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Super Eddington Atmospheres and their Winds

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Abstract.
We present a model for the steady state winds of super-Eddington systems. These radiatively driven winds are expected to be optically thick and clumpy as they arise from a porous atmosphere. The model is then used to derive the mass loss of bright classical novae. The long duration super-Eddington outflows that are clearly observed in at least two cases (Nova LMC 1988 #1 & Nova FH Ser) are naturally explained. Moreover, the predicted mass loss and temperature evolution agree nicely with the observations, as do additional features. η Car is then used to double check the theory which predicts the observed mass shed in the great eruption.

1. Introduction

η Car was super-Eddington (hereafter SE) during its 20 year long eruption (e.g., Davidson & Humphreys 1997). Yet, its observed mass loss and velocity are inconsistent with a homogeneous solution for the wind (Shaviv 2000b). Basically, the sonic point obtained from the observed conditions necessarily has to reside too high in the atmosphere, at an optical depth of only ~ 1 to ~ 300, while the critical point in a homogeneous atmosphere necessarily has to reside at significantly deeper optical depths. The inconsistency arises because the sonic and critical points have to coincide in a steady state solution.

A solution was proposed in which the atmosphere of η Carinae is inhomogeneous, or porous (Shaviv 2000b). The inhomogeneity is a natural result of the instabilities of atmospheres that are close to the Eddington luminosity (Shaviv 2000a). The inhomogeneities, or "porosity", reduce the effective opacity and increase the effective Eddington luminosity (Shaviv 1998). Here, we are interested in understanding the wind generated in cases in which the luminosity is SE. To do so, it is advantageous to find a class of objects for which better data than for η Car exists. One such class of objects is novae. Their advantage over other types is that their mass and luminosity is known better than all other SE objects, allowing a detailed analysis.

2. The Fundamental Structure of Super-Eddington Winds (SEWs)

The above considerations lead us to propose the structure described in fig. 1 for a SE atmosphere and its SEW. The most important point raised here is the identification of the location of the sonic point: If the flux corresponds to an

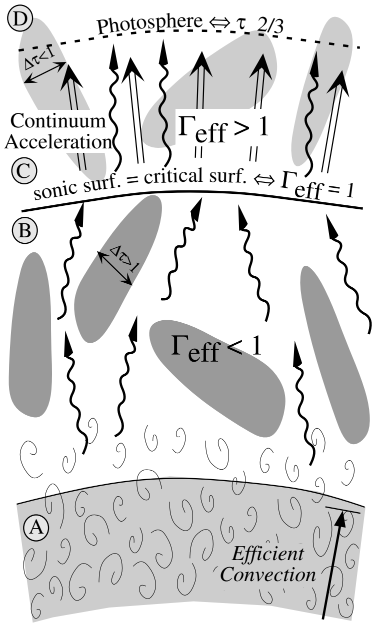

Figure 1. The structure of a super Eddington atmosphere and the wind that it generates. **Region A**: A Convective envelope – where the density is sufficiently high such that the excess flux above the Eddington luminosity is advected using convection. The radiative luminosity left is below the classical Eddington limit: $L_{\mathrm{rad}} < \mathcal{L}_{\mathrm{Edd}} < L_{\mathrm{tot}}$. Convection is always excited before the Eddington limit is reached. Thus, if the density is high enough and the total flux is SE, this region has to exist. **Region B**: A zone with lower densities, in which convection becomes inefficient. Instabilities render the atmosphere inhomogeneous, thus facilitating the transfer of flux without exerting as much force. The effective Eddington luminosity is larger than the classical Eddington luminosity: $\mathcal{L}_{\mathrm{Edd}} < L_{\mathrm{rad}} = L_{\mathrm{tot}} < \mathcal{L}_{\mathrm{eff}}$. η Car has shown us that the existence of this region allows for the steady state outflow during its 20 year long eruption (Shaviv 2000b). **Region C**: A region in which the effect of the inhomogeneities disappears and the luminosity is again SE. When perturbations arising from the instabilities, which are expected to be of order the scale height in size, become transparent, the effective opacity tends to the microscopic value and the effective Eddington limit tends to the classical value. At the transition between (B) and (C), the effective Eddington is equal to the total luminosity. This critical point is also the sonic point in a steady state wind. Above the transition surface, $L_{\mathrm{tot}} > \mathcal{L}_{\mathrm{eff}} \rightarrow \mathcal{L}_{\mathrm{Edd}}$ and we have an optically thick super-sonic wind. **Region D**: The photosphere and above. Since the wind is thick, region (C) is wide.

