A TWO-ARMED PATTERN IN FLICKERING MAPS OF THE NOVA-LIKE VARIABLE UU AQUARII¹

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ABSTRACT

We report the analysis of a uniform sample of 31 light curves of the nova-like variable UU Aqr with eclipse-mapping techniques. The data were combined to derive eclipse maps of the average steady-light component, the long-term brightness changes, and the low- and high-frequency flickering components. The long-term variability responsible for the “low-brightness” and “high-brightness” states is explained in terms of the response of a viscous disk to changes of 20%–50% in the mass transfer rate from the donor star. Low- and high-frequency flickering maps are dominated by emission from two asymmetric arcs reminiscent of those seen in the outbursting dwarf nova IP Peg, and they are similarly interpreted as manifestations of a tidally induced spiral shock wave in the outer regions of a large accretion disk. The asymmetric arcs are also seen in the map of the steady light aside from the broad brightness distribution of a roughly steady-state disk. The arcs account for 25% of the steady-light flux and are a long-lasting feature in the accretion disk of UU Aqr. We infer an opening angle of 10° ± 3° for the spiral arcs. The results suggest that the flickering in UU Aqr is caused by turbulence generated after the collision of disk gas with the density-enhanced spiral wave in the accretion disk.

Subject headings: accretion, accretion disks — binaries: eclipsing — novae, cataclysmic variables — shock waves — stars: activity — stars: individual (UU Aquarii)

Online material: color figures

1. INTRODUCTION

In cataclysmic variables (CVs) a late-type star overfills its Roche lobe and transfers matter to a companion white dwarf (WD) via an accretion column or disk. The CV zoo comprises low mass transfer dwarf novae and high mass transfer novae and novae-like systems. The light curves of these binaries show intrinsic brightness fluctuations (flickering) of 0.1–1 mag on timescales from seconds to tens of minutes, considered a basic signature of the accretion disk. An obvious next step would be to perform a spatially resolved study of flickering on an eclipsing nova-like system to test these ideas.

UU Aqr is a bright, eclipsing nova-like variable with an orbital period of 3.9 hr and a mass ratio $q = M_2 / M_1 < q_{\text{crit}}$ (e.g., Whitehurst & King 1991) and a mass ratio of $0.35 ± 0.02$ for the accretion disk. Earlier studies (Bruch 1992, 1996, 2000) led to the suggestion that there are mainly two sources of flickering in CVs: the stream-disk impact region at disk rim and a turbulent inner disk region in the vicinity of the WD (possibly the boundary layer), the relative importance of which varies from system to system. The spatially resolved study of flickering in the dwarf nova V2051 Oph by Baptista & Bortolletto (2004, hereafter BB04) revealed a more complex scenario, in which the low-frequency flickering is associated with an overflowing gas stream (possibly as a consequence of unsteady mass transfer from the mass donor star; e.g., Warner & Nather 1971) and the high-frequency flickering is distributed over the surface of the accretion disk, possibly as a consequence of magnetohydrodynamic (MHD) turbulence or events of magnetic reconnection at the disk chromosphere (Geertsema & Achterberg 1992; Kawaguchi et al. 2000). The identification of a disk component to the flickering and the consequent estimation of the disk viscosity $\alpha$-parameter (Shakura & Sunyaev 1973) through the application of an MHD turbulence model raised the expectation that the technique could be applied to measure the accretion disk viscosity of other CVs. In particular, the tight correlation between the flickering disk component and the steady-light emission in V2051 Oph (BB04) suggested that this could be the dominant source of flickering in nova-like systems, with their hot and bright accretion disks. An obvious next step would be to perform a spatially resolved study of flickering on an eclipsing nova-like system to test these ideas.

¹ Based on observations made at the Laboratório Nacional de Astrofísica, CNPq, Brazil.
The light curves were phase-folded according to the linear ephemeris (B. Borges 2005, private communication)

\[ T_{\text{mid}} = \text{HJD 2, 446, 347.2659} + 0.1638049430E, \quad (1) \]

where \( T_{\text{mid}} \) gives the WD mideclipse times. Figure 1 shows the light curves of UU Aqr superimposed in phase. The top panel depicts the light curves of a comparison star with the same brightness as UU Aqr around mideclipse. The constancy of the comparison-star flux over time indicates that all brightness variations seen in UU Aqr are intrinsic to the variable. The scatter with respect to the mean level is significantly larger in UU Aqr and is caused by a combination of flickering and long-term brightness changes.

