A STUDY OF THE EVOLUTION OF THE ACCRETION DISK OF V2051 OPHIUCHI THROUGH TWO OUTBURST CYCLES

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ABSTRACT

We follow the changes in the structure of the accretion disk of the dwarf nova V2051 Oph along two separate outbursts in order to investigate the causes of its recurrent outbursts. We apply eclipse-mapping techniques to a set of light curves covering a normal (2000 July) and a low-amplitude (2002 August) outburst to derive maps of the disk surface brightness distribution at different phases along the outburst cycles. The sequence of eclipse maps of the 2000 July outburst reveal that the disk shrinks at outburst onset while an uneclipsed component of 13% of the total light develops. The derived radial intensity distributions suggest the presence of an outward-moving heating wave during rise and an inward-moving cooling wave during decline. The inferred speed of the outward-moving heating wave is \( \approx 1.6 \) km s\(^{-1}\), while the speed of the cooling wave is a fraction of that. A comparison of the measured cooling wave velocity on consecutive nights indicates that the cooling wave accelerates as it travels toward disk center, in contradiction with the prediction of the disk instability model. From the inferred speed of the heating wave we derive a viscosity parameter \( \alpha_{\text{hot}} \approx 0.13 \), comparable to the measured viscosity parameter in quiescence. The 2002 August outburst had a lower amplitude (\( \Delta B \approx 0.8 \) mag), and the disk at outburst maximum was smaller than on 2000 July. For an assumed distance of 92 pc, we find that along both outbursts the disk brightness temperatures remain below the minimum expected according to the disk instability model. The results suggest that the outbursts of V2051 Oph are caused by bursts of increased mass transfer from the mass-donor star.

Key words: accretion, accretion disks — novae, cataclysmic variables — stars: individual (V2051 Ophiuchi)

Online material: color figures

1. INTRODUCTION

Cataclysmic variables (CVs) are close interacting binaries in which a late-type star (the secondary) overfills its Roche lobe and loses matter to a white dwarf (WD) companion via an accretion disk or column (Warner 1995). The subclass of dwarf novae comprises low mass transfer CVs in which mass is fed to a weakly magnetic (\( |B| \leq 10^6 \) G) WD. These binaries show recurrent outbursts of up to 5 mag on timescales of weeks to months as a consequence of a sudden increase in mass inflow in the accretion disk.

There are two competing models to explain the cause of the sudden increase in mass accretion. In the disk-instability model (DIM), matter is transferred at an essentially constant rate to a low-viscosity disk and accumulates in an annulus until a thermal-viscous instability switches the disk to a high-viscosity regime and the gas diffuses rapidly inward and onto the WD. In this case, the outburst starts at the radial position where the thermal instability first occurs and propagates as a heating wave on the rise and as a cooling wave along the decline back to quiescence (Hameury et al. 1998; Lasota 2001). In the mass transfer instability model (MTIM), the outburst is the time-dependent response of a high-viscosity accretion disk to a burst of enhanced mass transferred from the secondary star (Bath 1975). This model predicts that the disk shrinks at the onset of the outburst in response to the sudden addition of matter with low angular momentum, and that the disk viscosity in quiescence and in outburst are similar. DIM predicts no reduction of disk radius at outburst start but demands that the viscosity parameter in quiescence be 5–10 times smaller than the viscosity in outburst. The thermal limit cycle of DIM also predicts that the outbursting parts of the accretion disk should be hotter than a critical temperature \( T_{\text{eff}}(\text{crit}) \) (Warner 1995). Furthermore, the inward cooling wave is expected to decelerate as it travels toward the disk center (Menou et al. 1999). Thus, there are several predictions that can be tested from observations of accretion disks through outburst cycles with the aid of indirect imaging techniques such as eclipse mapping (Horne 1985).

The interest in testing both models against observations has somehow reduced over the last two decades as a consequence of a wide acceptance of DIM as the correct explanation. Two arguments have been key in setting the dominance of DIM. They are based on the assumption that the matter transferred from the secondary star is deposited at the disk rim, where the gas stream hits the accretion disk to form a bright spot (BS). Given this assumption, one may predict that (1) a burst of enhanced mass transfer rate would inevitably lead to an increase in the luminosity of the BS and that (2) an MTIM-driven outburst can only lead to outside-in outbursts because the additional matter is always deposited at the disk rim. The existence of inside-out outbursts and the lack of observational support for an increase in BS luminosity at outburst onset seem to argue against MTIM. However, one should note that both arguments (and the reasoning to drop MTIM) fall apart if the assumption on which they rely is incorrect. As we see later (§ 5), this may indeed be the case.

V2051 Oph is an ultrashort-period CV (\( P_{\text{orb}} < 2 \) hr), almost all of which are either polars with highly magnetic WDs (\( |B| \sim 10^7 \) G) or members of the SU UMa subclass of superoutbursting dwarf novae (Warner 1995). The binary was discovered by...
Sanduleak (1972), and since then several classifications have been proposed. Warner & O’Donoghue (1987) listed some characteristics of the object that distinguish it from other CVs: with its $P_{\text{orb}} = 90$ minutes it has one of the shortest periods known; it is one of the few short-period CVs to show deep eclipses ($B \simeq 2.5 \text{ mag}$); unlike other eclipsing systems, it possesses strong flickering (random brightness fluctuations of 0.1–1 mag on timescales from seconds to minutes) and flare activity, which produce a wide assortment of eclipse morphologies (Warner & Cropper 1983). V2051 Oph was proposed to be a low-field polar system by Warner & O’Donoghue (1987) based on the interpretation of their eclipse maps and on the observation of a 42 s oscillation in the optical during outburst, reminiscent of the rapid oscillation seen in polars. A consensus was reached with the observation of a superoutburst during which superhumps were detected (Kiyota & Kato 1998; Vrielmann & Ofelt 2003), establishing its classification as an SU UMa–type dwarf novae.

As part of a long-time campaign to study the flickering properties of a sample of eclipsing CVs (e.g., Baptista & Bortolotto 2004), we have observed V2051 Oph in outburst on two occasions. This paper reports the analysis of the light curves of V2051 Oph collected along these two outbursts with eclipse-mapping techniques. The resulting maps deliver the disk brightness distribution in quiescence, on the rise to maximum, during maximum light, and in the decline phase. Section 2 describes the observations, and § 3 gives the details of the data analysis. The results are presented in § 4 and discussed in § 5 in a comparison with predictions from the dwarf nova outburst models.

### 2. THE OBSERVATIONS

Time series of high-speed CCD photometry of V2051 Oph were obtained with a CCD camera ($385 \times 578$ pixels, 0.58” pixel$^{-1}$) attached to the 1.6 m telescope of Laboratório Nacional de Astrofísica (LNA) in Itajubá, Brazil, between 2000 July 28 and August 5, in the $B$ and $V$ bands, and on 2002 August 4, 5, and 7 in the $B$ band. The observations are summarized in Table 1. Column (2) lists the starting time of the observations in Julian Date, and columns (3) shows the time resolution in seconds ($\Delta t$). Column (4) lists the number of points in the light curve ($N_p$). Column (5) lists the eclipse cycle number ($E$); the numbers in parentheses indicate observations that, because of interruptions caused by, e.g., clouds, do not cover the eclipse itself. Column (6) indicates the binary phases covered by the observations (running from $-0.5$ to $+0.5$ with eclipse center at phase 0.0), and column (7) lists the number of points in the light curve ($N_p$). Column (8) gives an estimate of the quality of the observations. The seeing ranged from $1.0''$ to $2.2''$. Part of the data (quiescence) was presented in Baptista & Bortolotto (2004), but is repeated here for completeness. All light curves were obtained with the same instrumental set and telescope, which ensures a high degree of uniformity to the data set.