Eddington parameter Γ, then the optical depth at which perturbations cannot reduce the effective Eddington parameter to unity, should scale as $\Gamma - 1$. The reason is that the needed luminosity decrease should be proportional to the deviation of the actual luminosity from the Eddington one. Namely, when close to the Eddington limit, a blob with the same geometry needs a smaller density fluctuation and with it a smaller change in the opacity, to reduce the effective opacity by the amount needed to become Eddington. Thus, when closer to the Eddington limit, the sonic point can sit higher in the atmosphere.

By writing the expression for the scale height, which is expected to be of order the typical size of the perturbations, one obtains the mass loss:

$$\dot{M} = 4\pi R_\star^2 f \rho_\star v_s = \mathcal{W}(\Gamma) \frac{L_{\mathrm{tot}} - \mathcal{L}_{\mathrm{Edd}}}{c v_s}, \tag{1}$$

where $1-f$ is the covering factor of the dense blobs and $\mathcal{W}(\Gamma)$ is a dimensionless function that is expected to be almost a constant of order of unity, or perhaps somewhat larger, depending on the efficiency at which the effective opacity can be reduced (the smaller the efficiency, the larger will $\mathcal{W}$ be). It is only with more elaborate simulations or with more accurate observations, that a more accurate functional form can be deduced. For the meantime, we settle with this simplifying yet reasonable assumption. We will show in the rest of the paper that eq. 1 provides an explanation to the mass loss from bright classical novae as well as from η Car and allows us to connect between the observed luminosity and mass loss rate, a relation which hitherto did not exist for SE systems.

Before we compare to observations, we need to consider that the winds generated are heavy and a significant part of the radiation can be used to drive the wind up the potential well and to accelerated it. We use the relations of Owocki & Gayley (1997) to relate the parameters important for the wind at its base (e.g., $\Gamma_\star$, v_{esc}) to the parameters observed at infinity (e.g., Γ_∞, $v_{\rm esc}$). An example can be found in fig. 2 which depicts the observed parameters as a function of $\Gamma_\star$ and $\tilde{\mathcal{W}} \equiv v_{\rm esc}/(2 v_s c)\mathcal{W}$.

3. Application of the SEW theory

We now proceed to apply the SEW theory to systems that clearly exhibited SE outflows over dynamically long durations. We then continue with general predictions pertaining to novae and SEWs.

– **The wind parameter:** Each of the three SE objects was studied in a different manner since the observational data was different. FH Ser has measurements of the time evolution of the bolometric flux, color temperature and velocity at infinity (Friedjung 1989). The data for LMC 88 #1 (Schwarz 1998) do not have proper measurements of the velocity evolution, but the temperatures given are the effective ones. η Car is a markably different system than that of novae and since it doesn't have proper measurements of the evolution of temperature and luminosity during its great eruption, we just take the estimates given by Davidson (1999) for the integrated mass loss and energy radiated during the eruption. Using the SEW theory we find the following values for the wind parameter: $\mathcal{W} = 2.8 \pm 1.4, (7.5 \pm 4)/\delta^{3/4}, 4.5 \pm 3.3$ for Novae LMC 88#1, FH Ser, and η Car respectively. $\delta^2 \equiv \left\langle \rho^2 \right\rangle / \left\langle \rho \right\rangle^2$ is the clumpiness parameter. It enters the analysis of FH Ser when translating the color temperature into a mass loss rate. As expected, we find that all $\mathcal{W}$'s obtained are consistent with each other and the theory provided that there is some clumping in the wind. Clumping is however predicted since SEWs originate from inhomogeneous atmospheres. The amount of clumping needed is similar to that already observed in WR winds (e.g., St.-Louis et al. 1993).

– **Temperature evolution:** In the case of FH Ser, where good data for the evolution of the velocity are present, a better prediction for the evolution of the temperature can be made using the observed luminosity . The agreement between the predicted temperature and the observed temperature is seen in fig. 3.

– **Super Eddington fluxes:** In a homogeneous atmosphere, one expects the steady state structure to relax into a sub-Eddington state, as is given by the core-mass luminosity relation (Paczynski 1970). The fact that a reduced effective opacity is obtained for an inhomogeneous system, implies that the "saturation" luminosity should be the modified Eddington luminosity, which of course is larger than the classical Eddington one.