We applied the “single” (Bruch 1996, 2000) and “ensemble” (Horne & Stiening 1985; Bennie et al. 1996) methods to the set of light curves of UU Aqr to derive the orbital dependency of its steady-light, long-term brightness changes, and low- and high-frequency flickering components. The reader is referred to BB04 for a detailed description and combined application of both methods.

UU Aqr was in its “high-brightness” state during the 1998 and 2001 observations and in its “low-brightness” state during the 1999 and 2000 runs. The curves of the high- and low-brightness states are identified in Figure 1 by black and gray symbols, respectively. We note that the average out-of-eclipse flux level increases steadily from the 1999 to the 2001 data, and that the nominal separation between the low- and high-brightness states is a rather arbitrary one. Because of the scatter produced by the strong flickering (with an average peak-to-peak amplitude of \( \approx 3 \text{ mJy for both brightness levels} \)), there is an overlap in flux between the curves of the low and high states. In order to test the influence of the brightness state on the flickering behavior, we applied the ensemble method separately for the data of the high- and low-brightness states. We found no evidence of a dependence of the flux level or eclipse shape of the flickering curve.

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changes caused by the eclipse. In order to overcome this limita-
tion, we subtracted the average steady-light curve from each indi-
vidual light curve before applying the single filtering process to 
eliminate the steep gradients produced by the eclipse in the 
light curve. Our single light curve includes flickering components 
with frequencies \( f_c > 2 \text{ mHz} \) (timescales shorter than \( \tau_c = 500 \text{ s} \); 
Fig. 2). Single curves obtained with cutoff frequencies of \( f_c = 3 \text{ mHz} (\tau_c = 333 \text{ s}) \) and \( f_c = 5 \text{ mHz} (\tau_c = 100 \text{ s}) \) show the same 
morphology as the lower cutoff frequency curve. Because of 
the reduced power, these other curves are noisier and are not 
presented here.

The steady-light curve, the long-term changes curve, and the 
flickering curves were analyzed with eclipse-mapping techniques 
(Horne 1985; Baptista & Steiner 1993) to solve for a map of the 
disk surface brightness distribution and for the flux of an addi-
tional uneclipsed component in each case. The uneclipsed com-
ponent accounts for all light that is not contained in the eclipse 
map (i.e., light from the secondary star and/or a vertically ex-
tended disk wind). The reader is referred to Rutten et al. (1992) 
and Baptista et al. (1996, hereafter BSH96) for a detailed descrip-
tion of and tests with the uneclipsed component and to Baptista 
(2001) for a recent review of the eclipse-mapping method. Out-of-
eclipse brightness changes (not accounted for by the standard 
eclipse-mapping method) were removed from the light curves 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 (e.g., BSH96).

Our eclipse map is a flat Cartesian grid of \( 51 \times 51 \) pixels cen-
tered on the WD 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 
the scale of the map is set by \( R_{L1} \). We adopted \( R_{L1} = 0.744 R_\odot \), 
\( q = 0.3 \), and \( i = 78^\circ \) (BSC94), which correspond to a WD eclipse 
width of \( \Delta \phi = 0.051 \text{ cycles} \). This combination of parameters 
ensures that the WD is at the center of the map. The reconstruc-
tions were performed with a polar Gaussian default function 
(Rutten et al. 1992) with radial blur width \( \Delta r = 0.02R_{L1} \) and 
azimuthal blur width \( \Delta \theta = 30^\circ \) and reached a final reduced 
\( \chi^2 \) of \( 1 \) for all light curves. The uncertainties in the eclipse maps 
were derived from Monte Carlo simulations with the light curves 
using a bootstrap method (Efron 1982; Watson & Dhillon 2001), 
generating a set of 20 randomized eclipse maps (see Rutten et al. 
1992). These were combined to produce a map of the standard

with brightness level in UU Aqr. We therefore combined all the 
light curves for the following analysis. The difference in the aver-
age brightness level seen in UU Aqr along the observations is 
properly taken into account in the ensemble method by the curve 
of the long-term changes (see below; BB04).

