EMISSION-LINE FLICKERING FROM THE SECONDARY STAR IN CATACLYSMIC VARIABLES? 
A STUDY OF V3885 SAGITTARII

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ABSTRACT

Spectrophotometric observations of the Hα and He i λ6678 emission lines of the nova-like cataclysmic variable V3885 Sgr are presented and analyzed. The binary orbital period was determined as \( P = 0.20716071(22) \) days. Doppler tomography was performed with both Hα and He i lines. Disk radial emissivity profiles were also computed. The tomography mapping of flickering sources was performed using the Hα line, from which we concluded that the flickering is not uniformly distributed on the disk. The observed tomogram of the flickering was compared with simulations, suggesting that the most intense flickering source in the Hα is not located in the accretion disk. It is proposed that the main flickering source might be associated with the illuminated secondary star.

Key words: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (V3885 Sagittarii)

1. INTRODUCTION

Cataclysmic variables (CVs) are close binary systems composed of a white dwarf, also called the primary, and a red dwarf star, the secondary. The secondary fills its Roche lobe and transfers matter to the primary. Due to the binary angular momentum, the matter does not fall toward the white dwarf, forming an accretion disk. The accretion disk emission is complex; it has regions of enhanced emission such as the hot spot, the location of the stream of matter coming from the secondary reaches the disk, and the boundary layer, the inner part of the accretion disk where the matter is decelerated to the white dwarf’s equatorial velocity. The disk’s vertical profile is not flat; it presents a higher thickness in its outer parts. A review of CVs is presented in Warner (1995).

The CVs are grouped into many classes and subclasses; one of these is the nova-like class that harbors noneruptive objects. V3885 Sgr is one of the brightest CVs. It is a non-eclipsing system classified as a UX UMa nova-like star. V3885 Sgr was discovered by Bidelman & Bond (1968), who detected broad Balmer emission lines. Bond & Landolt (1971) identified the continuum slope as being similar to those of DA white dwarfs. Wegner (1972) observed the continuum distributions, Haug (1987) described the spectral energy distribution of the disk as that of a stationary disk with a high mass transfer rate. Hartley et al. (2005) calculated \( P_{\text{orb}} = 0.207135(15) \) days for this system, solving previous inconsistencies concerning the orbital period. They also presented a radial velocity study and Hβ, Hγ, and He i λ4471 Doppler maps, and they showed evidence of irradiation for the secondary star.

Flickering or rapid variability is observed as a stochastic variation of the emitted radiation, with timescales from seconds to tens of minutes and amplitudes ranging from a few percent of a magnitude to more than 1 mag. Flickering is associated with mass transfer and occurs in objects other than CVs, such as symbiotic stars (Mikołajewski et al. 1990) and X-ray binaries (e.g., Baptista et al. 2002). Furthermore, flickering not only occurs in systems in which an accretion disk is present, but is also observed in magnetic CVs. The flickering in the continuum could be produced in different regions of the system. Warner & Nather (1971) observed that the flickering in U Gem disappeared during the eclipse, and since the central part of the disk was not occulted during the eclipse, they associated the flickering source with the hot spot. Vogt et al. (1981) verified that the flickering in OY Car persists during a hot spot eclipse. The same was observed for HT Cas by Patterson (1981) and Z Cha by Wood et al. (1986). Horne & Stiening (1985) identified the flickering in some eclipsing systems as originating near the center of the accretion disk. In addition, Horne et al. (1994) associated the flares observed in OY Car with the innermost part of the disk. Bruch (1996) observed that the flicker-forming region in Z Cha is located near the white dwarf and that there could be other flickering sources seen in different photometric states.

In §2 we detail the observations and data reduction procedure. In §3 the average spectrum is described and a long-term ephemeris is given. The system masses and orbital inclination are constrained. Doppler tomography and flickering Doppler tomography results are presented. Furthermore, the observed flickering tomograms are compared with flickering simulations. The implications of our results are discussed in §4. The conclusions are outlined in §5.

2. OBSERVATIONS AND DATA REDUCTION

The time-resolved spectroscopic observations were made using the 1.60 m telescope at Observatório Pico dos Dias (Laboratório Nacional de Astrofísica [LNA]/CNPq) and the 1.5 m telescope at Cerro Tololo Inter-American Observatory. For more details about the observations, see the observations journal (Table 1). The atmospheric conditions on the observing runs ranged from photometric to spectroscopic. Differential spectrophotometric techniques were employed. The LNA observations were made using a Cassegrain spectrograph, equipped with a 1200 groove mm⁻¹ grating blazed at 4550 Å, and a back-illuminated 1024 × 1024 CCD. The CTIO observations were also carried out with a Cassegrain spectrograph, a 1200 groove mm⁻¹ grating, but blazed at 7500 Å, and a
TABLE 1