Data reduction procedures included bias subtraction, flat-field correction, cosmic-ray removal, and aperture photometry extraction.
Time series were constructed by computing the magnitude difference between the variable and a reference comparison star with scripts based on the aperture photometry routines of the IRAF APHOT package. Light curves of other comparison stars in the field were also computed in order to check the quality of the night and the internal consistency and stability of the photometry over the time span of the observations.

We estimate that the absolute photometric accuracy of these observations is about 10%. On the other hand, the analysis of the relative flux of the comparison star of all observations indicates that the internal error of the photometry is less than 2%. The individual light curves have typical signal-to-noise ratios of S/N = 40–50 out-of-eclipse and S/N = 10–20 at mideclipse. Additional details of the data reduction procedures are given in Baptista & Bortolothe (2004).

The historical light curve of V2051 Oph around the epoch of both outbursts is shown in Figure 1. The star went in outburst between 2000 July 30 and 31 (about JD 2,451,758; Fig. 1, top). This was a normal outburst, with an amplitude of 2 mag and a time span of 2 days. Our observations cover 3 days before maximum, the outburst maximum, and 2 days along the decline phase. The star was also seen in outburst on 2002 July 9 (Fig. 1, bottom). We did not observe this outburst. Our observations at this epoch cover the following low-amplitude (±0.8 mag) and short outburst on 2002 August 5 (JD 2,452,493). The runs on 2002 August 4 and 7 frame the day before outburst and a late decline stage when the star was almost back to its previous quiescent brightness level, respectively. A similar low-amplitude outburst occurred 20 days after the one recorded in our data.

Average out-of-eclipse $B$ and $V$ magnitudes measured from our light curves are superimposed on the AAVSO historical data (Fig. 1). The $B$-band magnitudes were displaced vertically by −0.5 mag for visualization purposes. Only $B$-band data are available for the 2002 outburst. The $V$-band magnitudes are consistent with the visual observations. However, the $B$-band magnitudes are systematically fainter than both the $V$-band and visual contemporaneous measurements, implying a color index $(B - V) ≃ +0.5$ mag. This is noticeably redder than the color of V2051 Oph previously reported in the literature, $−0.1 ≤ (B - V) ≤ +0.2$ (Bruch 1983; Vogt 1983), and may be associated with the extended state of lower brightness the object went through in 1996 (see Baptista et al. 1998). The color index changed from $(B - V) = +0.4$ mag to $(B - V) = +0.6$ mag from quiescence to outburst maximum in 2000.

3. DATA ANALYSIS

3.1. Light-Curve Construction

The $B$- and $V$-band individual light curves of V2051 Oph are shown in Figure 2, with arbitrary adjustments in the $x$-axis separation and $V$-band fluxes for visualization purposes. The data were grouped per passband and outburst stage and combined to produce light curves of improved S/N and reduced flickering influence. The $B$-band data from 2000 July 28 and 29 were combined into a single average light curve representative of the quiescence state (hereafter Jul2829) because they are at the same brightness level and there is no perceptible difference in light-curve morphology from one night to the other. The $B$-band data from 2000 July 30 (Jul30B) were treated separately, as they show a decrease in brightness with respect to the data from the previous two nights, as well as changes in eclipse shape (Fig. 3). There is a continuous decrease in brightness along the observations on 2000 July 31 and August 1. The individual light curves of those nights were scaled (by factors of ≤10%) to a mean, common out-of-eclipse flux level before combining them. For both nights it was possible to
obtain a good match of the eclipse shape and out-of-eclipse level for all combining curves.

For each light curve, we divided the data into phase bins of 0.003 cycles and computed the median flux at each bin to reduce the influence of flickering. The median of the absolute deviations with respect to the median flux was taken as the corresponding uncertainty for each bin. The light curves were phase-folded according to the linear ephemeris (Baptista et al. 2003)

\[ T_{\text{mid}} = \text{BJDD} 2,443,245,97752 + 0.0624278634E, \]

where BJDD denotes Barycentric Dynamical Time. A small phase correction of +0.0061 cycles was further applied to the 2002 data to remove the long-term cyclical period changes (Baptista et al. 2003) and to make the center of the WD eclipse coincident with phase zero.

WD and BS eclipses are seen as sharp changes in the slope of the eclipse shape in quiescence light curves (e.g., Fig. 3). We separated the contribution of the WD from the Jul2829, Jul30B, and Aug04 average light curves with a light-curve decomposition technique (Wood et al. 1985) in order to compute eclipse maps of only the accretion disk. A zoom of the Jul2829 and Jul30B light curves around eclipse is shown in Figure 3.

The original light curve is smoothed with a median filter of width 0.006 cycles (the phase width of the WD ingress/egress feature), and its numerical derivative is calculated. The derivative curve is smoothed with the same median filter as above to reduce noise and improve the detection of the WD and BS features. The WD and BS ingress/egress features are seen as those intervals where the derivative is significantly different from zero. A spline function is fitted to the remaining regions in the derivative to remove the contribution of the slowly-varying eclipse of the extended disk, and estimates of the WD flux are obtained by integrating the spline-subtracted derivative curve at ingress and egress. The light curve of the WD is reconstructed by assuming that its flux is zero between ingress and egress and constant outside eclipse. The WD contribution is then removed from the data by subtracting the reconstructed WD curve from the original light curve. The eclipse maps of the Jul2829, Jul30B, and Aug04 data shown in §4.2 were computed using WD-subtracted light curves.

A close inspection of the light curves in Figure 3 reveal that, while the phase width of the WD ingress/egress feature is the same on both nights, the integrated WD flux is reduced by \( \sim 25\% \) on Jul30B. This could be caused by an increased optical depth of the inner disk gas or by a thicker disk rim on that night, resulting in a lower visible fraction of the WD surface.

The average light curves are shown in the left panels of Figures 4, 5, and 6. The Jul2829 and Aug05 light curves have flares at \( \phi \approx -0.11 \) cycles. The error bars around these flares were artificially increased to minimize their influence on the eclipse-mapping modeling.

### 3.2. Eclipse Mapping

The eclipse-mapping method (Horne 1985) is an inversion technique that uses the information in the eclipse shape to reconstruct the disk surface brightness distribution. The reader is referred to
Baptista (2001) for a review on the subject. Eclipse-mapping techniques (Baptista & Steiner 1993) were applied to the average light curves of $x^{3.1}$ to solve for a map of the disk surface brightness plus the flux of an additional uneclipsed component in each case. The uneclipsed component accounts for all light that is not contained in the eclipse map (i.e., light from the secondary star, a vertically extended disk wind, or both). The reader is referred to Rutten et al. (1992b) and Baptista et al. (1996) for the details of and tests with the uneclipsed component.

All variations in a light curve in the standard eclipse-mapping method are interpreted as being caused by the changing occultation of the emitting region by the secondary star. Thus, any out-of-eclipse brightness change (e.g., the orbital hump caused by anisotropic emission from the BS) has to be removed before applying the technique to a light curve. This was done by fitting a spline function to the phases outside eclipse, dividing the light curve by the fitted spline, and scaling the result to the spline function value at phase zero in each case. This procedure removes orbital modulations with minimal effects on the eclipse shape itself.

