The boundary layer of VW Hyi in quiescence

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ABSTRACT

In this letter, we suggest that the missing boundary layer luminosity of dwarf novae in quiescence is released mainly in the ultraviolet (UV) as the second component commonly identified in the far ultraviolet (FUV) as the "accretion belt".

We present the well-studied SU UMa-type system VW Hyi in detail as a prototype for such a scenario. We consider detailed multiwavelength observations and in particular the recent FUSE observations of VW Hyi which confirm the presence of a second component (the "accretion belt") in the FUV spectrum of VW Hyi in quiescence. The temperature (≈50,000K) and rotational velocity (>3,000km s⁻¹) of this second FUV component are entirely consistent with the optically thick region (τ ≈ 1) located just at the outer edge of optically thin boundary layer in the simulations of Popham (1999).

This second component contributes 20% of the FUV flux, therefore implying a boundary layer luminosity: \( L_{BL} = 2 \times (0.2 \times L_{UV} + L_{X-ray}) = 0.6 \times L_{disc} \), while the theory (Kluźniak 1987) predicts, for the rotation rate of VW Hyi's WD, \( L_{BL} \approx 0.77L_{disc} \). The remaining accretion energy (< 0.1L_{acc}) is apparently advected into the star as expected for optically thin advection dominated boundary layers. This scenario is consistent with the recent simultaneous X-ray and UV observations of VW Hyi by (Pandel, Córdova & Howell 2003), from which we deduced here that the alpha viscosity parameter in the boundary layer region must be as small as \( \alpha \approx 0.004 \).

Key words: accretion, accretion discs, -stars:individual: VW Hyi - novae, cataclysmic variables.

1 INTRODUCTION: VW HYI - A KEY SYSTEM FOR UNDERSTANDING DWARF NOVAE

Dwarf novae (DNe) are mass-exchanging binaries in which a low-mass main sequence-like star (the secondary) fills its Roche lobe and loses hydrogen-rich matter to a white dwarf (WD) star (the primary). The mass transfer is regulated by an accretion disc, which undergoes cyclic changes of the mass accretion rate \( \dot{M} \). The low mass accretion rate \( (\dot{M} \approx 10^{-11}M_\odot \text{ yr}^{-1}) \) quiescent stage is interrupted intermittently every few weeks (to months) by a high mass accretion rate \( (\dot{M} \approx 10^{-8}M_\odot \text{ yr}^{-1}) \), the DN outburst stage which lasts days (to weeks).

At 65 pc VW Hyi is one of the closests (Waner 1987) and brightest example of the SU UMa sub-class of DNe, which undergo both normal DN outbursts and superoutbursts. The mass of the accreting WD was estimated to be 0.63 \( M_\odot \) (Schoembs & Vogt 1981), but more recently a gravitational redshift determination yielded a larger mass \( M_{wd} = 0.86M_\odot \) (Sion et al. 1997). The inclination of the system is \( \approx 60 \) degrees (Schoembs & Vogt 1981) and, with an orbital period of 107 minutes, it lies below the CV period gap, where gravitational wave emission is thought to drive mass transfer, resulting in very low accretion rates during dwarf nova quiescence. In addition, it lies along a line of sight with an ideally low HI interstellar column of \( \approx 6 \times 10^{17} \text{ cm}^{-2} \) (Podidid, Mauche & Wade 1990). As a consequence, VW Hyi has been observed in nearly all wavelength ranges, and it is, therefore, one of the best-studied systems.

However, there have been some discrepancies between the observed X-ray luminosity and the expected boundary layer (BL) luminosity in VW Hyi and other systems. We suggest here that the missing boundary layer luminosity in quiescence is released mainly in the ultraviolet as the second FUV component commonly identified as the "accretion belt".

In the next section we review multi-wavelength observations of VW Hyi and identify each components in the system. In particular, in section 3, we suggest that the second FUV component is the optically thick region at the outer edge the optically thin boundary layer. We discuss the implications of this suggestion for VW Hyi in detail in section 4, and we conclude this letter in section 5.
2 MULTIWAVELENGTH OBSERVATIONS OF VW HYI

2.1 The Disc in the Optical

In quiescence VW Hyi has an optical magnitude of about 13.8, and an optical flux of about $F_{\text{opt}} = 8.5 \times 10^{-11}$ erg cm$^{-2}$s$^{-1}$ (van Amerongen et al. 1987, Pringle et al. 1987). Because of its low mass accretion rate and temperature (< 8,000K), the accretion disc is expected to be the main source of the optical flux in quiescence, namely $F_{\text{disc}} = F_{\text{opt}} = 8.5 \times 10^{-11}$ erg cm$^{-2}$s$^{-1}$. The energy, dissipated and radiated locally in the disc, is exactly half of the accretion energy (Shakura & Sunyaev 1973, Lynden-Bell & Pringle 1974):

$$L_{\text{disc}} = \frac{L_{\text{acc}}}{2} = \frac{GM_{\text{wd}} \dot{M}}{2R_{\text{wd}}},$$

where $G$ is the gravitational constant, $M_{\text{wd}}$ is the mass of the WD, $R_{\text{wd}}$ is the radius of the WD and $\dot{M}$ is the mass accretion rate.