| Observation Date | Telescope | Exp. Time (s) | No. of Spectra | No. of Cycles |
|------------------|-----------|--------------|---------------|--------------|
| 1999 Sep 1       | 1.60 m LNA | 45           | 280           | 1.17         |
| 1999 Sep 2       | 1.60 m LNA | 45           | 390           | 1.55         |
| 2000 Jul 7       | 1.60 m LNA | 30           | 148           | 0.46         |
| 2000 Jul 8       | 1.60 m LNA | 30           | 72            | 0.28         |
| 2000 Jul 9       | 1.60 m LNA | 30           | 134           | 0.54         |
| 2001 Mar 21      | 1.60 m LNA | 45           | 112           | 0.45         |
| 2001 Mar 22      | 1.60 m LNA | 45           | 62            | 0.28         |
| 2001 Sep 10      | 1.60 m LNA | 90           | 128           | 1.13         |
| 2001 Sep 11      | 1.60 m LNA | 90           | 30            | 0.31         |
| 2001 Sep 18      | 1.60 m LNA | 100          | 117           | 1.06         |
| 2001 Sep 19      | 1.60 m LNA | 100          | 89            | 0.88         |
| 2002 Jun 16      | 1.5 m CTIO  | 180          | 25            | 0.26         |
| 2002 Jun 17      | 1.5 m CTIO  | 180          | 25            | 0.26         |
| 2002 Jun 18      | 1.5 m CTIO  | 180          | 32            | 0.38         |
| 2002 Jun 19      | 1.5 m CTIO  | 180          | 30            | 0.35         |
| 2002 Jun 20      | 1.5 m CTIO  | 180          | 37            | 0.39         |
| 2002 Jun 21      | 1.5 m CTIO  | 180          | 36            | 0.38         |
| 2002 Jun 22      | 1.5 m CTIO  | 180          | 29            | 0.47         |
| 2002 Jun 23      | 1.5 m CTIO  | 180          | 42            | 0.46         |

1200 × 800 Loral 1K CCD. All the observations were centered at the Hα line. A spectral resolution of about 2 Å was achieved. The spectral coverage also included the He i λ6678 spectral line.

Bias and flat-field images were taken to adjust the zero-level count and to correct for response. When the observational conditions allowed, twilight flat images were also taken to derive the CCD illumination correction. The data were bias-subtracted, flat-fielded, and illumination-corrected using standard IRAF1 procedures. The spectra were extracted using an optimal extraction algorithm (Horne 1986) for both the object and a comparison star.

Each spectrum was then corrected for possible cosmic rays by interpolating neighboring pixels. We set the optimal extraction to trim only the most intense cosmic rays, as a sharp line profile feature (i.e., due to flickering) could be confused with a cosmic ray and trimmed. So we preferred to eliminate the less intense cosmic rays by hand. The cosmic rays in the sky background were fielded, and illumination-corrected using standard IRAF1 procedures. The spectra were extracted using an optimal extraction algorithm (Horne 1986) for both the object and a comparison star.

The averaging method was performed by intercalating the Ne-Ar arc-lamp spectra (Hamuy et al. 1994) observations were taken for flux calibration. To allow the correction of light losses at the spectrograph’s slit and to perform small sky-transparency corrections, a tertiary standard photometric star was included in the slit. Wide-slit tertiary standard photometric star (Hamuy et al. 1994) observations were taken for flux calibration. To allow the correction of light losses at the spectrograph’s slit and to perform small sky-transparency corrections, a nearby comparison star was included in the slit. Wide-slit (7iam) spectra of the comparison star were also acquired. This differential calibration procedure also corrects the spectra for atmospheric dispersion effects.

As the Hα line region includes telluric lines and bands, we performed a correction using a telluric template with the same spectral resolution. The telluric template was scaled and shifted to correct the telluric features using an averaged spectrum of the target. This correction was then applied to each spectrum of our data set. For this reason, the correction should be good enough for the average spectrum and may not be as accurate for each individual spectrum. Individual correction factors of each spectrum are unreliable because of their low signal-to-noise ratio (S/N).

All derived quantities involve averaging data over phase bins; therefore, we do not foresee any impact on the measured quantities.

3. RESULTS

3.1. Spectral Features

The averaged spectrum (Fig. 1) has a spectral coverage of 6400–6714 Å, showing Hα and He i λ6678 emission lines. The continuum has a blue slope, without any other visible feature. Here Hα appears as single-peaked and He i as double-peaked. The former line presents a small absorption component at the blue side of the profile, indicating a P Cygni profile or an underlying absorption. The Hα line has a FWHM of 780 km s⁻¹, EW = −4.1 Å, and a line profile integrated flux \( F_{\text{H}\alpha} = 5.7 \times 10^{-13} \text{ergs s}^{-1} \text{cm}^{-2} \), while the He i λ6678 line has a FWHM of 820 km s⁻¹, \( EW = -0.48 \text{ Å} \), and an integrated flux \( F_{\text{He}i} = 6.40 \times 10^{-14} \text{ergs s}^{-1} \text{cm}^{-2} \), thus, the equivalent width of the Hα line is 8.5 times the He i one.

