environs Interaction

Stellar winds also exhibit strong interactions with their environs, for example with wind outflow from a previous epoch, or with the surrounding interstellar medium. The latter are often observed as roughly spherical "wind-blown ISM bubbles". The scale is set by a rough mass balance between emitted wind and swept-up ISM. For a wind mass loss rate $\dot{M}_{-6}$ (in units of $10^{-6} M_\odot/yr$) and ISM particle density $n_1$ (in units of $1 cm^{-3}$), the characteristic radius (in parsecs) is given roughly by

$$r_{pc} \approx \sqrt{\frac{\dot{M}_{-6} \tau_6}{n_1}},$$

where $\tau_6$ is the wind lifetime (in units of $10^6$ years).

In many instances, observed wind-interaction nebulae are not spherical, but axially symmetric, most usually prolate. In some cases, the source system may be a binary, but it is unclear under what circumstances this will lead to the observed axisymmetric form. This could also result from magnetic channeling, e.g. by a dipole magnetic field at the stellar surface; but so far there has not been much detailed MHD modelling of this possibility.
Figure 5. Density distribution in simulations of cases with (a) spherical wind expansion into equatorially enhanced density, or (b) asymmetric wind with higher mass flux and velocity at higher latitudes.

Alternatively, there are also two types of competing models that link the axisymmetric form to rotational effects. Langer et al. (1999) proposed that the prolate shape of η Car arises from the interaction of spherically symmetric fast wind with an equatorially enhanced disk. They argue that such a disk was ejected during the 1840 outburst when the star exceeded a rotationally modified form of the standard “Eddington limit”, which they term the “Omega limit”, wherein centrifugal effects combine with radiation pressure to overcome gravity and thus propel equatorial material outward into a disk. This notion has been criticized by Glatzel (1998), who points out that inclusion of gravity darkening effects causes the net reduction in effective gravity to be constant in latitude. Indeed, radiatively driven wind simulations tend to show an enhanced mass loss from the brighter regions toward the pole, not equator (Owocki et al. 1998; Petrenz and Puls 2000). Frank et al. (1998) show that such enhanced mass loss toward the pole, combined with the lower expected outflow speed toward the equator, could by itself lead to a prolate wind-blown nebulae. Figure 5 shows examples of their simulation models to illustrate the similar overall form that results for cases with (a) spherical expansion into equatorial disk, and (b) prolate wind expansion.
Figure 6. Illustration of shock-interface instabilities. (a) Rayleigh-Taylor instability of heavier over lighter material within an accelerating medium. (b) Kelvin-Helmholtz instability of shearing layer. (c) Vishniac or Thin-shell instabilities of ram-gas or ram-ram interface. (d) Cooling layer overstability.

5. Shock Interface Instabilities

Finally, we note that in many of the above types of interactions, the interface is subject to various kinds of instabilities. Figure 6 illustrates some of these. (See also review in Pittard 2000.) Rayleigh-Taylor instabilities arise when denser fluid is accelerated by impact from more rarefied material. Kelvin-Helmholtz instabilities form along the shear layers between oppositely directed flows. The ram-ram or ram-gas pressure balance interaction of colliding fluids is also subject to finite-amplitude instabilities (Vishniac 1983, 1994). Finally the cooling layer behind shocks is subject to an overstability that leads to interface oscillations in 1D models (e.g., Chavalier and Imamura 1982), but a complex interaction structure in multi-dimensional simulations (e.g., Walder and Folini 1998).

Overall these many types of instabilities suggest that the interaction layers of interacting winds are likely to be extremely complex, with extensive turbulent mixing that may mute key observational signatures like the X-ray emission.
6. Open Questions

Let me conclude with a summary of some specific open questions in each of the categories of interacting winds from massive stars.

6.1. Internal Interactions

- What induces large-scale DAC and PAM structure? Magnetic fields? Non-radial pulsations?

- What is the lateral scale of instability-generated structures? Pancakes? Blobs?

- What is the origin of WR wind blobs? Instability? Pulsation?

- What causes the slow, extended acceleration of WR-wind blobs?

6.2. Wind-wind collision in binary systems


- Does radiative braking occur? Even in a clumped flow?

- How does a dust spiral form?

6.3. Wind interaction with environs

- How does rotation affect mass loss? Through Omega limit? Gravity darkening?

- What determines a nebula's shape, e.g. prolate vs. spherical?

- What causes the axisymmetry? Magnetic field? Binarity? Rotation?

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References

Discussion

Orsola De Marco: Concerning the momentum balance where you have two shocks that are balanced by the radiative forces in the WR + O binary scenario: Are these two interfaces different enough so you can distinguish them from the variability in the optical lines?