The remaining available accretion energy, in the form of rotational kinetic energy, is expected to be dissipated in the so-called boundary layer (BL) - the interface between the inner edge of the fast rotating Keplerian disc and the slowly rotating surface of the accreting WD. This energy amounts (Klužniak 1987):

$$\frac{L_{\text{BL}}}{L_{\text{disc}}} = \left(1 - \frac{V_{\text{wd}}}{V_K(R_{\text{wd}})}\right)^2,$$

where $V_{\text{wd}}$ is the (equatorial) rotational velocity of the WD surface and $V_K(R_{\text{wd}})$ is the Keplerian speed at one stellar radius. For VW Hyi we have $V_{\text{wd}} \sin i = 400\text{km s}^{-1}$ and we set $V_K(R_{\text{wd}}) \sin i \approx 3,200\text{km s}^{-1}$ (Godon et al. 2004), this leads to a ratio $L_{\text{BL}}/L_{\text{disc}} = 0.77$. For a non-rotating WD one has $L_{\text{BL}} = L_{\text{disc}} = \frac{1}{2}L_{\text{acc}}$. Because of its small radial extent, the BL is expected to be very hot (with a temperature $T_{\text{BL}} \approx 10^8\text{K}$) and optically thin during quiescence, as the density there is very low. This tiny component is therefore expected to emit basically the other half of the accretion energy in the X-ray band.

X-ray observations of VW Hyi in quiescence first carried out with EXOSAT and ROSAT (van der Woerd & Heise 1987, Belloni et al. 1991 - using a single temperature plasma) revealed an X-ray bolometric flux $F_{\text{X-ray}} \approx 1.5 - 1.9 \times 10^{-11}$ erg cm$^{-2}$s$^{-1}$. Subsequent X-ray observations with ASCA and XMM-Newton (using two- and multitemperature plasma models (Hasenkopf & Eracleous 2002, Pandel et al. 2003 - respectively) revealed a total X-ray bolometric flux smaller by a factor of about 2: $F_{\text{X-ray}} \approx 5 - 8 \times 10^{-12}$ erg cm$^{-2}$s$^{-1}$. The X-ray observations all revealed a temperature $kT \sim$ a few keV, and possibly as high as $kT \approx 6 - 8\text{keV}$. Pandel et al. (2003) fit the line profile assuming that the X-ray emitting region is a thin equatorial belt near the surface of the WD with a rotational velocity $v \sin i = 540\text{km s}^{-1}$.

However, so far the X-ray observations for VW Hyi have revealed a much smaller BL luminosity than expected: $L_{\text{BL}} \approx 0.1L_{\text{disc}}$ (Belloni et al. 1991), while from geometrical consideration, namely assuming that the star occults half of the BL, Pandel et al. (2003) obtained $L_{\text{BL}}/L_{\text{disc}} = 0.2$.

2.3 The WD in the Ultraviolet

In general the WD in DNe has a typical temperature of about $T_{\text{wd}} \approx 15 - 50,000\text{K}$, and it is expected to dominate the ultraviolet (UV) light in most DNe in quiescence: $L_{\text{UV}} = L_{\text{wd}}$. For VW Hyi in quiescence, early IUE Observations (Mateo & Szkody 1984) revealed that the UV light from the system was dominated by the WD with $T_{\text{eff}} = 18,000 \pm 2,000\text{K}$. Verbunt et al. (1987) and Pringle et al. (1987) later estimated that the flux observed at IUE wavelengths was about the same as the one observed at optical wavelengths, namely $F_{\text{UV}} = F_{\text{opt}} = 8.5 \times 10^{-11}$ erg cm$^{-2}$s$^{-1}$. Much higher S/N spectra were later obtained with HST/STIS by Sion et al. (1995, 1996, 2001), who confirmed the basic shape of the spectrum. They found that the WD had a temperature of about 20,000K which varied by at least 2,000 K, depending on the time since outburst) with a rotation rate of about $\sim 400\text{km s}^{-1}$.

