APPLICABILITY OF STEADY MODELS FOR HOT-STAR WINDS

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ABSTRACT Non-Sobolev models of radiatively driven stellar winds based on a pure-absorption approximation do not have a well-defined steady state. Here we examine the implications of this for flow time-dependence, showing that, under such circumstances, instabilities in the flow attain an absolute character that leads to intrinsic variability. In this case, steady solutions are inherently inapplicable because they do not represent physically realizable states. However, for actual hot-star winds, driving is principally by scattering, not pure-absorption. In practice, the relatively weak force associated with slight asymmetries in the diffuse, scattered radiation field may play a crucial role in breaking the solution degeneracy and reducing the instability from an absolute to an advective character.

INTRODUCTION

This conference aims to discuss phenomena in hot stars and their winds within the context of steady, time-independent, models. In this regard, the preceding paper by Poe et al. (1989a, hereafter POC-I; see also Poe, Owocki, and Castor 1989b, hereafter POC-II) presents something of a problem, since it shows that, when one relaxes the usual Sobolev approximation for treating the line-driving of such winds, there is no uniquely defined steady state (at least for a pure-absorption model). In this paper, we examine the consequences of this degeneracy of steady solutions. To do so requires, however, that we violate this restriction to time-independence, and consider the nature of instability and variability in such flows.
INSTABILITY AND VARIABILITY IN HOT STAR WINDS

The driving of hot-star winds by spectral-line scattering of the star's continuum radiation is understood to be very unstable (Lucy and Solomon 1970; Owocki and Rybicki 1984, 1985), and it seems likely that such instability is a root cause of numerous observational phenomena – X-ray emission, nonthermal radio emission, variable narrow absorption components in UV spectra, black UV profiles, superionization – that are difficult to understand in the context of a smooth, time-independent model. Nonetheless, such steady-state models have enjoyed considerable success in explaining gross wind properties like the mass loss rate $\dot{M}$ and terminal flow speed $v_\infty$ (Abbott 1988; Kudritzki et al. 1988), implying that variability may not be too fundamental a characteristic. Given the great additional complexity that one confronts in temporal variability, the traditional approach, adopted at this conference, has thus been first to explore extensively steady models, if only as a basis for eventually examining unsteady ones. A principal aim of this paper then is to delineate the circumstances for which variability in such winds might be considered a correction to an underlying steady flow, from those for which it must be considered as a fundamental property.

$$\frac{V_{TH} / R}{V_{TH} / R} = 1/2$$

$$\frac{V_{TH} / R}{V_{TH} / R} = 3/8$$

Figure 1  Perspective plot of the velocity vs. both time and height in two unperturbed models computed with the OCR time-dependent code. Model A with $v_{th}/a = 1/2$ approaches a smooth steady-state given by the well-defined solution found by POC, while Model B with $v_{th}/a = 3/8$, for which there is a degenerate family of steady solutions, shows persistent, intrinsic variability.

To illustrate this distinction, let us consider the character of instability and variability for two absorption-line-driven wind models for which the type of steady-state solutions is quite different. The parameters (given in Table 1 of POC-II) for both models are identical except for the ratio of the thermal speed to sound speed $v_{th}/a$, which is taken to be 1/2 for Model A, but 3/8 for
Model B. Analysis of the time-independent equations (POC I and II) shows that Model A has a steeper-slope, distinct, steady solution, whereas Model B has a shallower-slope, degenerate family of solutions.

What is most interesting is that this difference in the character of the steady solutions corresponds also to a marked difference in the flow's temporal behavior. This is illustrated in figure 1, which shows 3-D perspective plots of the velocity versus height and time for the two unperturbed wind models computed with the time-dependent radiation-hydrodynamics code developed by Owocki, Castor and Rybicki (1988; OCR). In both cases, the flow is initially disrupted because the assumed initial condition, given by the Castor, Abbott, and Klein (1975; CAK) Sobolev-theory model, is not an appropriate steady-state for either non-Sobolev model, particularly in the subsonic wind base. For Model A, however, the wind then quickly relaxes to the appropriate, well-defined steeper solution, whereas for Model B, for which there is no unique steady solution, the flow never settles down, but exhibits a nearly periodic variability. This variability persists despite the explicit time-independence of the boundary conditions, which are designed to transmit with minimal reflection (< 5%) any waves propagating out of the flow, and not to introduce any wave variation propagating into the flow. In contrast, Model A is still unstable, but variability now requires explicit perturbation, and so dies away for these steady boundary conditions.