Stan Owocki: Well, among all the different scenarios of the instabilities, there are details. If you look at the simulations like how fingered the structure is, you tend to get Rayleigh-Taylor instabilities, which tend to be very long. So there are details on that level and the level of radiative braking versus ram pressure. One of the things that you predict in radiative braking is that the bow shocks should be much broader than you would expect if they collapsed onto the star. And I think that generally speaking the observations for V444 Cygni, for example, support that the bow shock is off of the surface and is much broader. So I think that radiative braking really is occurring. But one of the questions is: Does radiative braking survive if you have a very clumpy structure - you know, two clumped winds colliding? That is something that is still being worked on. But a lot of people have the impression from the summary talk at the meeting in Puerto Vallarte [IAU Symposium No. 193], that radiative braking would have to be intrinsically unstable. Normally you think of a shock as a supersonic flow that’s slowing down and that’s going to have to be unstable and brake into a shock. But that’s an argument that comes from pure gas dynamics, that says that the limiting transmission speed is the gas sound-wave speed. But radiation, of course, has the speed of light, so it isn’t true. And indeed, the instability of line driving is actually working in reverse. It’s like a dampening effect for radiative braking. And so in the numerical simulations that we do, the radiative braking front is not necessarily unstable at all. It can actually be quite smooth. It really depends on what you assume about the radiative cooling-law, whether it ends up actually being structured or not.

Sean Dougherty: Stan, when you say broad you mean a big opening angle?

Stan Owocki: Yes, a big opening angle.

Allan Willis: Well, it depends on the binary of course.

Stan Owocki: It depends on which system you’re talking about. You’re adding more momentum to the star that’s holding off the other wind and you expect in general that the opening will be broader because you’re actually pushing the shock front back.

Tony Moffat: You said that the blobs probably have to be optically thick.

Stan Owocki: Some can be.

Tony Moffat: Yet Lépine et al. (2000) showed that they probably weren’t.

Stan Owocki: It depends on the optical thickness of the line.

Tony Moffat: Those are line observations. You couldn’t explain certain statistical, observed properties otherwise.

Stan Owocki: Well, it’s something we should talk about.
Sergey Marchenko: This is mainly a comment regarding the first point in your question list. We had three stars in the MEGA campaign [15 days of continuous IUE coverage: see Massa et al. 1995, ApJ, 452, L53]; now we have two stars out of three showing very strong driving coming from the core, with the same periods as the structures observed in the winds. Of course the source of this driving is unknown.

Stan Owocki: Pulsational driving?

Sergey Marchenko: Yes, exactly. We have periodic and coherent pulsations, with the two periods exactly fitting the periods observed in the wind structures.

Stan Owocki: Yes. I’ve tried to get funding from NSF, for example, to do a careful study of non-radial pulsation effects versus magnetic fields on winds, because I think there will be differences that you’ll be able to compare with observations. But at this level I don’t think we really know enough about how those two things will be different. But in your case maybe there are specific signatures.

Sergey Marchenko: Unfortunately we cannot say. Is this due to pulsation or magnetic fields? But still, when the core brightens, then everything up in the wind reacts.

Stan Owocki: Oh, sorry - if you mean that there is clearly a link between the star and the wind variation, that’s clear from the fact there’s rotational modulation.

Sergey Marchenko: No, I mean short periods, a few hours. It’s not a long rotation effect.

Stan Owocki: But the point is that it could be multiple structures on the star.

Sergey Marchenko: Yes, exactly.

Stan Owocki: Or NRP, nobody knows which one it is so far. I would like to give a plug to a student of mine who won’t be giving a talk here. He’s actually doing his Ph.D. thesis on the magnetic idea and I’d be interested in other people who are working on the pulsations. In principle, you could do simulations of that.

Nicole St-Louis: I’d just like to ask the last question. What do you think is the main difference in the physics of all these different wind-wind interactions? You talked about the instabilities there in most of the cases. But what’s the difference in the physics of the three different interaction types: energy level? excitation mechanism?

Stan Owocki: Well, scale. I mean one of the problems you have doing the kind of detailed hydrodynamics that I like to do is that you can only infer it spectroscopically, and so you have to use indirect mechanisms to test your theories. However, when you go to the large scales - the bubbles, or with these beautiful observations of the spiral arms, you have more direct evidence. And that’s a lot easier to sell, frankly. When you show a picture, you get a lot more people to pay attention than when you show a spectrum. And so that’s a really important factor because it really drives our thinking, I think.

Tony Moffat: But what determines the scale?
Stan Owocki: The physical scale of the problem is that a wind-blown bubble's going to be parsecs in scale because that's where the mass and the momentum are in balance. In the instability it's all very small-scale structure set by the Sobolev length, for example, so that it's just the intrinsic differences in the problems. But what that means is that it's just more difficult observationally to test the theories, because you have to use spectroscopic methods. But the stuff that you and Sébastien have done has really given a lot of detailed data to shoot for.

Stan’s multi-facets
La vie des madelinots: la pêche, garder le phare, le foyer...
SESSION B

 STELLAR WINDS INTERACTING WITH THEIR INTERSTELLAR AND CIRCUMSTELLAR ENVIRONMENTS

B1. Interaction of Stellar Winds and the Interstellar Medium

Chair: Peredur Williams
Cristina Cappa enjoying the cape; Cristina with cohorts (Virpi Niemela & You-Hua Chu); island scene without Cristina or cohorts