2.4 The Second Component in the Far Ultraviolet

However, there have been some indications of an additional component besides the white dwarf in the FUV spectrum of VW Hyi and other DNe in quiescence (e.g. the presence of emission lines and the bottoms of Lyman alpha profiles which do not go to zero as in pure white dwarf). While the dominant component is that of a WD, the second component is a rather flat continuum with an effective temperature that is much higher than that of the WD. Long et al. (1993) first suggested a fast rotating hot accretion belt around the WD as a second component to fit HUT observations of U Gem. Long et al. (1993) remarked that the physical basis for an accretion belt might be the spin-up of the surface layers of the WD during outburst and the slow conversion of kinetic energy to heat as a result of viscous heating in the differentially rotating atmosphere (Kippenhahn & Thomas 1978, Kutter & Sparks 1987, 1989).

The presence of the accretion belt was confirmed later for VW Hyi from its HST/STIS spectra (Sion et al. 1995, 1996 & 2001) and from its IUE spectra (Gänsicke & Bergermann 1996). It was found that the second component contributed about 20% of the FUV flux (with the WD contributing the remaining 80%) and remains pretty much the same 5 days apart (Sion et al. 2001).

More recently, a Far Ultraviolet Spectroscopic Explorer (FUSE) spectrum of VW Hyi was taken during quiescence (Godon et al. 2004), 11 days after outburst. With a usable wavelength range of 904-1188 Å, FUSE is able to probe the wavelength range $\lambda < 1150\text{Å}$ (while both STIS & IUE have $\lambda > 1150\text{Å}$) where the 20,000K WD is not expected to contribute to the spectrum, therefore making it possible to unambiguously decide on the nature of the second component. The best-fitting model to the FUSE data was a composite model consisting of a 23,000K WD rotating at $V_{\text{rot}} \sin i = 400\text{km s}^{-1}$ with a $\approx 48,000 - 50,000\text{K}$ accretion belt rotating at a velocity of $V_{\text{belt}} \sin i > 3,000\text{km s}^{-1}$. In this model, the white dwarf contributed 83% of the FUV flux and the accretion belt 17% of the FUV flux.
3 THE NATURE OF THE SECOND FUV COMPONENT

The picture of the second component that emerges from all the FUV observations of VW Hyi is that of a fast rotating hot component. However, if this component is an accretion belt formed during outburst, then one expects its velocity and temperature to decrease during quiescence. However, observations show that this accretion belt remains pretty much the same during quiescence, whether it is observed a few days or two weeks after outburst. This has led us to look for a different interpretation of the fast rotating hot component.

The only other region in the system that has such a high velocity and temperature is just at the interface between the inner edge of the disc and the outer edge of the boundary layer, as shown in the simulations of the optically thin BL during quiescence (Narayan & Popham 1993, Popham 1999). These simulations show that in the boundary layer itself the central temperature is very high ($\approx 10^6$K) but the effective temperature is low because of the low optical depth. However, except for the X-ray emitting region directly adjacent to the stellar surface, the only other region in the BL where the effective temperature is high is in a small region just outside the boundary layer, where the optical depth is of the order of one. This region coincides with a density increase at the inner edge of the disc at the so-called transition radius $R_{trans}$. For $r < R_{trans}$ the BL is optically thin, for $r > R_{trans}$, the disc is optically thick, and around $r \approx R_{trans}$, one has an optical depth $\tau \approx 1$. For an accretion rate $\dot{M} = 3.16 \times 10^{-11} M_* \text{yr}^{-1}$, Popham (1999) found $R_{trans} = 1.4 R_{\text{ad}}$ with a maximum temperature in the transition region reaching about 60,000K. The temperature and velocity of this transition region are both in agreement with the observations of the second component in the FUV spectrum of VW Hyi in quiescence, therefore implying that the transition region is probably the source emitting the second FUV component. In the one-dimensional simulations of Popham (1999), this second component forms a hot ring at the inner edge of the disc.

Further evidence to support such a scenario was advanced recently by Pandel et al. (2003) who carried out simultaneous X-ray and UV observations of VW Hyi. They found that the variability of the X-ray and UV bands are correlated and that the X-ray flux is delayed by about 100 s over the UV flux. They too suspected that the UV flux is emitted near the BL (at $r \approx R_{trans}$) and pointed out that accretion rate fluctuations in this UV region are propagated in the X-ray emitting part of the BL within 100 s. However, no temperature or velocity of the emitting UV source was derived in Pandel et al. (2003) and therefore the values of $T \approx 50,000 \text{K}$ and $V \sin i > 3,000 \text{km} \text{s}^{-1}$ derived in Godon et al. (2004) for the second FUV component provides solid evidence to support that scenario in which the boundary layer emits a substantial fraction of its energy in the FUV.