Our eclipse map is a flat Cartesian grid of $75 \times 75$ pixels centered on the primary star with side $2R_{L1}$ (where $R_{L1}$ is the distance from the disk center to the inner Lagrangian point L1). The eclipse geometry is defined by the mass ratio $q$ and the inclination $i$, and

![Eclipse maps and light curves](image-url)
the scale of the map is set by $R_{L1}$. We adopted the values of Baptista et al. (1998), $R_{L1} = 0.422 \ R_\odot$, $q = 0.19$, and $i = 83^\circ$, which correspond to a WD eclipse width of $\Delta\phi = 0.0662$ cycles. This combination of parameters ensures that the WD is at the center of the map. The reconstructions were performed with a polar Gaussian default function (Rutten et al. 1992b) with radial blur width $\Delta r = 0.0266 R_{L1}$ and azimuthal blur width $\Delta \theta = 30^\circ$. The reconstructions reached a final $\chi^2$ near or equal to 1 for all light curves.

The statistical uncertainties in the eclipse maps are estimated with a Monte Carlo procedure (see, e.g., Rutten et al. 1992b). For a given input data curve, a set of 20 artificial light curves are generated in which the data points are independently and randomly varied according to a Gaussian distribution with standard deviation equal to the uncertainty at that point. The artificial curves are fitted with the eclipse-mapping algorithm to produce a set of randomized eclipse maps. These are combined to produce an average map and a map of the residuals with respect to the average, which yields the statistical uncertainty at each pixel. A map of the statistical significance (or the inverse of the relative error) is obtained by dividing the true eclipse map by the map of the standard deviations. The uncertainties obtained with these procedures are also used to estimate the errors in the derived radial intensity and temperature distributions.

4. RESULTS

4.1. Bright Spot Phases and Disk Radius Changes

We used the derivative technique of § 3.1 to measure the midingress/egress phases of the BS ($\phi_{bs}, \phi_{be}$) and to estimate the disk radius under the assumption that the BS is located where the stream of transferred matter hits the edge of the accretion disk. Here $\phi_{bs}$ and $\phi_{be}$ are taken as the phases of, respectively, minimum and maximum of the features corresponding to BS ingress/egress in the smoothed and spline-subtracted derivative of the light curve.

The BS midingress/egress phases for the light curves Jul2829 and Jul30B are shown as vertical dashed lines in Figure 3 (left). We find $\phi_{bs} = -0.0170 \pm 0.0015$ and $\phi_{be} = +0.0822 \pm 0.0006$ for Jul2829, and $\phi_{bs} = -0.0142 \pm 0.0007$ and $\phi_{be} = +0.073 \pm 0.001$ for Jul30B. The BS enters eclipse later and reappears from eclipse earlier on Jul30B, indicating that the disk radius was smaller on that night.

Each pair of ($\phi_{bs}, \phi_{be}$) values maps into a single position in the orbital plane for an assumed binary geometry ($i, q$). The $x$-$y$ positions corresponding to the measured ($\phi_{bs}, \phi_{be}$) values are indicated by diamonds in the binary diagram shown in Figure 3 (right). The measured BS positions consistently fall along the gas stream trajectory for the assumed mass ratio $q = 0.19$. The circles that pass through these points are $R_{bs} = (0.480 \pm 0.015)R_{L1}$ and $0.380 \pm 0.015R_{L1}$ for Jul2829 and Jul30B, respectively. The difference between the two values is formally significant at the $6 \sigma$ confidence level. Thus, there is evidence that the disk shrinks at outburst onset (i.e., the night before outburst maximum), in agreement with the expectations of MTIM.

Note that this result comes mainly from one light curve (Jul30B). Given the large flickering amplitude of V2051 Oph, one cannot exclude the possibility that the BS eclipse phases in this single light curve are affected by flickering. We attempted to strengthen the Jul30B result by repeating the analysis for the $V$-band light curves of the same night. While the measured $\phi_{bs}$ is in good agreement with the $B$-band measurement, $\phi_{be}$ is unfortunately lost in the flickering on a slow egress slope. A comparison of the eclipse shape of the $B$- and $V$-band light curves of 2000 July 30 indicates that the BS is less compact in the $V$ band than in the $B$ band.

We further tested whether the reduction in brightness and radius of Jul30B was a common, short-lived effect caused by rapid changes in mass transfer rate (on timescales shorter than that of an outburst). We measured BS eclipse phases in the individual light curves of the previous nights, while the star was in quiescence. We gave particular attention to the first two eclipses on 2002 July 28, for which the star had a brightness level comparable to that of the Jul30B light curve. In all cases the BS eclipse phases (and inferred disk radius) are consistent with the measurements obtained when we combine all data taken on 2000 July 28–29. While the out-of-eclipse flux varies by $\simeq 20\%$ among the individual light curves, we find no evidence of decrease in disk radius nor correlation of disk radius with out-of-eclipse brightness. This suggests that the observed reduction in disk radius reflects a change in disk structure particular to that night.

4.2. Accretion Disk Structure

4.2.1. The 2000 July Outburst

$B$-band median light curves (circles with error bars) and eclipse-mapping model curves (solid lines) are presented in Figure 4 (left). Figure 4 (right) shows the corresponding eclipse maps in a common logarithmic gray scale. The sequence of eclipse maps allows us to trace changes in the accretion disk structure at five different occasions along the outburst: in quiescence (Jul2829), at outburst onset (Jul30B) and maximum (Jul31B), and on two consecutive nights along the decline (Aug01 and Aug02).

The light curve and eclipse map in quiescence are very similar to those of Baptista & Bortoletto (2004), with enhanced emission along the gas stream trajectory inward of the BS position. The tip of the asymmetric emission is consistent with the position where the ballistic stream trajectory intercepts the $0.48R_{L1}$ quiescent disk radius. The disk becomes fainter, smaller, and largely asymmetric on Jul30B, with emission only along the gas stream trajectory. The lack of emission from the inner disk regions suggests a reduction of accretion onto the WD, possibly as a consequence of redistribution of matter and angular momentum in the disk following outburst onset.

The disk brightness distribution changes significantly on the timescale of 1 day, from outburst onset (Jul30B) to outburst maximum (Jul31B). The wide, $V$-shaped, and fairly symmetric eclipse of Jul31B maps into a broad brightness distribution that fills the primary Roche lobe, with a small asymmetry toward the trailing side of the disk (the one containing the stream trajectory). The brightness distribution is not concentrated in the inner disk regions as would be expected for an opaque steady state disk following the $T(R) \propto R^{-3/4}$ law (e.g., Frank et al. 2002). The eclipse becomes progressively narrower and U-shaped along the following nights (Aug01 and Aug02). The corresponding brightness distributions show the inward cooling and fading of the outer disk regions, whereas the inner disk remains at the same brightness level of outburst maximum. On Aug02 the outer disk is faint enough that an asymmetric and azimuthally extended emission from the BS region becomes clear. The evolution of the disk brightness distribution after outburst maximum is similar to that of the long-period dwarf nova EX Dra (Baptista & Catalán 2001).

The $V$-band light curves and eclipse maps of the 2000 July outburst at outburst onset (Jul30V) and maximum (Jul31V) are shown in Figure 5. The Jul31V light curve and eclipse map are similar to the corresponding $B$-band outburst maximum data.
The Jul30V light curve has steeper ingress and egress slopes than the Jul30B light curve, and the resulting eclipse map shows an additional light source at disk center aside from the enhanced emission along the stream trajectory. We investigated whether this could be a consequence of underestimating the contribution of the WD to the $V$-band light curve with the following exercise. We assumed progressively larger WD contributions to the Jul30V light curve and computed eclipse maps from the resulting WD-subtracted light curves (see § 3.1). The additional contribution at disk center is present in the eclipse map even at the limit where the WD-subtracted light curve starts to show a reverse slope at WD ingress/egress phases (signaling that too much flux was removed in the light-curve decomposition process). Thus, we conclude that the extra light at disk center in the Jul30V light curve is not related to the WD. Since there are no $V$-band observations in the previous nights, it is not possible to check whether the reduction in flux of the inner disk regions observed in the Jul30B B-band map is also present in the $V$ band. The tip of the emission pattern along the stream trajectory on Jul30V occurs at a radius smaller then the 0.48$R_{\text{L1}}$ quiescent disk radius, in agreement with the inferred reduced radius at that date (§ 4.1).