The difference in the two cases reflects the advective vs. absolute nature of the instability (Bers 1982; Owocki and Rybicki 1986). In an advective instability, a perturbation grows to large amplitude only as it propagates or is advected away, whereas in an absolute instability, any perturbation (even thermal noise) can disrupt the flow at the point it is introduced. Apparently, Model A is only advectively unstable, and so, in the absence of explicit perturbations, relaxes to a steady state. Model B, on the other hand, appears to be absolutely unstable, and this leads to intrinsic variability that persists even without explicit perturbations.

NATURE AND CONSEQUENCES OF INSTRINSIC VARIABILITY

Figures 2-5 illustrate further the nature of the absolute instability of Model B, showing some of the consequences of the resulting intrinsic flow variability. Figures 2 a-d gives snapshots of the spatial variation of the density, velocity, and mass-loss rate at various times from the CAK initial condition. Note that there do exist brief intervals when the flow approaches a nearly smooth, CAK-like state, but then, despite the lack of any explicit perturbations, the state becomes disrupted. Once the structure arising from this disruption is advected away, the wind again briefly approaches a smooth, CAK-like model which, however, then becomes disrupted again. Note that the temporal and spatial scale of the fluctuations that are amplified are actually quite small, but the recovery from the resulting disruption has a much longer time scale reminiscent of a relaxation oscillation.

As shown in figure 3 (see also the lowermost curves of figures 2), this overall oscillation appears to be regulated by the induced variation in the base mass flux, which ranges from about zero to two times the mean value with a nearly regular periodicity of about 55 ksec. This triggers quasi-regular disruptions, resulting
Figure 2  Snapshots of the base spatial variation of density, velocity, and mass loss rate (arbitrary units) at various times (labeled in ksec) after the initial CAK condition in Model B. The intrinsic variability of the model is manifest as alternating periods of smooth and structured flow that repeat every ~55 ksec.
Figure 3  Perspective plot of the mass loss rate vs. height (now up to 4 R.) and time (0–200 ksec after the CAK initial condition). Note the self-excited variation at the base and the resulting periodic ejection of dense shells.

Figure 4  Line-optical depth vs. time and frequency x from line-center in Doppler units, viewed from a perspective along the time axis. Note the extensive variability at the blue edge frequency x ≈ 40 (v ≈ 1200 km/s ≈ v∞), and moving narrow ridges reminiscent of "narrow absorption components".
in the formation of a series of dense shells that propagate outward through the wind.

Figure 4 shows that the evolution of these dense shells in time and space is quite well tracked by the variation versus time and frequency of the optical depth for a typical strong line. The moving narrow ridges in optical depth arise from the dense shells that form near the wind base and are then accelerated outward; in lines with unsaturated absorption troughs, they will likely give rise to narrow absorption features quite similar to the moving narrow absorption components commonly observed in unsaturated UV lines from hot stars (Rogerson and Lamers 1975; Prinja and Howarth 1988). However, variations with respect to frequency do not always track spatial variations. For example, the blue-edge variability, which occurs at frequencies z above that corresponding to the flow terminal speed \( v_\infty \), arises from the high-velocity (but low-density) flow fluctuations that are relatively near, not far, from the star; this again mimics observations, which often show extensive variability at the blue edges of even saturated UV lines from hot stars.

Figure 5  Snapshot of the wind structure out to a height of 25 R\(_{\odot}\) a long time (600 ksec) after the CAK initial condition (smooth curves).