It is important here to remark, however, that the one-dimensional ‘classic picture’, in which the boundary layer is treated as part of the disc, does actually break down when the boundary layer becomes optically thin and advection dominated. The geometry of the advection dominated accretion flow changes dramatically from being thin and flattened to being approximately spherical (Popham 1999, Popham & Sunyaev 2001 - where the disc thickness $H$ becomes large: $H/r \approx 1$). In that case the boundary layer has to be treated as part of the star rather than part of the disc, as pointed out by Inogamov & Sunyaev (1999), who carried out such a treatment for accretion on to a neutron star. In this approach, the accreting gas reaches the equatorial region of the star spinning at the Keplerian velocity and forms a layer on the stellar surface which spreads from the equator toward the poles and form a so-called “spread layer” rather than a “boundary layer”. The deceleration of Keplerian rotation and energy release take place on the stellar surface in a latitude belt. As the matter loses angular momentum, the centrifugal force decreases, allowing the matter to move from the equator toward the poles. The combined effect of centrifugal force and radiation pressure (dominant in the case of accretion on to a neutron star) gives rise to two latitude rings of enhanced brightness which are symmetric about the equator. Such a treatment has not been carried out for accretion on to a WD in the optically thin regime and it is not clear whether two such rings would form in that case. However, what is clear is that the optically thin boundary layer has to be spherical and envelops the equatorial region of the star (spreading to some extent toward the poles). The X-ray are expected to be emitted closer to the stellar surface while the UV is emitted just outside the BL, where it meets the disc. The X-ray emitting region and the UV emitting region are separated by the optically thin spherical BL of thickness $\Delta R \approx 0.4 R_{\text{ad}}$ (Popham 1999).

4 DISCUSSION: THE CASE OF VW HYI

Here, we discuss the results obtained so far for VW Hyi and assess the luminosity and the viscosity parameter in the BL of VW Hyi.

4.1 The Luminosity

We suggest that the second component observed in the FUV spectrum of VW Hyi, commonly identified as the accretion belt, is really the outer edge of the spread boundary layer and therefore its contribution in the FUV flux has to be taken into account when computing the boundary layer luminosity. This belt accounts for 20% of the FUV flux, and consequently the boundary layer luminosity that is observed actually:

$$L_{BL} = L_X + 0.2 \times L_{\text{opt}} = 0.3 \times L_{\text{opt}},$$

where we have substituted $L_X = 0.1 L_{\text{opt}}$ (Belloni et al. 1991) and $L_{\text{UV}} = L_{\text{opt}}$ (Pringle et al. 1987). And since one-half of the boundary layer is occulted by the star, the total emission from the boundary layer is twice the amount observed, such that one has:

$$\frac{L_{BL}}{L_{\text{disc}}} = 0.6,$$

since it is assumed that $L_{\text{dis}} = L_{\text{opt}}$. To summarize, from an expected 0.77$L_{\text{disc}}$, the boundary layer radiates 0.6$L_{\text{disc}}$, one third of which is emitted in the X-ray and two third emitted in the FUV (as predicted by Pandel et al. 2003). The remaining energy is most probably advected into the outer layer of the star (implying $L_{\text{adv}} = 0.17 L_{\text{disc}}$), as expected.
for advection dominated optically thin boundary layers solutions (Narayan & Popham 1993, Popham 1999). However, no quantitative results have been presented for the optically thin branch of solutions of the boundary layer. The only quantitative results for advection dominated boundary layers are for the optically thick branch (Popham 1997, Godon 1997) which predict a ratio $L_{\text{adv}}/L_{\text{acc}} \approx 0.1 - 0.2$ in rough agreement with what we find here $L_{\text{adv}}/L_{\text{acc}} \approx 0.085 \approx 0.1$.

### 4.2 The Viscosity

X-ray observations of VW Hya in outburst (van der Woerd & Heise 1987) have revealed the presence of a 14s DNO, which has been associated with the rotation period of the Keplerian flow in the very inner disc. On the other hand, Pandel et al. (2003) found that the time it takes for the matter to transit through the boundary layer is about 100s, which is equivalent to the time it takes to spin down the matter from Keplerian speed to a stellar rotational velocity. We use here these two basic time scales to assess the viscosity parameter in the boundary layer of VW Hya.