4.2.2. The 2002 August Outburst

The B-band light curves and corresponding eclipse maps along the 2002 August outburst are shown in Figure 6. The gray scale of the eclipse maps is the same as in Figure 4. This outburst is poorly sampled by amateur astronomers (Fig. 1) and by our observations (Fig. 2). It is possible to associate the Aug04 data with the quiescent, preoutburst stage and the Aug07 data with the late decline stage of the short outburst, but it is not clear whether the Aug05 data correspond to outburst maximum. Figure 2 shows that there was no perceptible change in out-of-eclipse brightness over the >3 hr long observing run of that night, in contrast with the clear decrease in brightness observed along the observations of the 2000 July outburst. The constancy of the out-of-eclipse brightness suggests that the Aug05 observations framed a fairly stable brightness stage of the outburst presumably not too far from outburst maximum.

The symmetric and broad eclipse of Aug04 maps into an axisymmetric disk brightness distribution with no evidence of BS or enhanced emission along the gas stream trajectory, in contrast with the 2000 July quiescent data. Also, the brightness distribution extends up to a smaller radius than in 2000 July. This eclipse map is reminiscent of that of the “faint” quiescent state of Baptista & Bortoletto (2004), which may be attributed to a lower (long-term) mass transfer rate at that epoch. The Aug05 light curve shows an asymmetric V-shaped eclipse with two low-amplitude and extended bulges at ingress and at egress. This leads to an eclipse map with an elongated annular structure of asymmetric brightness distribution superimposed on an axisymmetric broad baseline distribution. This disk brightness distribution bears some resemblance to the eclipse map of OY Car on the rise to maximum of a normal outburst (a ring-like structure; see Rutten et al. 1992a) and to the He n 4686 eclipse map of IP Peg at outburst maximum (a two-armed spiral structure on top of an extended brightness distribution; see Baptista et al. 2000). The disk radius increases with respect to Aug04 but is far from filling the primary Roche lobe. This seems in accordance with the markedly lower amplitude of this outburst. The Aug07 light curve has a U-shaped symmetric eclipse. The disk has decreased in size back to the preoutburst radius, but the inner disk regions remain at the intensity level of the Aug05 map. The brightness distribution is skewed toward the L1 point to account for an eclipse width at half-depth slightly wider than the eclipse of the WD.

4.3. Radial Intensity Distribution

4.3.1. The 2000 July Outburst

A more quantitative description of the disk changes during outburst can be obtained by analyzing the evolution of the radial intensity distribution. Figure 7 (left) illustrates the evolution of the radial intensity distribution of the B-band maps along the outburst. We divided the eclipse maps in radial bins of 0.03$R_{\text{L1}}$ and computed the median intensity at each bin. These are shown as interconnected circles in Figure 7. The dashed lines show the ±1 σ limits on the average intensity. The labels are the same as in Figure 4. The large dispersion seen in the intermediate regions of the Jul30B map and in the outer regions of the Aug02 map reflects the large asymmetries present in these eclipse maps (gas stream and BS, respectively).

In order to quantify the changes in disk size during outburst we defined the outer disk radius in each map as the radial position at which the intensity distribution is log $I_B = -4.8$, which corresponds to the maximum intensity of the BS in the Jul2829 quiescence eclipse map. The computed outer disk radius is shown as a vertical tick mark in each panel. As a reference, the radial position of the quiescent BS is marked by a vertical dotted line.

The disk shrinks from $R_d = (0.48 \pm 0.02)R_{\text{L1}}$ in quiescence to $R_d = (0.40 \pm 0.11)R_{\text{L1}}$ at outburst onset (Jul30B), underscoring the result of § 4.1. The accretion disk then expands and reaches $R_d = (0.78 \pm 0.07)R_{\text{L1}}$ at outburst maximum (Jul31B). The disk decreases in radius to $R_d = (0.70 \pm 0.09)R_{\text{L1}}$ on Aug01 and remains at that radius on the following night (Aug02).

The DIM predicts that heating and cooling wave fronts propagate through the disk during the transitions between the low-viscosity quiescent state and the high-viscosity outburst state. The eclipse maps may be used to measure the movement of transition fronts. In order to test for the presence and to trace the movement of transition fronts in the accretion disk, we defined an arbitrary reference intensity level log $I_B = -4.77$. This choice is justified by the following arguments: $I_B > I_{\text{bs}}$ is required in order for it to trace the movement of regions inside the outer disk radius. Furthermore, $I_B$ cannot be much higher than the chosen value; otherwise, the whole of the brightness distribution on Jul30B would be below the reference intensity level. Choosing other $I_B$ values in the above range leads to results which are indistinguishable from the ones present here.

In order to minimize the possible contribution of the BS and gas stream emission to the disk brightness distribution we calculated the symmetric disk-emission component. The symmetric component is obtained by slicing the disk into a set of radial bins and fitting a smooth spline function to the median of the lower quartile of the intensities in each bin. The spline-fitted intensity in each annular section is taken as the symmetric disk-emission component. This procedure preserves the baseline of the radial distribution while removing all azimuthal structure. In doing this we are implicitly assuming that the global changes in the structure of the accretion disk with time (i.e., transition fronts and alike) are roughly axisymmetric. The statistical uncertainties affecting the fitted intensities are estimated with the Monte Carlo procedure described in § 3.2.

The radial position at which the intensity distribution falls below the reference intensity level $I_B$ is indicated by vertical tick marks in Figure 7 (right). It is seen that the radial position of the reference intensity changes significantly along the outburst, moving outward on the rising branch and inward along the decline. These changes suggest the propagation of an outward-moving heating wave on the rise and of an inward-moving cooling wave on the decline.
Assuming that the changes in the radial position of the reference intensity level represent the changes in position of the heating and the cooling waves, we used the measured positions together with the inferred time interval between consecutive eclipse maps to estimate the velocities of the waves along the outburst. The reference time associated with each eclipse map is the average of the mideclipse times of all eclipses included in the corresponding median light curve. The errors in the derived velocities have contributions from the uncertainties in the time interval between consecutive eclipse maps and the uncertainties in the measured radial positions. The inferred speed of the heating wave is \( v_{\text{heat}} \gtrsim (1.56 \pm 0.05) \text{ km s}^{-1} \). We quote this value as a lower limit because one cannot discard the possibility that outburst maximum (or largest disk radius) occurred earlier than our 2000 July 31 observations. The inferred speed of the inward-moving cooling wave is \( v_{\text{cool}} = (-0.30 \pm 0.07) \text{ km s}^{-1} \) and \( v_{\text{cool}} = (-0.90 \pm 0.09) \text{ km s}^{-1} \) at one and two nights after maximum, respectively. The results are summarized in Table 2. We observe an acceleration of the cooling wave as it travels across the disk, in contradiction with the predictions of the DIM (Menou et al. 1999). This result is statistically significant at the 6 \( \sigma \) confidence level.

