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THE OUTER EVOLUTION OF STRUCTURE IN RADIATIVELY DRIVEN STELLAR WINDS

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RESUMEN

Presentamos un nuevo método para estudiar la evolución de la estructura generada por las inestabilidades en los vientos externos de las estrellas calientes. Acuñamos para este método el nombre de técnica de la caja seudo-plana periódica en movimiento. Se utiliza el hecho de que la evolución externa de estructura se puede simplificar a un problema puramente de dinámica de gases. Se sigue a una caja que se mueve hacia afuera a velocidad constante, que contiene una parte representativa de la estructura generada por un modelo impulsado por radiación. El método nos permite seguir la estructura hasta más que un millar de radios estelares, a un costo computacional relativamente bajo. Hemos utilizado una cota de línea fuerza menos artificial que en modelos previos. También hacemos un primer intento de mejorar el tratamiento del balance de energía en el viento.

ABSTRACT

We present a new method to study the evolution of instability-generated structure in the outer winds of hot stars. We coin this method a pseudo-planar moving periodic box technique. It makes use of the fact that the outer evolution of structure can be simplified to a pure gasdynamical problem. It follows a box moving out at a constant speed, containing a representative portion of the structure generated by a radiatively driven model. The method allows us to follow structure out to more than a thousand stellar radii, at relatively low computational cost. We have used a less artificial line-strength cut-off than previous models. We also make a first attempt at improving the treatment of the energy balance in the wind.

Key Words: **HYDRODYNAMICS — INSTABILITIES — STARS: EARLY-TYPE — STARS: MASS LOSS — STARS: WINDS, OUTFLOWS**

1. INTRODUCTION

Hot stars have strong stellar winds, driven by the scattering of radiation in spectral lines. This driving mechanism is inherently unstable (Milne 1926; Owocki & Rybicki 1984). Time-dependent hydrodynamical calculations of unstable winds (e.g., Owocki, Castor, & Rybicki 1988; Owocki & Puls 1999) agree on the main features of such flows: the wind is pervaded by strong shocks (reverse and forward) that compress the gas into dense clumps and heat a limited amount of material to temperatures in excess of a million degrees. The structure caused by the instability is stochastic and should not be confused with the large, ordered structures that are thought to explain the recurrent features seen in ultraviolet spectral lines.

Most papers on instability-generated wind structure focus on the inner wind. There are a number of good reasons, however, to study the structure at large distances from the star. The thermal radio emission commonly used to determine the mass-loss rate can be formed at a few hundred stellar radii. X-rays in stars such as ζ Pup also originate beyond a hundred stellar radii. Finally, it has been suggested that some of the structure seen in circumstellar nebulae could be an imprint from wind structure.

2. RADIATIVELY DRIVEN MODELS OF OUTER WIND STRUCTURE

In a previous paper (Runacres & Owocki 2002, hereafter Paper I), we investigated structure up to a distance of $100\,R_*$, using Eulerian, one-dimensional, time-dependent hydrodynamical models that take into account the instability of the driving. In these models, the material is compressed into a sequence of narrow, dense shells, bounded by shocks. These shells expand at a few times the sound speed as they move out at approximately the terminal velocity of the wind. There are supersonic velocity differences between individual shells, causing them to collide and form narrow, dense shells. The importance of similar shell-shell collisions for the production of X-rays has already been pointed out by Feldmeier, Puls, & Paudrach (1997). We found that these collisions effectively hinder the decay of the structure initiated in the inner wind, so that the clumps can survive to substantial ($\gtrsim 100\,R_*$) distances.

In modeling the distant wind structure, we found that it is necessary to maintain a relatively fine grid spacing to resolve the often quite narrow dense clumps. We also found that the energy balance plays a crucial rôle in determining the rate at which structure decays. The gas in these simulations cools both adiabatically and radiatively. The combined effect of this cooling is balanced by photoionization heating from the star's ultraviolet radiation. We mimic the effect of radiative heating by setting a floor temperature, beyond which the temperature is not allowed to drop. The value of this floor temperature influences the expansion speed of the shells. For a low value of the floor temperature, the dissipation of the structure will be slower.