– **The "Transition Phase":** One of the seemingly odd behavior that is displayed by a large majority of all the classical nova eruptions is a transition

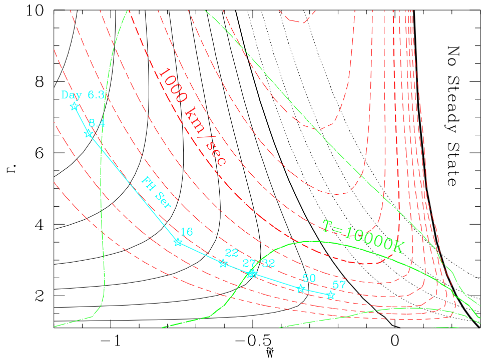

Figure 2. The evolution of FH Ser in the $\Gamma_\star$ - $\tilde{W}$ plane. The lines are iso-contours of Γ_∞ (the solid lines for $\Gamma_\infty \geq 1$ are spaced at 0.2 dex, and dotted spaced linearly at 0.2 intervals for $\Gamma_\infty < 1$), v_∞ (short-long dashed lines spaced at intervals of 100 km/sec, higher are larger) and the color temperature of the photosphere $T_{\rm ph}$ (dot-dashed lines spaced at 2500°K, lower is hotter).

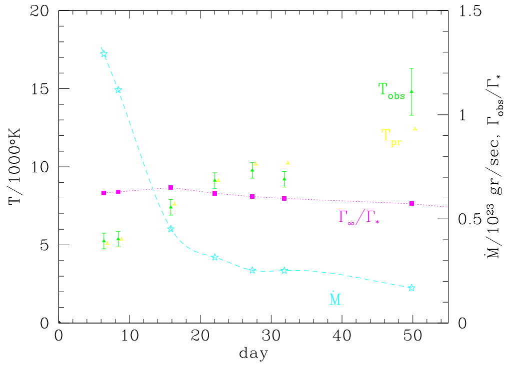

Figure 3. The observed temperature behavior $T_{\rm obs}$ of FH Ser as compared with the predicted temperature behavior $T_{\rm pr}$ from the observed luminosity and wind model, for the best fit model assuming $M_{\rm WD} = 0.8 M_\odot$ and $X = 0.7$. Additional plots are of the mass loss and the ratio of Γ_∞ to $\Gamma_\star$.

phase. If it appears, it starts once the visual magnitude has decayed by 3 to 4 magnitudes. During the transition phase, the light curve can display strong deepening, quasi-periodic oscillations, erratic changes or other complicated behavior. The SEW theory can naturally explain the transition phase. If we look at the Γ_0 - $\tilde{W}$ trajectory of FH Ser in fig. 2 (which had a transition phase), one cannot avoid the extrapolation of the trajectory into the zone of "no steady state configuration". In this zone, the wind is too thick for the radiation field to push to infinity. The wind then naturally stagnates and it does not allow a steady state. Non trivial 2D or 3D flows that must result could potentially yield the non trivial variability observed. The phase is expected to end once the luminosity at the base of the wind falls below the Eddington limit, shutting off the SEW, at which point the "naked" white dwarf should emerge.

– **General Mass Loss of Novae:** We can use the trends observed for the nova population in general to predict an average mass-loss. To do so, we create a template nova as a function of white dwarf mass and explore its properties. Its predicted mass loss is then compared with the observed integrated mass loss. Clearly, we expect the theoretical prediction to provide the guide line to which the *average* behavior should be compared to. Using general relations between average observed novae parameters, we can write down the peak bolometric luminosity of the nova as a function of WD mass. We assume that the transition phase corresponds to the nova's base bolometric luminosity crossing the Eddington limit. If we further assume that it decays exponentially (or linearly), we can calculate the total mass loss by integrating eq. 1. The results are plotted in fig. 4 together with the observed determinations of ejecta masses. Evidently, the SE bolometric behavior of classical novae agrees well with the observed mass loss if we use the SEW theory described here. Note that the standard simulations of

TNRs using a *homogeneous* atmosphere predict a mass loss that is an order of magnitude smaller for the large WD masses.