In terms of the \( \alpha \) disk formulation of Shakura & Sunyaev (1973), the nondimensional viscosity parameter of the high state, \( \alpha_{\text{hot}} \), can be written as the ratio of the speed at which the heating front travels across the disk, \( v_{\text{heat}} \), and the sound speed inside the heating front, \( c_s \) (Lin et al. 1985; Canizzo 1993),

\[
\alpha_{\text{hot}} \approx \frac{v_{\text{heat}}}{c_s} = 0.082 \left( \frac{v_{\text{heat}}}{\text{km s}^{-1}} \right) \left( \frac{T_f}{18,000 \text{ K}} \right)^{-1/2}
\]

where \( T_f \) is the temperature of the heating front. Assuming \( T_f = 18,000 \text{ K} \) (Menou et al. 1999), we find \( \alpha_{\text{hot}} \gtrsim 0.13 \), comparable to the measured viscosity parameter in quiescence \( \alpha_{\text{cool}} \approx 0.16 \) (Baptista & Bortoletto 2004). Unrealistically low \( T_f \) values (<1000 K) are required in order to obtain \( \alpha_{\text{hot}} \) significantly larger than \( \alpha_{\text{cool}} \). This result is in contrast with the predictions of DIM, which requires that the viscosity in outburst be significantly larger than in quiescence (i.e., \( \alpha_{\text{hot}} > 5 \alpha_{\text{cool}} \)).

4.3.2. The 2002 August Outburst

The radial intensity distributions along the 2002 August outburst are shown in Figure 8. We assumed the same reference intensity levels \( I_{\text{bs}} \) and \( I_f \) as before to trace the changes in disk radius and to estimate the velocity of the heating and cooling waves. The derived \( \nu \) values (and their quoted errors) do not account for the uncertainty in associating the Aug05 eclipse map with outburst maximum and, therefore, should be looked at with caution and skepticism. Moreover, there is a further uncertainty in the measured heating wave speed in this case because the Aug04 data do not correspond to outburst onset but to a preoutburst, quiescent state.

![Fig. 7.—Evolution of the B-band radial intensity distribution through the 2000 July outburst. Left: Average intensity distributions. Dashed lines show the ±1 \( \sigma \) limits on the average intensity. A vertical dotted line indicates the radial position of the BS in quiescence, \( R_{\text{bs}} = 0.48R_{\text{L1}} \) (Jul2829), while vertical tick marks indicate the radius at which the distribution reaches the BS reference intensity level log \( I_{\text{bs}} = -4.8 \). Right: Symmetric disk-emission distribution, obtained from a cubic spline fit to the median of the lower quartile of the radial brightness distribution. Vertical tick marks indicate the radial position at which the disk intensity is log \( I_f = -4.77 \).](image-url)
The disk expands from \( R_{bs} = (0.35 \pm 0.02)R_{L1} \) in quiescence (Aug04) to \( R_{bs} = (0.50 \pm 0.08)R_{L1} \) at maximum observed brightness (Aug05) and shrinks back to the Aug04 radius two nights after that (Aug07). We estimated an outward-moving heating wave speed of \( v_{heat} \approx 0.31 \text{ km s}^{-1} \) and an inward-moving cooling wave speed of \( v_{cool} \approx -0.15 \text{ km s}^{-1} \).

4.4. Radial Temperature Distribution

A simple way to test theoretical disk models is to convert the intensities in the eclipse maps to blackbody brightness temperatures, which can then be compared to the radial run of the effective temperature predicted by steady state, optically thick disk models. It is important to bear in mind that \( B- \) and \( V- \)band brightness temperatures are a good approximation to the effective temperature only for optically thick disk regions (see, e.g., Baptista et al. 1998). Because it is hard to assess the optical depth of the disk gas along the outburst with the data at hand, the results from this section should be looked on with some caution.

Figures 9 and 10 show the evolution of the disk radial temperature distribution along the 2000 July outburst in a logarithmic scale. The temperature distributions of the 2002 August outburst are shown in Figure 11. The blackbody brightness temperature that reproduces the observed surface brightness at each pixel was calculated assuming distances of 146 pc (Vrielmann et al. 2002b) and of 92 pc (Saito & Baptista 2006). These are shown in the left and right panels, respectively, of Figures 9–11. We neglected interstellar reddening, since there is no sign of interstellar absorption feature at 2200 Å in spectra obtained with the Hubble Space Telescope (Baptista et al. 1998). The disk was divided into radial bins of 0.03\( R_{L1} \) and a median brightness temperature was derived for each bin. These are shown as interconnected symbols in Figures 9–11. The dashed lines show the ±1 \( \sigma \) limits on the average temperatures. The larger \( \sigma \)-values in the Jul30B, Jul30V, and Aug02 distributions reflect the azimuthal asymmetries caused by the gas stream and BS in these maps. Steady state disk models for mass accretion rates of \( \dot{M} \approx 10^{-9}, 10^{-10}, \) and \( 10^{-11} M_{\odot} \text{ yr}^{-1} \) are plotted as dotted lines for comparison. These models assume \( M_1 = 0.78 M_{\odot} \) and a primary radius of \( R_1 = 0.0103 \, R_{\odot} \) (Baptista et al. 1998).

The computed brightness temperatures depend on the assumed distance to the binary. For a given (fixed) observed flux, the disk is fainter (and cooler) if the distance is smaller. The temperatures and mass accretion rates quoted in the remainder of this section are for a 92 pc distance to the binary.

Let us first discuss the 2000 July outburst distributions. The quiescent disk (Jul2829) shows a flat temperature distribution for \( R < 0.3R_{L1} \) reminiscent of those seen in other dwarf novae.
The temperatures range from \( \approx 7000 \) K in the inner disk \((R = 0.1 R_{\odot})\) to \( \approx 5000 \) K in the outer disk regions \((R = 0.4 R_{\odot})\). The whole disk brightens at outburst maximum \((\text{Jul}31 \text{B} \text{and} \text{Jul}31 \text{V})\), but the outer disk regions become relatively brighter and hotter, leading to a temperature distribution even flatter than in quiescence for \( R < 0.4 R_{\odot} \). This is in marked contrast with what is seen, e.g., in Z Cha (Horne & Cook 1985; Wood et al. 1986) and OY Car (Rutten et al. 1992a), the accretion disks of which transition from a flat brightness temperature distribution in quiescence to a steep distribution in good agreement with the \( T \propto R^{-3/4} \) law in outburst. Along decline the V2051 Oph inner disk remains at about the same temperature \((\approx 10000 \) K\) while the flat portion of the distribution progressively recedes toward smaller radii as the outer disk regions cool down. Except for the inner disk regions \((R \leq 0.2 R_{\odot})\) —where the extra light source results in higher brightness temperatures—the \( V \)-band distributions are in agreement with their \( B \)-band counterparts, suggesting that, at least on 2000 July 30 and 31, the outer disk was optically thick and the derived brightness temperatures are a good approximation to the gas effective temperature.

The temperature distributions share a common feature: all show a flat inner portion which turns into a steep gradient closely following the \( T \propto R^{-3/4} \) law in the outer disk regions. We fitted steady state disk models to the steep regions of the temperature distributions to infer mass accretion rates of \( \dot{M} = (1.0 \pm 0.1) \times 10^{-10} M_\odot \text{yr}^{-1} \) in quiescence, \((6.4 \pm 0.1) \times 10^{-10} M_\odot \text{yr}^{-1} \) at outburst maximum, \((3.7 \pm 0.5) \times 10^{-10} M_\odot \text{yr}^{-1} \) on Aug01, and \((0.9 \pm 0.1) \times 10^{-10} M_\odot \text{yr}^{-1} \) on Aug02. In the framework of the MTIM, the evolution of the outer disk temperature distribution could be interpreted as the response of a viscous disk to a sudden increase in mass transfer rate by a factor of 6.5. This corresponds to a brightness increase of \( \Delta B = 2 \) mag, in line with the observed 2000 July outburst amplitude.