In order to apply the ensemble method, we define a reference 
out-of-eclipse flux \( f_{\text{ref}} \) (the mean flux over the phase range 0.15– 
0.80) for each individual light curve, and we divide the data into a 
set of phase bins. A linear fit to the \( f_i \) versus \( f_{\text{ref}}(i) \) diagram for 
each phase bin (e.g., Fig. 2 of BB04) yields an average flux (the steady-
light component), an angular coefficient (which measures the long-
term change), and a standard deviation with respect to the linear 
fit (the scatter curve, with added contributions from the Poisson 
noise and the flickering). We multiply the nondimensional angular 
coefficients by the amplitude of the variation of the reference flux 
in the data set, \( \Delta f_{\text{ref}} = 5.5 \pm 0.1 \text{ mJy} \), to express the long-term 
changes in terms of the amplitude of the flux change per phase 
bin, \( \Delta f_i(\phi) \).

The average steady-light curve was subtracted from each individ-
ual light curve to remove the DC component, and a Lomb-Scargle 
periodogram (Press et al. 1992) was calculated. The periodograms 
of all light curves were combined to yield a mean periodogram 
and a standard deviation with respect to the mean. Figure 2 shows 
the resulting average power density spectrum (PDS) binned to a 
resolution of 0.02 units in log(frequency). The PDS is well de-
scribed by a power law \( P(f) \propto f^{-1.5} \). It becomes flat for \( f_{\text{low}} \leq 0.15 \text{ mHz} (t_{\text{low}} > 111 \text{ minutes}) \) and disappears in the white noise 
for \( f_{\text{high}} \geq 20 \text{ mHz} (t_{\text{high}} < 50 \text{ s}) \). The slope of the PDS distribution 
is reminiscent of those seen in other CVs, which can be well 
described by power laws with an average exponent \( P(f) \propto f^{-2.0\pm0.8} \) 
(Gruch 1992).

The ensemble method samples flickering at all frequencies. But 
because of the power-law dependency of the flickering, an 
ensemble curve is dominated by the low-frequency flickering 
components. On the other hand, the filtering process of the single 
method produces curves which sample the high-frequency flick-
ering. The combination of both methods allows one to separate the 
low- (ensemble) and high-frequency (single) components of the 
flickering.

The Achilles heel of the single method is its difficulty in separ-
ating the high-frequency flickering from the rapid brightness 
changes caused by the eclipse. In order to overcome this limita-

![Fig. 1.—Light curves of UU Aqr (bottom) and a comparison star (top) super-
imposed in phase. The data of the high- and low- brightness states are plotted with 
black and gray symbols, respectively. [See the electronic edition of the Journal for 
a color version of this figure.]](image1)

![Fig. 2.—Average PDS. Dotted lines show the 1 \( \sigma \) limits on the average 
power. The best-fit power law \( P(f) \propto f^{-1.5} \) is shown as a dashed line. A vertical 
tick marks the low-frequency cutoff of the filtering process applied to derive the 
single scatter curve.]](image2)
deviations with respect to the true map. A map of the statistical significance (or the inverse of the relative error) was obtained by dividing the true eclipse map by the map of the standard deviations (Baptista et al. 2005).

4. RESULTS

The light curves and corresponding eclipse maps are shown in Figure 3. For a better visualization of the structures in the disk brightness distributions, the asymmetric disk components are also shown. An asymmetric component is obtained by slicing the disk into a set of radial bins and fitting a smooth spline function to the mean of the lower half of the intensities in each bin. The spline-fitted intensity in each annular section is taken as the symmetric disk-emission component. The asymmetric disk component is then obtained by subtracting the symmetric disk from the original eclipse map (e.g., Saito & Baptista 2006). This procedure removes the baseline of the radial distribution while preserving all azimuthal structure.

4.1. Steady-Light and Long-Term Changes

The steady-light light curve gives the flux per phase bin for the midreference flux level and represents the median steady brightness level along the data set. Because it is obtained by combining 31 light curves, it has a high S/N, and the corresponding eclipse map is of high statistical significance (typically $>10 \sigma$).

