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On the appearance of super-Eddington states in various astrophysical systems

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Abstract. We briefly review the characteristics of super-Eddington (SED) states which arise in various astrophysical systems. These include classical nova eruptions, giant LBV eruptions, super-massive objects (SMOs) and very high accretion rate flows. The former two have ample observational data to establish the existence of SED states and learn of their behavior. When applying this understanding to the latter two, very interesting conclusions can be drawn. For example, "super-Eddington" black hole growth through accretion is possible, but SMOs cannot provide the photoionizing radiation in the early Universe, though they can provide seed black holes.

Key words. Stars: atmospheres – Accretion Disks

1. Introduction

The notion that *steady state* objects cannot surpass the Eddington luminosity, without evaporating themselves on short time scales, rests on the assumption that the average opacity "seen" by the outgoing photons cannot decrease below that of Thomson scattering[1]. As described below, however, observations tell us that steady state SED configurations are possible.

The understanding of how SED states arise and what their characteristics are, rests on several several key points:
(1) Atmospheres become unstable as they approach the Eddington limit. In addition to instabilities that operate under various special conditions (e.g., Photon bubbles in strong magnetic fields or the s-mode instability under special opacity laws), two instabilities were found to operate in Thomson scattering atmospheres (Shaviv 2001a). Moreover, one of these instabilities does not depend on the boundary conditions and is therefore extremely general. It implies that *all atmospheres will become unstable already before reaching the Eddington limit*.

(2) The effective opacity relevant for the calculation of the radiative force on an inhomogeneous atmosphere is not necessarily the microscopic opacity (Shaviv 2001b). Instead, it is given by $\kappa_V^{\mathrm{eff}} \equiv \langle F\kappa_V \rangle_V \,/\, \langle F \rangle_V$. The situation is very similar to the Rosseland vs. Force opacity means used in non-gray atmospheres, where the inhomogeneities are in frequency space as opposed to real space. For the special case of Thomson scattering, the effective opacity is always reduced.

(3) Even if the bulk of the atmosphere remains sub-Eddington (either through the triggering of convection deep inside the atmosphere, or through the appearance of the porosity described above, the region where the inho-

[1] At very high temperatures, the Klein-Nishina reduction can reduce the opacity, but the radiation would necessarily be in γ-rays.

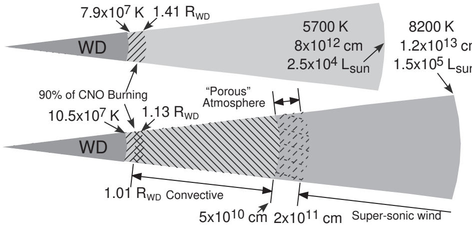

Fig. 1. The structure of a CNO shell burning $1M_\odot$ white dwarf with a $10^{-4}M_\odot$ envelope. Unlike the top panel which is described by the classical CMLR, the bottom panel describes an atmosphere in which the radiative instability is taken into account, such that it can become porous. This allows the occurrence of a super-Eddington steady state. A convection zone arises and its inner boundary is well within the nuclear burning zone. A continuum driven wind is launched such that the photosphere is in a wind.