Let us now turn our attention to the 2002 August outburst. The morphology of the temperature distribution and its evolution with time are similar to those of the 2000 July outburst, although the disk is cooler at maximum observed brightness \((\text{Aug}05)\). The temperatures in the quiescent disk \((\text{Aug}04)\) are comparable to those of Jul2829. The temperature distribution is flatter at maximum observed brightness, with \( T \approx 8000 \) K in the inner disk regions \((\text{flat portion of the distribution})\) and \( T \approx 5700 \) K at \( R = 0.4 R_{\odot} \). At the late decline stage \((\text{Aug}07)\) the temperatures in the innermost disk regions \((R < 0.15 R_{\odot})\) are still comparable to those at maximum brightness, while the outer disk has returned to the temperatures at quiescence. Fitting steady state disk models to the steep outer disk regions of the temperature distributions one finds mass accretion rates of \( \dot{M} = (0.8 \pm 0.1) \times 10^{-10} M_\odot \text{yr}^{-1} \) in quiescence, \((1.7 \pm 0.1) \times 10^{-10} M_\odot \text{yr}^{-1} \) at maximum observed brightness, and \((0.81 \pm 0.05) \times 10^{-10} M_\odot \text{yr}^{-1} \) at late decline. This could be interpreted as the response of a viscous disk to a sudden increase in mass transfer rate by a factor of 2.1, corresponding to a brightness increase of \( \Delta B = 0.8 \) mag, again in line with the observed 2002 August outburst amplitude.

Although the nominal temperatures and mass accretion rates change if one instead assumes the 146 pc distance, the qualitative results remain the same.

According to the DIM, there is a critical effective temperature, \( T_{\text{eff}}(\text{crit}) \), below which the disk gas should be white in quiescence in order to allow the thermal instability to set in, and above which the disk gas should remain in a steady, high mass accretion regime \((\text{e.g., Warner} 1995)\). In other words, outbursting accretion disks should be hotter than \( T_{\text{eff}}(\text{crit}) \). The \( T_{\text{eff}}(\text{crit}) \) relation is plotted as a dot-dashed line in each panel of Figures 9–11.

The distance to the binary is the crucial parameter for the \( T_{\text{eff}}(\text{crit}) \) test. If \( d = 146 \) pc, the evolution of the radial temperature distribution is consistent with the DIM: the disk temperatures are everywhere below \( T_{\text{eff}}(\text{crit}) \) in quiescence and the outbursting disk shows temperatures clearly above that limit. However, for a 92 pc distance the outburst occurs at temperatures below \((2002 \) August\) or barely at \((2000 \) July\) \( T_{\text{eff}}(\text{crit}) \). The Aug05 outbursting disk temperatures are systematically lower than \( T_{\text{eff}}(\text{crit}) \) for distances \( d \approx 120 \) pc.

### 4.5. The Uneclipsed Flux

The uneclipsed flux is displayed as a horizontal tick centered at phase zero in the left panels of Figures 4, 5, and 6. The measured values are listed in Table 3. We estimated the fractional contribution of the uneclipsed component to the total flux by computing the ratio of the uneclipsed flux, \( F_{\text{un}} \), to the average out-of-eclipse flux level of the corresponding light curve, \( F_{\text{out}} \). The results are shown in the third column of Table 3.

The uneclipsed component accounts for a small fraction \((1.5\%)\) of the total system brightness on Jul2829 but increases to \(13\%\) on Jul30B, the highest relative contribution measured. This is in line with the significant changes in disk radius and structure observed on Jul30B and corroborates the idea that this night corresponds to outburst onset. Although the absolute value of \( F_{\text{un}} \) is larger at outburst maximum, its fractional contribution decreases steadily since 2000 July 30 and becomes negligible on 2000 August 2. The behavior in the \( V \)-band is analogous to that in the \( B \)-band, with a nonnegligible \( F_{\text{un}} \) value on Jul30V increasing to a maximum \((\text{in absolute terms})\) on the following night. The uneclipsed component is negligible throughout the fainter 2002 August outburst. We draw attention to the fact that the increase in \( F_{\text{un}} \) in the 2000 data precedes outburst maximum by about 1 day.

The fact that the uneclipsed component is negligible in quiescence and its variability during outburst indicate that this light does not arise from the secondary star. Significant \((\text{and variable})\) uneclipsed components during outburst were reported for OY Car \((\text{Rutten et al.} 1992a)\) and EX Dra \((\text{Baptista \\& Catalan} 2001)\). Two possible explanations to account for the observed behavior would be a variable and largely uneclipsed disk wind or a flaring of the accretion disk during outburst.

Detailed simulations by Wood \((1994)\) show that eclipse maps obtained including an uneclipsed component or assuming a flared disk may lead to equally good fits to the data light curve, making it hard to distinguish between the two models. Further simulations by Baptista \\& Catalan \((2001)\) show that modeling the eclipse of a flared disk with the assumption of a flat disk leads to

### Table 3

| Map            | \( F_{\text{un}} \) (mJy) | \( F_{\text{un}}/F_{\text{out}} \) |
|----------------|--------------------------|-----------------------------------|
| Jul2829        | 0.03 \pm 0.02            | 0.015                             |
| Jul30B         | 0.20 \pm 0.04            | 0.13                              |
| Jul31B         | 0.42 \pm 0.07            | 0.04                              |
| Aug01          | 0.17 \pm 0.06            | 0.02                              |
| Aug02          | 0.00 \pm 0.01            | ...                               |
| Jul30V         | 0.10 \pm 0.02            | 0.04                              |
| Jul31V         | 0.62 \pm 0.06            | 0.04                              |
| Aug04          | 0.01 \pm 0.01            | ...                               |
| Aug05          | 0.02 \pm 0.01            | ...                               |
| Aug07          | 0.00 \pm 0.01            | ...                               |
the appearance of a spurious uneclipsed component, the flux of which scales with the disk opening angle, $\theta_d$.

For a mass accretion rate of $\sim 10^{-10} \, M_\odot \, yr^{-1}$ ($\S$ 4.4), we estimate a quiescent disk opening angle of $\theta_d \approx 2^\circ$ (Meyer & Meyer-Hofmeister 1982; Smak 1992). To be accounted for by a flaring of the accretion disk, the observed increase in uneclipsed flux by a factor of $\gtrsim 7$ from Jul2829 to Jul30B would demand an increase in $\theta_d$ by factors of $7$–$25$ (see Baptista & Catalán 2001), leading to obscuration of a large portion of the accretion disk, in particular the disk center. This is hard to reconcile with the fact that the WD at disk center was still visible in the 2000 July 30 light curves. Thus, an outburst-driven disk wind seems the most plausible explanation for the observed uneclipsed flux.

5. DISCUSSION

5.1. The Distance to the Binary

Because the radial temperature distribution and the consequent comparison of disk temperatures with $T_{\text{eff}}(\text{crit})$ depend on the assumed distance to the binary, we now turn our attention to the distance estimates in the literature.