Figure 5 shows a snapshot of the wind spatial structure (up to 25R\(_{\odot}\)) a time long (600 ksec) after the initial condition. Note the multiple strong shocks with velocity amplitudes ranging up to 1000 km/s (see also figures 2 b and d). These can be expected to result in X-ray emission with roughly the observed intensity and spectral properties (OCR; MacFarlane and Cassinelli 1989). It also
seems quite hopeful that the intrinsic variability that arises so naturally from this time-dependent model could likewise qualitatively reproduce other observed phenomena (e.g., nonthermal radio emission, superionization, black absorption troughs) that are difficult to understand in terms of a smooth, steady-state picture. For comparison, the smooth curves in figure 5 show the corresponding height variations of the same parameters for the CAK initial condition. Clearly, such a steady-state model could only be considered a very gross representation of the conditions of this time-dependent flow. The variability in this case is thus not just a small correction to an otherwise steady, background flow, but rather is a dominant, intrinsic flow property.

DISCUSSION

It is important to emphasize that this model represents only a first attempt to study the nonlinear evolution of this instability, and, as such, makes several gross simplifications. It assumes a 1-D, spherically symmetric, isothermal flow driven by pure absorption of radiation in a fixed ensemble of isolated lines. Thus many crucial properties of the flow – e.g., horizontal extent of the dense shells, temperature structure behind shocks, etc. – are not addressed, and so quantitative comparisons with the resulting observational features – e.g., narrow absorption components, X-ray emission – are not yet appropriate.

Even more fundamental, however, is the question of whether the intrinsic variability characteristic of the pure-absorption model here is really applicable to actual hot-star winds, for which the line-driving is better described as pure scattering than pure absorption. Because of the near fore-aft symmetry of the diffuse radiation field, the force associated with scattering is typically small, of order \( v_{th}/v \) compared with that arising from extinction of the directed radiation from the stellar core. Nonetheless, it is possible that scattering effects could “break” the solution degeneracy found in pure absorption models, thus explaining why models based on comoving frame (CMF) solution of the scattering line transfer (Pauldrach et al. 1986) do not appear to have the same solution degeneracy as found in the POC pure-absorption models. Indeed, linear stability analyses have shown that this diffuse radiation can exert a strong drag on flow perturbations, particularly near the stellar surface (Lucy 1984; Owocki and Rybicki 1984, 1985); this might well stabilize the transonic flow region enough to make the overall flow only advectively rather than absolutely unstable. In this picture, variability, rather than being intrinsic, would result from amplification of fluctuations propagating upward from the underlying atmosphere, and so would only become dominant in the highly supersonic flow. The viewpoint that steady models are indeed applicable, at least as the underlying state on which variability occurs, would then be quite defensible.

Alternatively, it is possible that the basic degeneracy and intrinsic variability evident in the pure-absorption models would remain, at least in some cases, when scattering is included. Even if scattering effects break the solution degeneracy, so that a sufficiently sensitive iteration algorithm could relax (as in Pauldrach et al. 1986) to one particular solution, other solutions from the once degenerate family could still also represent viable steady states. In this case, one might imagine that the flow would be absolutely stable to infinitesimal perturbations, but still absolutely unstable to finite amplitude fluctuations, so
that variability, once initiated, could persist much in the manner seen in pure absorption models (cf. figure 1b).

To distinguish among these two possibilities, and so to decide the respective applicability of steady-state and/or pure-absorption models, will require a careful examination of the dynamical role of scattering in the transonic flow region. There seem two possible outcomes: Either the basic multiplicity of steady solutions will remain, implying that line-driven winds must be intrinsically variable; or else scattering will be found to play a crucial, heretofore unrecognized, role in determining, regulating, and stabilizing the steady outflow in such winds. Of course, it is also possible that both outcomes might apply in different cases: the former, say, to B stars, which are generally observed to be more variable, and the latter to O stars, for which recent steady-state models yield impressive quantitative agreement with detailed spectral observations (Kudritzki 1989; this volume). In any event, a fuller appreciation of the points raised here would seem important for building a sounder understanding of line-driven mass loss.

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