The eclipse map of the steady light shows an extended brightness distribution peaking at disk center with two asymmetric arcs on roughly opposite disk sides (Fig. 3, top row). The asymmetries are diluted by the dominant broad disk brightness distribution and only become clear in the asymmetric disk component. The arcs account for $\sim 25\%$ of the total flux of the steady-light map. They are located at different radii, with the one on the trailing side (the lower disk hemisphere in the eclipse maps of Fig. 3) being closer to disk center. The asymmetric arcs do not coincide with the WD at disk center or the bright spot at disk rim.

By transforming the intensities in the steady-light eclipse map into blackbody brightness temperatures (assuming a distance of 200 pc to the binary; BSH96) we find that the radial temperature distribution closely follows the $T \propto R^{-3.4}$ law for steady accretion in the outer disk and becomes flatter in the inner disk regions ($R \leq 0.2 R_{L1}$), leading to estimated mass accretion rates of $\dot{M} = 10^{-9.0 \pm 0.2} M_\odot$ yr$^{-1}$ at $R = 0.1 R_{L1}$ and $\dot{M} = 10^{-8.80 \pm 0.06} M_\odot$ yr$^{-1}$ at $R = 0.3 R_{L1}$. The brightness temperatures decrease steadily with radius, from $\sim 13,000$ K at $0.1 R_{L1}$ to $\sim 9400$–7000 K at $(0.2–0.4) R_{L1}$ (the radial range at which the asymmetric arcs are located) and $\sim 5500$ K at $0.5 R_{L1}$. We also find an uneclipsed
component of 6.4% ± 0.3% of the total steady-light flux. The inferred brightness temperatures, uneclipsed component, and mass accretion rates are in good agreement with previous results (BSH96; Baptista et al. 2000; Vrielmann & Baptista 2002).

The curve of the long-term changes measures brightness changes on timescales longer than the orbital period. It allows us to visualize the differences in disk structure between the observed low- and high-brightness states of UU Aqr.

The light curve of the long-term changes shows an eclipse with a pronounced shoulder at egress phases. The resulting eclipse map (Fig. 3, second row) has a bright source at disk center and an azimuthally extended (∆θ ≈ 90°) bright spot at disk rim, similar to those found in the eclipse maps of the high state of BSH96. The uneclipsed component is negligible. This map tells us that the difference between the low- and high-brightness states is caused by an increase in the luminosity of the outer parts of the disk (as previously found by BSH96) but also by a comparable increase in brightness of the innermost disk regions.

For a fixed distance, the intensities in the eclipse map scale linearly with the flux in the light curve (see, e.g., Baptista 2001). Because we choose to express the long-term changes curve in terms of the amplitude of the flux variation (∆I), the intensities in the corresponding eclipse map are given in terms of the amplitude of the variation in intensity between the minimum and maximum brightness states in the data set, ∆I (where I refers to each pixel in the eclipse map). Thus, eclipse maps representing the minimum and maximum brightness distributions can be obtained by adding (subtracting) the appropriate proportion of the long-term changes map to (from) the steady-light map, I,

\[
I_{\text{min}} = \tilde{I} - \frac{1}{2} \Delta I, \\
I_{\text{max}} = \tilde{I} + \frac{1}{2} \Delta I.
\]

As expected, the resulting minimum and maximum brightness maps (Fig. 4) are similar to the B-band eclipse maps of the low- and high-brightness states of BSH96 (see their Fig. 3).