Watts et al. (1986) found a distance between 90 and 150 pc assuming a steady state optically thick model for the quiescent accretion disk of V2051 Oph. However, the UV-optical spectrum of V2051 Oph is dominated by strong emission lines and a Balmer jump in emission (Watts et al. 1986; Baptista et al. 1998)—indicating an important contribution from optically thin emitting regions—and the flat temperature distribution of the inner disk regions in quiescence is in clear disagreement with the $T \propto R^{-3/4}$ law of steady state opaque disks (e.g., Fig. 9). Berriman et al. (1986) compared the eclipse shape in the H band with computed models to find distances in the range 120–170 pc. They assumed that the red dwarf has a flux density of 1.5 mJy at the $H$ band and that cool stars have approximately constant surface brightness at the $H$ band. Their models are a poor match to the observed eclipse shape. Both distance ranges are affected by arguable assumptions and/or too simple models.

Vrielmann et al. (2002b) applied a physical parameter eclipse mapping method (PPEM) to $UBVRI$ light curves of V2051 Oph in order to derive the spatial distribution of temperature and surface density in its accretion disk and to find a distance of $d = 146 \pm 20$ pc to the binary. This method requires the assumption of an a priori spectral model for the disk emission relating the temperature and surface density to the observed surface brightness in the $UBVRI$ passbands. The adopted spectral model is an isothermal, pure hydrogen slab of gas in LTE including only bound-free and free-free H and H$^-$. This model is not adequate to handle emission from disk atmospheres with vertical temperature gradients. In particular, it might fail to model a temperature inversion in the disk photosphere (i.e., a hot disk chromosphere with strong emission lines), as seems to be the case in V2051 Oph (Vrielmann et al. 2002b; Saito & Baptista 2006) and other quiescent dwarf novae. The application of this method and model to the dwarf nova HT Cas leads to a distance 50% larger than one inferred from the Na I and TiO absorption spectrum of the secondary star (Vrielmann et al. 2002a). The PPEM distance to V2051 Oph may be overestimated as well. Moreover, Vrielmann et al. (2002b) mistakenly adopted a WD radius of $R_1 = 0.0244 \, R_\odot$, a factor of 2.4 larger than the $R_1 = 0.0103 \, R_\odot$ value quoted by Baptista et al. (1998). As a result, the WD ingress and egress features in the light curve become artificially longer and the PPEM code associates more surface flux with the WD than it should. The WD accounts for a significant fraction of the V2051 Oph optical light in quiescence (see Fig. 3 of Vrielmann et al. 2002b) and dominates the procedure used to estimate the distance. The extra WD surface flux has to be compensated for by increasing the distance to the binary.

We are therefore left with the $d = 92_{-35}^{+30}$ pc distance estimate of Saito & Baptista (2006). This was obtained by fitting WD atmosphere models of solar composition to the extracted UV-optical WD spectra at the time the WD was most clearly seen in V2051 Oph (Baptista et al. 1998; Saito & Baptista 2006). In the absence of a more robust determination we take this as the best available distance estimate to V2051 Oph.

5.2. The Cause of the V2051 Oph Outbursts

Eclipse-mapping analysis along two outburst cycles in V2051 Oph allows us to test the predictions of dwarf novae outburst models listed in $\S$ 1. Here we discuss the cause of the outbursts of V2051 Oph under the light of the results presented in the previous sections.

MTIM predicts that the disk shrinks at outburst onset (e.g., Warner 1995 and references therein). We found that the disk decreased in brightness and radius at the night before the 2000 July outburst maximum, while the uneclipsed light in the $B$ band increased (from a negligible contribution) to 13% of the total light. It is hard to avoid the interpretation that the changes in disk structure and uneclipsed flux are a consequence of the outburst onset and the following conclusion that our result confirms the MTIM prediction.

DIM requires that $\alpha_{\text{hot}} \gtrsim 5 \alpha_{\text{cool}}$ (e.g., Lasota 2001). In MTIM, there is no reason for the viscosity parameter to change from quiescence to outburst. We measure $\alpha_{\text{hot}} \approx \alpha_{\text{cool}} \approx 0.13$, confirming another MTIM prediction. In favor of DIM, one could argue that the true $t_{\text{heat}}$ may be much larger than measured, contributing to an increase of $\alpha_{\text{hot}}$ relative to $\alpha_{\text{cool}}$. However, there is no observational support for an $\alpha_{\text{hot}}$ significantly larger than inferred. Vrielemann & Offutt (2003) measured a heating wave speed of $v_{\text{heat}} = +1.8$ km s$^{-1}$ during a superoutburst in V2051 Oph, in good agreement with our result. One could alternatively dismiss the $\alpha_{\text{cool}}$ measurement of Baptista & Bortolette (2004), leaving room for a much smaller $\alpha_{\text{cool}}$ value. Nevertheless, the good agreement between the radial temperature distribution of the outer disk and the $T \propto R^{-3/4}$ law suggests that the outer regions of the V2051 Oph accretion disk are in a steady state both in outburst and in quiescence, implying that the disk viscosity there is always high.

DIM predicts that the cooling wave decelerates as it travels toward disk center (Menou et al. 1999). In MTIM, the measured $v_{\text{cool}}$ reflects the local viscous timescale and may increase or decrease depending on the radial dependence of the viscosity parameter $\alpha$. We find that the cooling wave accelerates as it travels toward disk center, in clear disagreement with the DIM prediction.

DIM predicts that an outbursting accretion disk is hotter than $T_{\text{eff}}(\text{crit})$ (e.g., Warner 1995 and references therein). There is no quiescence/outburst temperature restriction in MTIM. For an assumed distance of 92 pc, we find that the whole of the low-amplitude 2002 August outburst occurs at temperatures below $T_{\text{eff}}(\text{crit})$, and that the hottest parts of the accretion disk during the normal 2000 July outburst barely reach $T_{\text{eff}}(\text{crit})$. The 2002 August outburst fails to meet the $T > T_{\text{eff}}(\text{crit})$ requirement for distances $d < 120$ pc. The morphology and time evolution of the radial temperature are similar in both outbursts, and there is no reason to believe they are powered by different physical mechanisms. If one admits that the 2002 August outburst is not driven by a thermal-viscous disk instability, the same conclusion must be applied to the normal 2000 July outburst. The inconsistency between DIM and the observations here could be alleviated if one
argues that the V2051 Oph accretion disk is not optically thick during outbursts and that the derived brightness temperatures underestimate the disk gas effective temperatures.

If taken separately, none of the individual results would be enough to discard DIM as a powering mechanism for the outbursts of V2051 Oph. Nevertheless, when taken in combination the above results make a strong case against DIM and in favor of MTM as the cause of the outbursts in V2051 Oph. All evidence discussed here leads to the conclusion that the outbursts of V2051 Oph are driven by episodes of enhanced mass transfer from its secondary star.

Before one claims that V2051 Oph cannot be considered a “true” dwarf nova, we remind that it is an SU UMa star, showing not only 2 mag amplitude normal outbursts, but also longer and brighter superoutbursts (Kiyota & Kato 1998; Vrielman & Offutt 2003). It is also worth noting that finding a dwarf nova the outbursts of which are not powered by disk instabilities does not necessarily kill DIM, but warns that the current view about dwarf nova outbursts must be revised to include the possibility that both outburst mechanisms coexist, perhaps on different dwarf nova subtypes that have not been clearly distinguished up to this point.