Finally, the amount of structure initiated in the inner wind strongly depends on the line driving parameters, in particular on the cut-off parameter $\kappa_{\max}$ that limits the maximum line strength (Owocki et al. 1988). For purely computational reasons, this parameter is usually set to artificially low values. We found that, with the relatively fine resolution of our calculations, it is possible to set this parameter to less artificial values. In summary, we can say that the amount of clumping in our simulations is largely determined by the grid spacing, the floor temperature and $\kappa_{\max}$.

On the other hand, we find that the clumping does *not* depend on the radiative force beyond $\sim 30\,R_*$. This reduces the outer evolution of structure to a pure gasdynamical model. As the evaluation of the radiative force dominates the computation time, this allows us to construct vastly more economical models, which we present in the following section.

3. A PSEUDO-PLANAR PERIODIC BOX TECHNIQUE

Even without the evaluation of the radiative force, the modelling of structure out to *very* large distances ($\sim 1000\,R_*$) is still expensive. Also, the fine grid spacing needed to resolve the shells results in an excessively large number of grid points, and impractically large files. Instead of keeping track of the whole stellar wind, an easier way to study such problems would be to follow a limited but representative portion of the structure as it moves out with the flow. The technique we present is a pseudo-planar, moving periodic box technique.

From a model extending out to $100\,R_*$, we select a portion of the wind at a given time and put it in a box that moves outward at a convenient speed, generally close to the terminal velocity. This cannot be done directly, as the spherical equations of hydrodynamics—unlike their planar counterparts—are not invariant under a Galilean transformation. We therefore rephrase them using variables that are scaled to take into account the secular expansion of the gas. For instance, the density ρ is related to the scaled density $\tilde{\rho}$ by

$$r_0^2 \tilde{\rho} = r^2 \rho, \tag{1}$$

where r_0 is a fiducial radius (e.g., the position of the box at $t = 0$). Scaling the pressure in the same manner and rewriting the equations as a function of the scaled variables produces equations that have a planar form (apart from a geometrical source term), but describe a spherical geometry (hence *pseudo-planar*). These can easily be used in a moving box. Finally, we impose periodic boundary conditions on the box. Details will be given in a subsequent paper (Runacres & Owocki 2003).

4. RESULTS

We first run a radiatively driven model to use as input for the pseudo-planar model. This model is similar to the reference model in Paper I. The parameters correspond to those of a supergiant such as ζ Pup. There are two differences with Paper I. In that paper, the floor temperature was taken equal to the effective temperature. This is a crude approximation and probably results in a wind that is too warm. As a first step towards a more realistic treatment of the energy balance, we used the detailed ionization and thermal equilibrium models by Drew (1989). These take into account the cooling by heavy element lines and predict an outward decreasing temperature that quickly reaches values substantially below the effective temperature. These temperature profiles can be adequately approximated by the expression

$$\frac{T(r)}{T_{\text{eff}}} = 0.79 - 0.51 \frac{v(r)}{v_\infty} \tag{2}$$

(Bunn & Drew 1992), which we used in the current models with a β velocity law with $\beta = 0.7$. Note that the temperature profile levels off at $0.28\,T_{\text{eff}}$. Although this is certainly an improvement over simply taking the effective temperature, it is far from perfect. The Drew models were only calculated to $10\,R_*$. Most importantly, they assume a smooth outflow. There are numerous ways in which the inhomogeneity of the outflow could influence the energy balance. A detailed investigation of the energy balance in a structured wind, however, is a complex task and falls beyond the scope of this study.