We now turn our attention to the interpretation of the structures seen in the long-term changes map. BSH96 suggested that the azimuthally extended spot seen in the high-brightness state reflects long-term changes in luminosity caused by variations in mass input rate at the outer disk. Baptista et al. (2000) noted that it could alternatively be the signature of an elliptical (precessing) map to (from) the steady-light map, thus, eclipse maps representing the minimum and maximum brightness distributions can be obtained by adding (subtracting) the appropriate proportion of the long-term changes map to (from) the steady-light map, I,

\[
I_{\text{min}} = \tilde{I} - \frac{1}{2} \Delta I, \\
I_{\text{max}} = \tilde{I} + \frac{1}{2} \Delta I.
\]

The ensemble and single curves show a double-stepped eclipse reminiscent of the occultation of the two-armed spiral structure

where $R_{\text{WD}}$ is the WD radius. Thus, the difference in temperature (and the corresponding difference in blackbody intensity) between two steady-state disk models increases with decreasing radius and peaks near disk center (at $R = 49/36 R_{\text{WD}}$). The difference in intensity also scales with $\partial M$. In searching for the pair of $(M_{\text{ref}}, \beta)$ values that best fit the observed brightness distribution, we find $M_{\text{ref}} = 10^{-9.1} \pm 0.1 M_\odot$ yr$^{-1}$ and $\beta = 1.35 \pm 0.15$. Figure 5 shows that the radial distribution of the central source of the long-term changes map is consistent, within the uncertainties, with the difference in intensity expected for an increase of 20%–50% in mass accretion rate of a steady-state disk with $10^{-9.1} M_\odot$ yr$^{-1}$. Because the radial temperature distribution of the steady-light map is actually flatter than the $T \propto R^{-3/4}$ law of steady-state disks, these results should be considered illustrative. Nevertheless, the inferred range of mass accretion rates ($10^{-9.1}$ to $10^{-8.5} M_\odot$ yr$^{-1}$) is in line with the values for the low- and high-brightness states found by BSH96.

Because in a steady-state disk the mass accretion rate reflects the mass transfer rate, $M_2$, we may interpret the map of the long-term changes in terms of the response of a high-viscosity disk to changes in $M_2$ of about 20%–50%. When $M_2$ increases, the luminosity of the bright spot at disk rim, as well as that of the inner disk regions, increases as a consequence of the increase of mass accretion through a disk close to a steady state.

4.2. Low- and High-Frequency Flickering

The ensemble and single curves show a double-stepped eclipse reminiscent of the occultation of the two-armed spiral structure
seen in eclipse maps of the dwarf nova IP Peg in outburst (e.g., Baptista et al. 2002, 2005) and lead to similar two-armed asymmetric brightness distributions (Fig. 3, third and fourth rows). The solid contour line overplotted on each eclipse map depicts the 3 σ confidence level region as derived from the map of statistical significance in each case (§ 3). The asymmetric arcs are at or above the 3 σ confidence level in both maps. Vertical tick marks in the ensemble panel of Figure 3 indicate the eclipse ingress/egress phases of the two bright arcs (labeled 1 and 2). Their location is depicted in the asymmetric component of the ensemble map. A simple comparison reveals that these are the same asymmetric arcs seen in the steady-light map. The major difference is that the arms dominate the emission in the flickering maps (the asymmetric components account for 53% and 41% of the total flux, respectively, for the ensemble and single maps). As already noted, they do not coincide with the WD at disk center or with the bright spot at disk rim.

Although it is possible to center the eclipse of source 1 by applying a phase shift to all light curves, this would lead to physically implausible brightness distributions for the steady-light and long-term changes maps, with highly asymmetric brightness distributions where the main sources fall at positions which cannot be associated with either the WD, the bright spot, or the gas stream (e.g., the azimuthally extended spot in the long-term changes map would fall at the edge of the primary Roche lobe, far away from the gas stream trajectory). It is also not possible to interpret the observed asymmetries in terms of enhanced emission from an elliptical outer disk ring because the asymmetries lie well inside the disk, far from its edge. Given the similarities to the IP Peg eclipse maps (e.g., see Fig. 3 of Baptista et al. 2002) and the lack of plausible alternative explanations, we interpret the asymmetries in the flickering and steady-light maps as consequences of tidally induced spiral shock waves in the accretion disk of UU Aqr (e.g., Sawada et al. 1986).