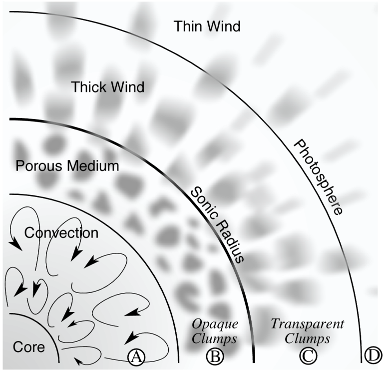

Fig. 2. The structure of a super-Eddington star. **(A)** Deep inside the star where the density is sufficiently high, any excess flux above the Eddington luminosity is carried by convection. Thus, we have a bound interior with $L_{\rm rad} < L_{\rm Edd} < L_{\rm tot}$. **(B)** Farther out, where convection is inefficient, radiative instabilities cause the atmosphere to become inhomogeneous. This reduces the effective opacity and thus increases the effective Eddington luminosity $L^{\rm eff}_{\rm Edd}$. As such, this layer is bound, not because the radiation flux is lowered (as occurs in the convective region), but because the effective opacity is reduced. Thus in this layer, $L_{\rm Edd} < L_{\rm rad} < L^{\rm eff}_{\rm Edd}$. **(C)** Opacity reduction can operate only if the inhomogeneity clumps are optically thick. Farther out, at lower densities, where the clumps become transparent, the effective opacity returns to the microscopic value and $L^{\rm eff}_{\rm Edd} \approx L_{\rm Edd}$. A sonic or critical point in the mass outflow will be located where $L = L^{\rm eff}_{\rm Edd} \gtrsim L_{\rm Edd}$. **(D)** Since the mass loss rate is large, the wind is optically thick and the photosphere resides in the wind itself.

mogeneities ("blobs") become optically thin, the atmosphere becomes SED, and a wind is driven. Shaviv (2001b) has shown that all steady state SED atmospheres will drive a wind with a mass loss of $\dot M = \mathcal{W}(L - L_{\rm Edd})/cv_s$, where $\mathcal{W}$ is a dimensionless wind constant, which can be a weak "function" of $L/L_{\rm Edd}$, and v_s is the speed of sound at the base of the wind. This mass loss formula correctly predicts the mass loss observed in novae and in η-Car.

When combining the above understanding, we can explain different SED objects—novae and η-Car, and correctly predict several of their main characteristics. We can then apply this understanding to other systems which are not observationally constrained—Super-Massive Objects (SMO's) and high accretion rate disks.

2. Classical nova eruptions

It was for long believed that once the thermonuclear runaway of classical novae stabilizes, the nova should be described by the classical Core Mass Luminosity Relation (CMLR, Paczyński 1970), that is, an inert core, a shell burning nuclear material, and an envelope which saturates at the Eddington luminosity.

However, classical novae exhibit long duration SED luminosities while in their eruptive state. At least, this is the conclusion that should be reached when combining that the peak luminosity of novae (with $M_{WD} \gtrsim 0.5M_\odot$, Livio 1992) is always SED and that in all cases where the bolometric evolution was recovered (using UV observations), it was shown to decay slowly (e.g., Friedjung 1987, Schwarz et al. 2001, Shaviv 2001b).

To understand their behavior, we solved for the steady state shell burning. When porosity is not included, the classical CMLR is recovered. However, once we introduce a modified opacity law of the form $\kappa = \kappa_0$ if $\Gamma < \Gamma_{\rm crit}$ and $\kappa = \kappa_0(\Gamma/\Gamma_{\rm crit})^{-\alpha}$ for $\Gamma > \Gamma_{\rm crit}$, together with a SED mass loss described above, we obtain a

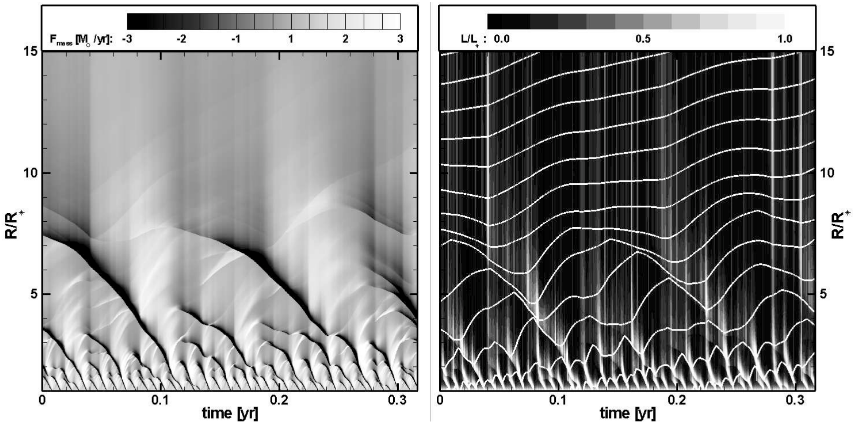

Fig. 3. Grayscale plot of radius and time variation of mass flux (left) and luminosity (right) in a time-dependent simulation of a SED wind with a porosity-mediated base mass flux above the photon tiring limit. The white contours on the right trace the height progression of fixed mass shells. For more information see van Marle et al. (2009).