We propose that the viscosity in the accretion disk of V2051 Oph is always high, independent of the disk mass inflow rate. In this scenario, there is no room for matter to accumulate in the outer disk regions nor for thermal-viscous instabilities to set in. Because of the low mass transfer rate and the efficient accretion engine, the disk has low densities. A low-density quiescent disk enables the (denser) infalling gas to “overflow” the outer disk regions, creating a bright gas stream along the ballistic trajectory ahead of the disk rim (cf. Baptista & Bortoletto 2004) and making the trailing lune of the disk significantly brighter than the leading lune, as observed by Watts et al. (1986). This is supported by numerical simulations of accretion disks, which show that when the infalling gas stream is significantly denser than the initial disk gas, the stream penetrates the disk—allowing matter to be deposited at the inner disk regions—and no BS forms at the disk rim (Bisikalo et al. 1999a, 1999b; Makita et al. 2000). Because the energy released at the disk rim is small in comparison to that of enhanced mass transfer at outburst ahead of the disk rim (cf. Baptista & Bortoletto 2004) and making the trailing lune of the disk significantly brighter than the leading lune, as observed by Watts et al. (1986). This is supported by numerical simulations of accretion disks, which show that when the infalling gas stream is significantly denser than the initial disk gas, the stream penetrates the disk—allowing matter to be deposited at the inner disk regions—and no BS forms at the disk rim (Bisikalo et al. 1999a, 1999b; Makita et al. 2000). Because the energy released at the disk rim is small in comparison to that of enhanced mass transfer at outburst before a superoutburst. Therefore, this scenario implies that the rare superoutbursts of V2051 Oph are also powered by (stronger) bursts of enhanced mass transfer from its secondary star.

The increase in the luminosity of the BS at outburst onset and the outburst-type issue (inside-out vs. outside-in) are not valid tests to distinguish between DIM and MTM in dwarf novae such as V2051 Oph. Are there other, useful tests to distinguish between the two outburst models? Section 1 gives a list of observational tests for which the predictions of both models are quite different (and, therefore, relatively easy to distinguish). Unfortunately, they are only applicable to the restricted group of eclipsing dwarf novae. Comparing the disk radius in quiescence and at outburst onset would be the most straightforward test, but also the hardest to perform because it requires observations framing a few hours around the highly unpredictable start of the outburst. The comparison of the disk brightness temperature distribution with the $T_{\text{eff}}$ (crit) relation requires good knowledge of the distance to the binary and depends on the assumption that the brightness temperature distribution is a good approximation to the disk gas effective temperature (or, alternatively, on the availability of an adequate model relating both temperatures). Tracing changes in speed of the cooling wave along the decline is probably the less demanding test from the observational point of view—one needs good sampling of the decline branch of the outburst—but may be inconclusive if one finds that the cooling wave decelerates. Because $\alpha_{\text{hot}}$ is easily inferred from the timescale of the outburst, the key aspect of the comparison of $\alpha_{\text{hot}}$ and $\alpha_{\text{cool}}$ is the measurement of the viscosity parameter in quiescence. A promising step in this regard may be to perform spatially resolved flickering studies of quiescent dwarf novae. The identification of a disk flickering component allows an estimate of the magnitude and the radial dependency of the disk viscosity (e.g., Baptista & Bortoletto 2004).

The present results raise a set of exciting and challenging questions: How many other high-viscosity disk dwarf novae similar to V2051 Oph are there? What fraction of the dwarf nova class do they account for? Why do their accretion disks have permanent high viscosity? Why and how do the secondary stars of CVs change their mass transfer rates by large amounts on short, 1–2 day timescales?

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REFERENCES

Baptista, R. 2001, in Astrotomography, Indirect Imaging Methods in Observational Astronomy, ed. H. M. J. Boffin, D. Steeghs, & J. Cuypers (Berlin: Springer), 307

Baptista, R., Borges, B. W., Bond, H. E., Jablonski, F., Steiner, J. E., & Grauer, A. D. 2003, MNRAS, 345, 889

Baptista, R., & Bortoletto, A. 2004, AJ, 128, 411

Baptista, R., & Catalán, M. S. 2001, MNRAS, 324, 599

Baptista, R., Catalán, M. S., Home, K., & Zilli, D. 1998, MNRAS, 300, 233

Baptista, R., Harlaftis, E. T., & Steeghs, D. 2000, MNRAS, 314, 727

Baptista, R., & Steiner, J. E. 1992, A&A, 277, 331

Baptista, R., Steiner, J. E., & Home, K. 1996, MNRAS, 282, 99

Bath, G. T. 1975, MNRAS, 171, 311
Berriman, G., Kenyon, S., & Bailey, J. 1986, MNRAS, 222, 871
Bisikalo, D. V., Boyarchuk, A. A., Chechetkin, V. M., Kuznetsov, O. A., & Molteni, D. 1998a, MNRAS, 300, 39
Bisikalo, D. V., Boyarchuk, A. A., Kuznetsov, O. A., & Chechetkin, V. M. 1998b, Astron. Rep., 42, 621
Bruch, A. 1983, Inf. Bull. Variable Stars, 2287, 1
Canizzo, J. K. 1993, in Accretion Disks in Compact Stellar Systems, ed. J. C. Wheeler (San Francisco: World Scientific), 6
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (2nd ed.; Cambridge: Cambridge Univ. Press)
Hameury, J.-M., Menou, K., Dubus, G., Lasota, J.-P., & Hure, J.-M. 1998, MNRAS, 298, 1048
Home, K. 1985, MNRAS, 213, 129
Home, K., & Cook, M. C. 1985, MNRAS, 214, 307
Kiyota, S., & Kato, T. 1998, Inf. Bull. Variable Stars, 4644, 1
Lasota, J.-P. 2001, NewA Rev., 45, 449
Lin, D. N. C., Faulkner, J., & Papaloizou, J. 1985, MNRAS, 212, 105
Makita, M., Miyawaki, K., & Matsuda, T. 2000, MNRAS, 316, 906
Menou, K., Hameury, J. M., & Stehle, R. 1999, MNRAS, 305, 79
Meyer, F., & Meyer-Hofmeister, E. 1982, A&A, 106, 34
Rutten, R. G. M., Kuulkers, E., Vogt, N., & van Paradijs, J. 1992a, A&A, 265, 159
Rutten, R. G. M., van Paradijs, J., & Tinbergen, J. 1992b, A&A, 260, 213
Saito, R. K., & Baptista, R. 2006, AJ, 131, 2185
Sanduleak, N. 1972, Inf. Bull. Variable Stars, 663, 1
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Smak, J. 1992, Acta Astron., 42, 323
Vogt, N. 1983, A&A, 53, 21
Vrielmann, S., Hessman, F. V., & Horne, K. 2002a, MNRAS, 332, 176
Vrielmann, S., & Offutt, W. 2003, MNRAS, 338, 165
Vrielmann, S., Stetina, R. F., & Offutt, W. 2002b, MNRAS, 334, 608
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press)
Warner, B., & Cropper, M. 1983, MNRAS, 203, 909
Warner, B., & O’Donoghue, D. 1987, MNRAS, 224, 733
Watts, D. J., Bailey, J., Hill, P. W., Greenhill, J. G., McCowage, C., & Carty, T. 1986, A&A, 154, 197
Wood, J. H. 1994, in ASP Conf. Series 56, Eclipse Mapping of Accretion Discs in Cataclysmic Variables, ed. A. W. Shafter (San Francisco: ASP), 48
Wood, J. H., & Crawford, C. S. 1986, MNRAS, 222, 645
Wood, J. H., Horne, K., Berriman, G., & Wade, R. 1989, ApJ, 341, 974
Wood, J. H., Horne, K., Berriman, G., Wade, R., O’Donoghue, D., & Warner, B. 1986, MNRAS, 219, 629
Wood, J. H., Irwin, M. J., & Pringle, J. E. 1985, MNRAS, 214, 475