Arc 1 is in the trailing side of the disk at $R_1 = 0.20R_{L1} \pm 0.05R_{L1}$; arc 2 is in the leading side of the disk and is farther away from disk center, $R_2 = 0.32R_{L1} \pm 0.05R_{L1}$. The two arcs have azimuthal extent $\Delta \theta \simeq 110^\circ$ and radial extent $\Delta R \simeq 0.2R_{L1}$. Baptista et al. (2005) devised a way to estimate the opening angle of the spirals from the azimuthal intensity distribution of the eclipse maps. We applied the same method to the flickering maps to estimate an opening angle of $\phi = 10^\circ \pm 3^\circ$, indicating that the spiral arms in UU Aqr are more tightly wound than in IP Peg at outburst ($\phi = 14^\circ \pm 34^\circ$; Baptista et al. 2005). They are also systematically closer to disk center than the arms seen in IP Peg (at average distances of $0.30R_{L1}$ and $0.55R_{L1}$; see Baptista et al. 2005). Because the opening angle of the spiral arms scales with the disk temperature (e.g., Steeghs & Stehle 1999), this suggests that the outer accretion disk of UU Aqr is cooler than that of IP Peg in outburst.

We find uneclipsed components of 13% ± 3% and 17% ± 7% of the total flux for the ensemble and single maps, respectively. This suggests that a sizable part of the flickering may arise from outside the orbital plane, perhaps in a vertically extended disk chromosphere + wind.

The ensemble map samples flickering at all frequencies, while the single map contains the high-frequency (timescales <500 s) flickering components. It is possible to separate the contribution of the low-frequency flickering by subtracting the single map from the ensemble map.

Figure 6 compares the relative amplitude of the low- (ensemble-) and high-frequency (single) flickering components in UU Aqr. The radial run of the relative amplitudes is obtained by dividing the average radial intensity distribution of these two flickering maps by that of the steady light. Dashed and dotted lines in the figure show the 1 σ limits on the average amplitude for the low- and high-frequency flickering, respectively. The large uncertainties
reflect the scatter introduced by the asymmetric arcs in the radial bins. The two distributions are comparable within the uncertainties. Flickering is negligible in the inner disk. The amplitude of the low-frequency flickering increases monotonically with radius, reaching 6% of the total light at 0.3R\textsubscript{L1}. The amplitude of the high-frequency flickering also increases with radius and peaks at the location of the spiral arms (\( \approx 0.3R\textsubscript{L1} \)). The distributions are not reliable for \( R \geq 0.45R\textsubscript{L1} \) because of the reduced statistical significance of the flickering maps and the rapidly declining intensities in the steady-light map. The bottom panel of Figure 6 depicts the ratio of the single to the ensemble distributions and measures the contribution of high frequencies (single) to the total flickering. The high-frequency flickering accounts for a roughly constant fraction of \( \approx 50\% \) of the flickering signal at all radii. There is no apparent difference in radial behavior between the low- and high-frequency flickering components, indicating that they not only arise from the same location but are also produced by the same physical mechanism.

We further note that our data cover a time interval of about 4 yr and that the eclipse maps yield the average behavior over this timescale, with the implication that the observed spiral shocks are a long-lasting feature in the accretion disk of UU Aqr.

5. DISCUSSION

BB04 found two independent sources of flickering in their study of the dwarf nova V2051 Oph: the low-frequency flickering is associated with inhomogeneities in the mass transfer process, while the high-frequency flickering originates in the accretion disk, possibly as a consequence of MHD turbulence (Geertsema & Achterberg 1992) or events of magnetic reconnection in the disk surface (Kawaguchi et al. 2000). Contrary to the suggestion of Bruch (2000), UU Aqr shows no evidence of flickering arising from a turbulent inner disk or from the bright spot. And, in contrast to V2051 Oph, it shows no disk-related flickering component. However, its high- and low-frequency flickering have the same origin. They are produced in a two-armed pattern reminiscent of the tidally induced spiral shocks seen in outbursting accretion disks of dwarf novae (Steeghs et al. 1997; Baptista et al. 2002). These shocks are produced by tidal effects when the disk expands beyond the 3:1 resonance radius. In a dwarf nova these spiral shocks are only seen during outburst, when the disk becomes hot and large. In a nova-like system, the spiral shocks may be a permanent feature if the hot disk is large enough for tidal effects to become relevant. The presence of spiral structures in the steady-light and flickering maps of UU Aqr is a likely indication that its accretion disk is large enough for the tidal pull of the mass donor star to be relevant for the gas dynamics in the outer disk regions. This is in line with the detection of long-lasting superhumps in this binary (Patterson et al. 2005); the tidal influence that leads to spiral density waves may also induce elliptical orbits in the outer disk regions. Because the spiral arms account for a small fraction of the steady light and are not related to the broad and brighter steady emission centered in the disk, one might conclude that they are not the dominant source of viscous dissipation and angular momentum removal in the UU Aqr accretion disk.