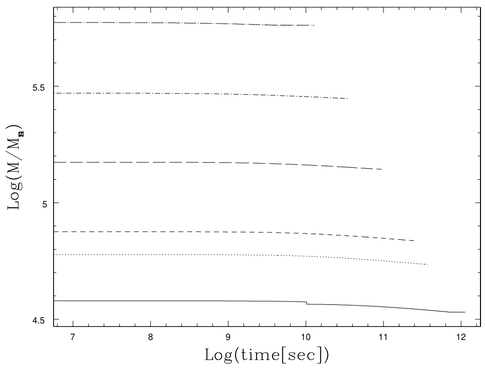

Fig. 4. The mass evolution of super-massive objects, which arises from their gravitational contraction. The zero-age mass of the objects is given by the intersection with the y-axis. The mass loss is due to the SED continuum driven winds. Although there is a large mass loss associated with the winds, it is insufficient to affect the evolution.

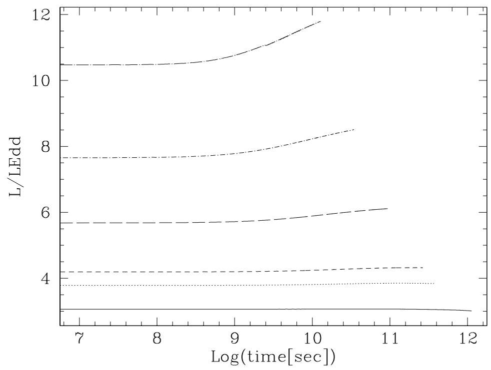

Fig. 5. The total luminosity evolution of super-massive objects. During their evolution, the objects shine at a few times the Eddington luminosity. Note that because of their large winds, the photosphere is at a very large radius and the temperature is low. Curves as in the previous figure.

SED state. This SED branch of the CMLR is not envelope mass independent anymore. The structure of the sub and SED solutions is compared in fig. 1.

It is interesting to note that the SED wind has several ramifications to the understanding of novae. First, the mass loss implies that the nova evolves primarily because the envelope mass is driven off, not because of depletion of the nuclear fuel. Second, the optically thick winds imply that the photosphere resides in them, such that the luminosity and temperature evolution are a manifestation of the evolving mass loss. The predicted evolution is consistent with the observed one.

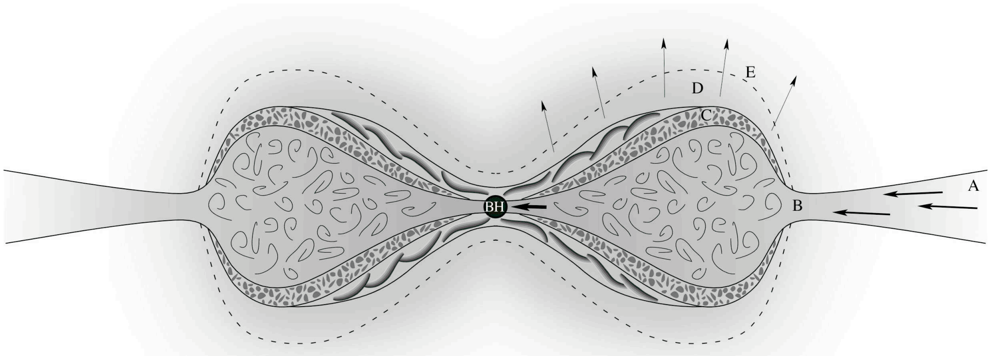

Fig. 6. The "slim" disk model for super-Eddington accretion modified to include SED states. (A) An accretion disk is responsible for loss of angular momentum and feeding the system with accretion mass. (B) The accretion disk looses its flat geometry at the radius where the energy release corresponds to the Eddington luminosity. The geometry remains that of a disk, though it puffs up and becomes radiation-pressure dominated. Because of the large optical depth, advection of the radiation field can be faster than its radiation through the surfaces (i.e., photon trapping can take place). However, once the existence of SED states are allowed to arise, the standard picture get modified. (C) A porous layer forms at the less dense regions above the convection layer. (D) At a height were the porous structure become optically thin, a wind is accelerated. (E) Since it is optically thick, the photosphere is located in the wind itself. (F) In the inner parts of the disk, the escape velocity is large enough to give rise to photon tired layer, which effectively moves the sonic point higher.