In the current paper, we have also used a more realistic value for $\kappa_{\max}$, namely $\kappa_{\max} = 0.1\kappa_0$, where

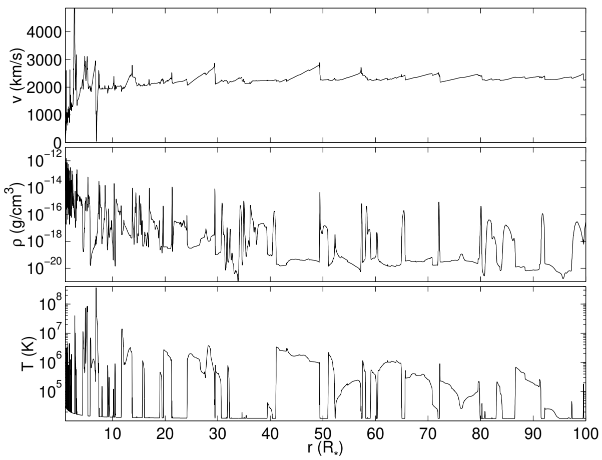

Fig. 1. Snapshot of the radiatively driven model used as input for the periodic box model. The panels, from top to bottom, are velocity, density and temperature.

the opacity constant κ_0 is related to the strength of the strongest line. This is a factor of hundred larger than in Paper I. The effect is to include a number of strong lines that become optically thin only for very large velocity gradients. This allows for much stronger rarefactions and shocks. The resulting models are extremely structured, as can be seen from the snapshot (Figure 1).

We select the region between 45 and 95 R_* as input for the pseudo-planar models. We follow this portion of the structure out to $\sim 1300\,R_*$. The box in this simulation moves out at $2370\,\mathrm{km\,s^{-1}}$. The evolution of structure can be usefully characterised by its statistical properties. Here we only use the clumping factor, defined as

$$f_{\mathrm{cl}} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}. \tag{3}$$

The clumping factor describes how mass is distributed; it becomes larger as mass is concentrated in a smaller volume. If most of the mass is in the clumps (which is the case in these models), the clumping factor is the inverse of the volume filling factor, and equals the density contrast of the clumps with respect to the mean density. Diagnostics sensitive to the square of the density (e.g., the radio continuum) will tend to overestimate the mass loss rate of a clumped wind by a factor of $\sqrt{f_{\mathrm{cl}}}$.

In Figure 2 we show the clumping factor as a function of radius.

The oscillating behaviour is indicative of the competition between pressure expansion and shell collisions. The supersonic collisions between shells tend to compress them further and increase the clumping factor, whereas their pressure expansion decreases the clumping factor. It is clear from the figure that, under the present assumptions, wind structure can survive to very large distances.

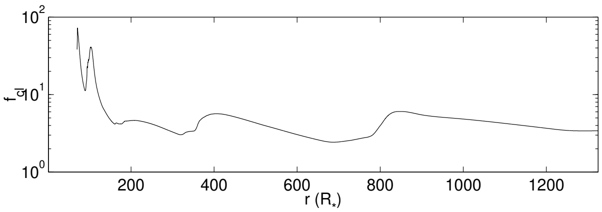

Fig. 2. Clumping factor as a function of radius.

One obvious limitation of the present model is its one-dimensionality. In three-dimensional space, clumps can pass each other without colliding, which is not possible in a one-dimensional model. Also, the structure initiated in the inner wind is bound to be different in three dimensions. Unfortunately, it is not yet possible to calculate a three-dimensional model taking into account the instability.

Both modifications with respect to the models from Paper I—the lower floor temperature and the larger value of the line-strength cut-off $\kappa_{\max}$—substantially increase the predicted level of clumping. The current model has a mass-loss rate of $\sim 4 \times 10^{-6} M_\odot\,\mathrm{yr}^{-1}$. With the extreme clumpiness predicted, the radio flux of this model is many times larger than the observed flux. This could mean that the mass-loss rate derived from the radio flux assuming a smooth wind is overestimated by more than the canonical factor of three often quoted. Explaining such a low mass-loss rate for an O-star might be problematic in terms of line-driving. Another possible explanation is that the clumpiness of the present model is exaggerated, perhaps due its one-dimensionality. These issues will be addressed in a forthcoming paper (Runacres & Owocki 2003).

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