Why do the asymmetric arcs flicker? We discuss three possibilities. One may consider that flickering is a consequence of unsteady dissipation of energy from a clumpy gas stream as it hits the two-armed spiral density wave in the disk (i.e., a mass transfer origin for the flickering, as proposed by Warner & Nather 1971). In this case the clumpy gas stream should also lead to detectable flickering at the location of the bright spot, where it first hits the accretion disk rim before reaching the spiral arms. However, while the bright spot is a significant light source in the long-term changes map (indicating that the stream-disk impact occurs at \( R \approx 0.6R\textsubscript{L1} \), farther out in the disk than the observed radial position of the spiral arms), it gives no contribution to the flickering. We may conclude that there is no evidence of clumpiness in the infalling gas stream, and, therefore, we exclude this as a viable explanation. A second possibility is to consider that flickering arises from reprocessing at tidally induced and vertically thickened disk regions of unsteady irradiation from the boundary layer (a boundary layer/WD flickering; Bruch 1992). The problem with this explanation is similar to that of the previous one: it would be hard to explain why we do not see optical flickering directly from the innermost disk regions. The third and most promising possibility is to assume that the observed flickering is the consequence of turbulence generated by the shock of disk gas as it passes through the tidally induced spiral density waves (i.e., a local origin for the flickering). Further numerical simulations of spiral shocks in accretion disks would be useful to verify the turbulent nature of the aftershock gas and to test whether such turbulence could generate the observed power-law dependency \( [P(f) \propto f^{-1.5}] \) of the resulting energy dissipation fluctuations.

Assuming that the disk gas moves in Keplerian orbits around the 0.67\( M_\odot \) WD (BSC94), the locations of the asymmetric arcs correspond to Doppler velocities of 900–1050 and 700–800 km s\(^{-1}\) for arcs 1 and 2, respectively. Given that the aftershock gas is expected to have sub-Keplerian velocities (\( \approx 15\%–40\% \) lower; see Steeghs & Stehle 1999; Baptista et al. 2005), these structures may appear as arcs of enhanced emission at velocities of \( \approx 450–650 \text{ km s}^{-1} \) in the upper left (arc 2) and lower right (arc 1) quadrant on a Doppler tomogram. Kaitchuck et al. (1998) and Hoard et al. (1998) report that UU Aqr disk line emission is largely asymmetric. Their tomograms show regions of enhanced emission which may be interpreted as arising from a two-armed spiral pattern in the disk. The asymmetry corresponding to arc 1 is clearly seen (e.g., see Fig. 6 of Hoard et al. 1998 and Fig. 15 of Kaitchuck et al. 1998), while that related to arc 2 may be blended with and hidden by the emission from the gas stream and bright spot impact site. This latter effect may help explain the large mass ratio \( q = 0.86 \) inferred by Kaitchuck et al. (1998) by fitting the gas stream trajectory to the asymmetry in the upper left quadrant of their Doppler tomograms.

6. SUMMARY

Our investigation of the source of variability in UU Aqr indicates that the long-term changes giving rise to the low- and high-brightness states can be accounted for by changes in the mass transfer rate of 20%–50%. A high S/N steady-light light curve reveals the presence of long-lasting (at least over the 4 yr period of the observations) asymmetric arcs in the accretion disk aside from the broad brightness distributions of a roughly steady-state disk. The arcs are interpreted as the consequence of tidally induced spiral shocks in an extended and hot accretion disk. The spiral arms account for 25% of the steady-light flux and are the dominant source of flickering at both low and high frequencies. They are more tightly wound than the spiral shocks found in the outbursting dwarf nova IP Peg. The observed flickering shows a power spectrum density with an \( f^{-1.5} \) power-law dependency and is best explained as resulting from turbulence generated after the collision of disk gas with the density-enhanced spiral wave in the accretion disk. There is no evidence of flickering originating in the bright spot at disk rim or in the innermost disk regions around the WD.
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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., & Bortolotto, A. 2004, AJ, 128, 411 (BB04)