3. Giant LBV eruptions - η-Carinae

The most impressive example of a "steady state" SED object is arguably the giant eruption of η-Carinae, 150 years ago. During its 20yr eruption, η-Car lost several solar masses. Given its mass, η-Car was clearly SED, yet, it is impossible to construct a model without the existence of a porous layer. Without it, one would have to drive a wind with a sonic point located at the top of the internal convection layer. Because of the much higher density there, a mass loss of order $\dot{M} \sim L/v_s^2$ would be generated. This is a much higher mass loss than observed. Moreover, with such a high mass loss, a large fraction of the emerging radiation flux would actually go to accelerate the wind, leaving a sub-Eddington object (Shaviv 2000).

Once a porous layer is added, the star obtains the structure described in fig. 2. An interesting modification arises when the predicted mass loss is too high for the available luminosity to push to $r \to \infty$. This happens when $v_{esc} \gtrsim \sqrt{v_s c/\mathcal{W}}$, and gives rise to "photon-tired winds" (Owocki & Gayley 1997).

The behavior of photon tired winds was studied by van Marle et al. (2009). It was found that a layer of shocks is formed in which there is a large kinetic flux without the associated mass flux. The structure of such a layer is demonstrated in fig. 3.

4. Super-massive objects

Stellar-like objects with $M \gtrsim 10^4 M_\odot$ never become real stars. As they contract and release their gravitational binding energy, GR corrections eventually become significant, and force the object to collapse and form a massive BH. This collapse takes place while the object's central conditions are insufficient to ignite nuclear burning. Today, because of the high metalicity, such objects cannot form to begin with, but they may have existed in the young universe.

Classically, the high radiation to gas pressure ratio implies that these high entropy objects are supposed to shine very close to the Eddington limit. Given our understanding of high luminosity atmospheres, we know that instabilities would reduce the effective opacity and form a SED object with a structure similar to the one described in fig. 2. The main

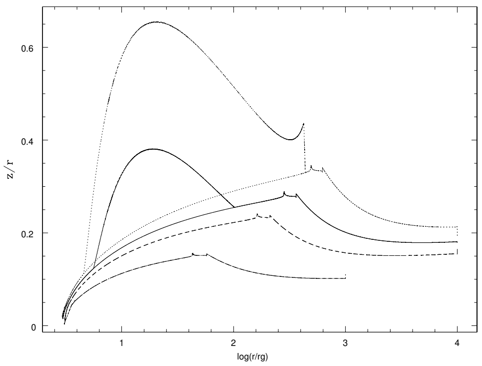

Fig. 7. The vertical height (z/r) of the accretion flow in a SED accretion disk, as a function of r/r_g. Solid lines denote the position of the photosphere when an optically thick wind is absent. The dashed lines denote the location of the photosphere when a thick wind is present, in which case the thick lines is the location of the sonic point where the wind is launched. From bottom to top, the accretion rates are $\dot{m} = 1\dot{m}_{crit}, 5\dot{m}_{crit}, 10\dot{m}_{crit}$ and $20\dot{m}_{crit}$. For the two bottom accretion rate, no optically thick wind is present. The spikes are numerical artifacts arising from the changing opacity law.

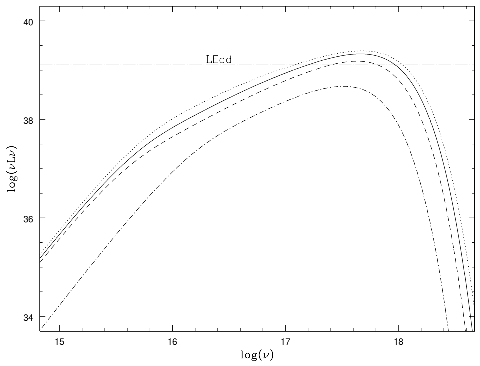

Fig. 8. The resulting integrated spectrum of the accretion disk, for an observer above the disk. The lines denote the same accretion rates as above.

difference is that unlike a normal star, there is no nuclear burning core. Instead, the energy radiated away is supplied from the gravitational contraction.