From simple hydrodynamical considerations, the spin-down (or spinup) time $\tau_{\text{spin}}$ of a rotating flow is the geometric mean of the rotation time $\tau_{\text{rot}}$ and the viscous diffusion time $\tau_{\nu}$ (Gill 1982):

$$\tau_{\text{spin}} = \sqrt{\tau_{\text{rot}} \times \tau_{\nu}},$$

or equivalently:

$$\tau_{\nu} = \frac{\tau_{\text{spin}}^2}{\tau_{\text{rot}}}. \quad (1)$$

Using the value $\tau_{\text{rot}} \approx 14s$ (van der Woerd & Heise 1987) and $\tau_{\text{spin}} \approx 100s$ (Pandel et al. 2003), leads to $\tau_{\nu} \approx 667s$.

An estimate of the viscosity coefficient $\nu$ in the boundary layer region can then be assessed using a basic scaling argument. The straight viscous diffusion in a flow would spread the boundary effects in a time $t$ outward to a distance $\delta$ given by $\delta = \sqrt{\nu t}$ (Gill 1982). Therefore the viscous diffusion time $\tau_{\nu}$ is given by the simple relation:

$$\tau_{\nu} = \frac{\Delta R^2}{\nu},$$

where $\Delta R$ is the size of the boundary layer. Inverting the relation, one obtains:

$$\nu \approx \frac{\Delta R^2}{\tau_{\nu}} \approx 1.5 \times 10^{14} \text{cm}^2 \text{s}^{-1}, \quad (3)$$

where we have assumed $\Delta R \approx H \approx 0.1R_{\text{rad}}$ (Popham 1999, Pandel et al. 2003) and $R_{\text{rad}} \approx 8 \times 10^8 \text{cm}$. This value is in agreement within one order of magnitude with the value expected for the disc viscosity. For a thinner boundary layer region of $\Delta R \approx 0.1R_{\text{rad}}$, the viscosity parameter is smaller by an order of magnitude $\nu \approx 10^{13} \text{cm}^2 \text{s}^{-1}$. For a temperature of $10^8 \text{K}$ in the BL, the sound speed is close to $c_s \approx 10^8 \text{cm} \text{s}^{-1}$ and one has

$$\alpha \approx \frac{\nu}{c_s H} \approx \frac{1.5 \times 10^{14}}{10^8 \times 0.4 \times 8 \times 10^8} \approx 0.004.$$ 

We find that in the BL region the viscosity parameter $\alpha$ is rather small.

For comparison, in the inner disc, at $r \approx 2R_{\text{rad}} \approx 1.6 \times 10^9 \text{cm}$, where $T < 10,000 \text{K}$, one has $H/r \approx 0.01$, $c_s \approx 10^8 \text{cm} \text{s}^{-1}$ and $\nu = \alpha c_s H \approx \alpha \times 10^{13} \text{cm}^2 \text{s}^{-1}$.

### 5 CONCLUSION

In this letter, we claim that the BL in VW Hya radiates 2/3 of its emission in the UV (as the component previously identified as the accretion belt) and 1/3 in the X-ray, summing up to 0.6 of the disc luminosity. The remaining BL energy ($0.17L_{\text{disc}}$) is apparently advected into the star. We suggest that the BL in most quiescent DN is probably radiating a large fraction of the emission in the UV.

We also estimated that the alpha viscosity parameter in the BL region of VW Hya is as small as $\alpha \approx 0.004$. The present findings are important, since the origin and nature of the viscosity in the boundary layer are not known and might be very different from that in the Keplerian disc. The Balbus-Hawley instability (Balbus & Hawley 1991) is not expected to work in the boundary layer since there the relation $dH/dR < 0$ does not hold, and in addition the boundary layer is stable to the centrifugal instability according to the Rayleigh criterion $d(\Omega R^2)/dR > 0$ (Popham & Sunyaev 2001). It has been remarked (Brandenburg et al. 1995, Popham & Sunyaev 2001) that non linear instabilities in Poiseuille and Couette flows, previously investigated as the origin of the turbulence in the disc itself (Zahn 1990, Dubrulle 1991), could apply in the boundary layer region, because there the flow is forced by the boundary in a similar way. (i.e. the flow between two co-rotating cylinders when the outer cylinder rotates much faster than the inner one).

It has also been argued that a should depend on the shear (Godon 1996, Abramowicz, Brandenburg & Lasota 1996) which is much larger in the boundary layer than in the disc.

### ACKNOWLEDGMENTS

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