Baptista, R., Haswell, C. A., & Thomas, G. 2002, MNRAS, 334, 198

Baptista, R., Morales-Rueda, L., Harlaftis, E. T., Marsh, T. R., & Steeghs, D. 2005, A&A, 444, 201

Baptista, R., Silveira, C., Steiner, J. E., & Horne, K. 2000, MNRAS, 314, 713

Baptista, R., & Steiner, J. E. 1993, A&A, 277, 331

Baptista, R., Steiner, J. E., & Cieslinski, D. 1994, ApJ, 433, 332 (BSC94)

Baptista, R., Steiner, J. E., & Horne, K. 1996, MNRAS, 282, 99 (BSH96)

Bennie, P. J., Hilditch, R., & Horne, K. 1996, in IAU Colloq. 158, Cataclysmic Variables and Related Objects, ed. A. Evans & J. H. Wood (Dordrecht: Kluwer), 33

Bessell, M. A. 1990, PASP, 102, 1181

Bruch, A. 1992, A&A, 266, 237

———. 1996, A&A, 312, 97

———. 2000, A&A, 359, 998

Efron, B. 1982, The Jackknife, The Bootstrap and Other Resampling Plans (Philadelphia: SIAM)

Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (2nd ed.; Cambridge: Cambridge Univ. Press)

Geertsema, G. T., & Achterberg, A. 1992, A&A, 255, 427

Graham, J. A. 1982, PASP, 94, 244

Hoard, D. W., Still, M. D., Szkody, P., Smith, R. C., & Buckley, D. A. H. 1998, MNRAS, 294, 689

Honigcutt, R. K., Robertson, J. W., & Turner, G. W. 1998, AJ, 115, 2527

Horne, K. 1985, MNRAS, 213, 129

Horne, K., & Stiepen, R. F. 1985, MNRAS, 216, 933

Kaitchuck, R. H., Schlegel, E. M., White, J. C., II, & Mansperger, C. S. 1998, ApJ, 499, 444

Kawaguchi, T., Mineshige, S., Machida, M., Matsumoto, R., & Shibata, K. 2000, PASJ, 52, L1

Kunze, S., Speith, R., & Riffert, H. 1997, MNRAS, 289, 889

Lamla, E. 1982, in Landolt-Börnstein Numerical Data and Functional Relationships in Science and Technology, Vol. 2, ed. K. Schaifers & H. H. Voigt (Berlin: Springer)

Murray, J. R., Warner, B., & Wickramasinghe, D. T. 2000, MNRAS, 315, 707

Osaki, Y. 1996, PASP, 108, 39

Patterson, J., et al. 2005, PASP, 117, 1204

Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1992, Numerical Recipes in C (Cambridge: Cambridge Univ. Press)

Rutten, R. G. M., van Paradis, J., & Tinbergen, J. 1992, A&A, 260, 213

Saio, R. K., & Baptista, R. 2006, AJ, 131, 2185

Sawada, K., Matsuda, T., & Hachisu, I. 1986, MNRAS, 219, 75

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Steeghs, D. 2001, in Astrotomography, Indirect Imaging Methods in Observational Astronomy, ed. H. M. J. Boffin, D. Steeghs, & J. Cuypers (Berlin: Springer), 45

Steeghs, D., Harlaftis, E. T., & Horne, K. 1997, MNRAS, 290, L28

Steeghs, D., & Stehle, R. 1999, MNRAS, 307, 99

Stone, R. P. S., & Baldwin, J. A. 1983, MNRAS, 204, 347

Vrielmann, S., & Baptista, R. 2002, Astron. Nach., 323, 75

Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press)

Warner, B., & Nather, R. E. 1971, MNRAS, 152, 219

Watson, C. A., & Dhillon, V. S. 2001, MNRAS, 326, 67

Whitehurst, R., & King, A. 1991, MNRAS, 249, 25