We constructed SED solutions to supermassive objects (Dotan & Shaviv 2009a). The results are summarized in figs. 4 and 5. The main conclusions we find are the following:

1. Because the objects are SED, they live shorter lives before reaching the GR instability. Unlike the standard solution which lacks any wind, SED SMOs have strong winds. However, because of their short lives, the winds are not sufficient to "evaporate" the objects before their collapse.
2. The winds however are optically thick, such that the photosphere resides at large radii. As a consequence, SMOs are not expected to emit photoionizing radiation as classical SMOs could. In fact, given the expected SED behavior, SMOs formed in the young universe should be seen today only in the IR.

5. Super-Eddington accretion disks

High accretion rate disks are too radiation pressure dominated, and as such, their structure is expected to change once we introduce the appearance of a porous layer with a reduced opacity.

High accretion rate disks, appear as standard Shakura-Sunyaev thin disks outward of the radius where the energy released in the accretion process is comparable to the Eddington luminosity. Inward of the critical radius, radiation pressure begins to dominate, the disk puffs up, and the flow becomes advection dominated. Classically, the local flux cannot surpass the Eddington flux, and thus the total total luminosity is bounded[2].

Once we allow the system to develop a porous layer with a reduced effective opacity in the radiation pressure dominant regions, we obtain super-Eddington solutions (Dotan & Shaviv 2009b). These solutions are heuristically described in fig. 6. Numerically, the solutions are obtained as a 1+1D solution.

[2] Because the effective area of a disk is larger than that of a sphere, the maximum luminosity possible is $\sim L_{\rm Edd} \ln(r_{\rm out}/r_{\rm in}) \sim L_{\rm Edd} \ln(\dot{m}/\dot{m}_{\rm crit})$ (Paczyński & Wiita 1980).

Table 1. Results for SED disks, with a central black hole of $M = 10M_{\odot}$. Note that the critical accretion rate is defined as $\dot{m}_{\rm crit} \equiv L_{\rm edd}/\eta_0 c^2$, with the standard efficiency being $\eta_0 = 0.0625$.

$\dot{m}/\dot{m}_{\rm crit}$	1	5	10	20
$\dot{m}_{\rm real}/\dot{m}_{\rm crit}$	0.75	2.42	3.8	5.7
$L/L_{\rm Edd}$	0.77	2.66	4.0	4.9

That is, the vertical structure is solved for, and any excess energy is advected with the flow.

Fig. 7 describes the vertical structure of the disks. The solution is of a slim disk. In particular, the height of static part of the disk is less than 30% of the radius even for $\dot{m} = 1\dot{m}_{crit}$. Fig. 8 describes the apparent spectrum. It has a much stronger long wavelength shoulder than could be expected from a standard slim disk. This is because of the optically thick wind.

The total luminosity and actual BH accretion rates are summarized in table 1.

6. Summary

Super-Eddington states appear to be a natural consequence of radiation pressure dominated systems. They seem to arise naturally in classical nova eruptions and in LBVs. Because of their ample observations, classical novae serve as fertile testing grounds for the SED theory, a theory which adequately describes the appearance and evolution of these objects.

We applied the SED theory to various radiation pressure dominated systems. Following are some of the conclusions we reached.

Classical Nova Eruptions are supposed to be described by the classical core-mass luminosity relation. Instead, the appearance of a super-Eddington state takes place once porosity arises. This new super-Eddington branch of the CMLR relation is not envelope mass independent anymore.

η-*Carinae*'s giant eruption and in particular its mass loss are well described by the present super-Eddington theory, and the wind that it accelerates. It is interesting that η-Car is close to, and may have reached the photon-tired limit. *Super-Massive Objects* are classically supposed to shine very close to the Eddington limit (because they are radiation pressure dominated). However, the SED theory provides us with solutions which are super-Eddington with an optically thick wind. Because the wind downgrades the photons to lower energy, SMOs cannot have provided the re-ionizing radiation of the young universe.

Super-Eddington Accretion disks. By allowing the existence of SED states, we obtained super-Eddington accretion disks which manifest themselves as super-Eddington objects and with super-Eddington accretion rates onto the central black hole. This allows for much higher maximal growth rates for galactic Black Holes.

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