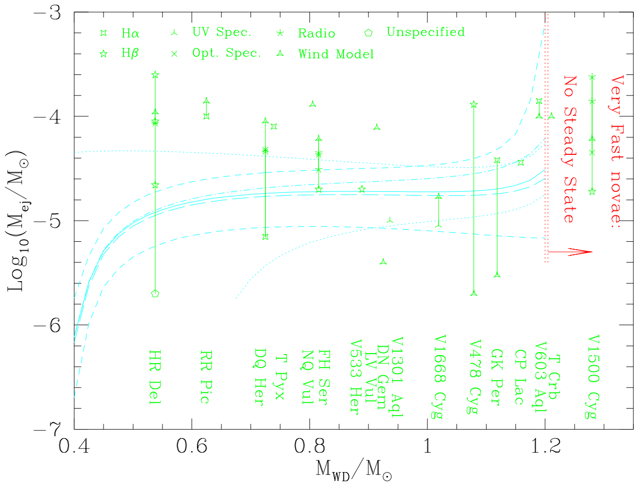

Figure 4. Nova ejected mass vs. WD mass. The solid line is obtained by the wind model assuming $\mathcal{W} = 2.8$, the long dashed line when X is changed from 0.7 to 0.3, the upper (and lower) short dashed lines when taking a value for $\mathcal{W}$ which is higher (lower) by 1.5, the dash-dotted line when a linear decay is assumed, and the dotted when taking into account the natural scatter in the t_3-$M_{\rm WD}$ relation.

– **A "Constant Bolometric Flux":** Some novae appear to have a plateau in their bolometric flux. If we look at fig. 2 and note that lines of constant radii are almost vertical, we see that for moderately "loaded" winds and $\Gamma_\star$ of a few, an evolution in which the temperature increases but the apparent luminosity remains constant is possible if the radius does not decrease dramatically. Under such conditions, the base luminosity of the wind does fall off to get a higher temperature, however, the lower mass loss predicted implies that less energy is needed to accelerate the material to infinity and so a larger fraction of the base luminosity remains after the wind has been accelerated, yielding an almost constant Γ_∞.
– **Clumpiness of the wind:** Since the atmospheres generating the SEWs are necessarily clumpy, the winds will be clumpy as well. By estimating the typical perturbation size in the unstable atmosphere, one can estimate the size of the blobs. In the case of novae and the instabilities found by Shaviv (2000a), the expected peak spherical harmonic of the clumpy wind is $\ell \lesssim 1000$.

4. Discussion & Summary

We have tried to present the following coherent picture which explains the observed existence of SE atmospheres: Homogeneous atmospheres becomes inhomogeneous as the the radiative flux approaches the Eddington limit. This is due to a plethora of instabilities. The particular governing instability depends on the details of the atmosphere. Due to the inhomogeneity, the effective opacity is then reduced as it is easier for the radiation to escape; consequently, the effective Eddington limit increases. SE configurations are now possible because the bulk of the atmosphere is effectively sub-Eddington. Very deep layers advect the excess total luminosity above Eddington by convection. Higher in the atmosphere, where convection is inefficient, the Eddington limit is effectively increased due to the reduced effective opacity. The top part of the atmosphere, where perturbations of order of the scale height become optically thin, has however to remain SE. Thus, these layers are pushed off by a continuum driven wind.

By identifying the location of the critical point of the outflow, one can obtain a mass-loss luminosity relation. The relation, given by eq. 1 is the main result of the paper. The relation has a universal dimensionless parameter which should be of order or somewhat larger than unity.

To check the result, we analyzed 2 novae and the star η Car. Although the two types of systems are markably different, as they have masses, luminosities and massloss rates which differ by orders of magnitude, the wind mass loss and the wind parameter are found to be in good agreement with the theoretical expectation. Moreover, the results are completely consistent with clumping — a natural prediction of SEWs since the atmospheric layers beneath the sonic point are predicted to be inhomogeneous.

We also identify the occurrence of the "transition phase" observed in a majority of the novae with the advance of the atmosphere into the "no steady state region". As the nova explosion progresses, its luminosity and radius decline. However, if the radius decreases too quickly, at some point the SEW predicted will be too heavy for the luminosity at the base to push to infinity. No steady state will then exist. The inconsistency might explain the strange behaviors observed in the transition phase of different novae.

The wind model presented is by no means a complete theory for novae since it cannot predict *ab initio* the luminosity at the base of the wind. To obtain the latter, one needs to solve for the complete evolution of a nova taking into account the porosity and lowered opacity in the nova atmosphere. One expects that the lowered opacity increases the luminosity obtained in the core-mass luminosity relation, and super-Eddington values therefore arise naturally.

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