It was not possible to identify any absorption spectral feature from the secondary in the phased spectra or in the averaged spectra. So, the secondary radial velocity amplitude \( K2 \) and the companion spectral type could not be directly determined in the present work.

3.2. System Parameters

A long-term ephemeris was derived using unambiguous cycle-counting between all observation nights in our data set. The calculated orbital period for V3885 Sgr is \( P_{\text{orb}} = 0.20716071(22) \) days and epoch \( E0 = 51,942.08371(46) \) MJJD, defined as the positive-to-negative crossing of radial velocity curves for the line wings. The uncertainties were obtained from a least-squares linear fit to all cycle timings. The residuals in the \( O - C \) diagram are well behaved, and there is no suggestion of a period derivative. This period is in agreement with the 0.207135(15) day period found by Hartley et al. (2005) within a 2σ interval.

Using the Schneider & Young (1980) method to measure the velocity in the line wings, we have constructed a diagnostic diagram for both Hα and He i as a function of the convolution mask Gaussian separation \( a \). The primary radial velocity \( (K1) \) values

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1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
remained almost constant inside the interval 300 km s\(^{-1}\) < \(a\) < 600 km s\(^{-1}\), presenting a slight decrease in velocity for \(a\) > 600 km s\(^{-1}\). The relative error on \(K_1\) as a function of \(a\) showed a minimum at \(a \approx 500\) km s\(^{-1}\). The rms exhibited this same behavior. From this diagnostic diagram, looking for a range in \(a\) that presents a plateau in \(K\) and minimum relative error and rms, we estimated the primary radial velocity from \(K_{\text{H}} = 139 \pm 25\) km s\(^{-1}\) for the H\(\alpha\) emission line and \(K_{\text{He}} = 188 \pm 25\) km s\(^{-1}\) for He\(\)i. These uncertainties were estimated on the basis of the assumption that the radial velocity measurements from both H\(\alpha\) and He\(\)i should be compatible. The \(K_1\) value does not vary significantly with the Gaussian mask width. The Gaussian mask FWHM widths were 200 km s\(^{-1}\) for H\(\alpha\) and 150 km s\(^{-1}\) for He\(\)i. These radial velocity values are compatible with the \(K = 166 \pm 6\) km s\(^{-1}\) presented by Hartley et al. (2005). The systemic velocity was also derived for both lines, \(\gamma_{\text{H}} = -43 \pm 25\) km s\(^{-1}\) and \(\gamma_{\text{He}} = -84 \pm 25\) km s\(^{-1}\).

The double-Gaussian convolution technique for radial velocity measurements is not immune to systematic errors (Unda-Sanzana et al. 2006). In some cases it produces incorrect mass estimates, even with large data sets like the one presented here. Unfortunately, there is no other way to constrain the primary mass in this non-eclipsing nova-like CV.

The mass diagram for V3885 Sgr (Fig. 2) was constructed using the H\(\alpha\) radial velocity semi-amplitude and its error. The solid vertical line at the right indicates the white dwarf upper mass limit. The two vertical lines at the left are the white dwarf lower mass limit for \(i = 75^\circ\) (dashed line) and \(i = 45^\circ\) (solid line). These limits were obtained from each line FWZI, considering a Keplerian disk and a mass-radius relationship (Hamada & Salpeter 1961) for the primary star. The diagonal straight line is the equal-mass line, plotted only as a reference, as the stable mass transfer line is not straight along the mass diagram and is also model-dependent. The quasi-horizontal solid line represents the upper mass limit for a main-sequence secondary filling its Roche lobe. The \(M_1:M_2\) relation is plotted for a few inclination values (\(i = 35^\circ\), dotted lines; \(i = 45^\circ\), dashed lines; \(i = 75^\circ\), dot-dashed lines), considering \(K_1\) and its uncertainty. The region of most probable masses is shown in gray. The primary mass is unconstrained between 0.3 and approximately 1.4 \(M_\odot\), and the secondary mass is possibly between 0.2 and 0.55 \(M_\odot\). The primary mass range obtained by Hartley et al. (2005) is 0.55 \(M_\odot\) < \(M_1\) < 0.8 \(M_\odot\). Another parameter that can be constrained from the mass diagram is the orbital inclination, which is found to be between 45° and 75°. The analysis and conclusions in the following sections are not dependent on a precise \(M_1\) value.

3.3. Doppler Tomography

The Doppler tomography method, proposed by Marsh & Horne (1988), uses the velocity information from spectral line profiles at various orbital phases in order to reconstruct the binary system’s emissivity in velocity space. The method is based on a few hypotheses listed below. All the emission-line production regions must always be visible and their line optical depth must be negligible, which is violated if observations during eclipses are used. The line flux at any point of the binary rotating frame of reference must be constant. Outbursts represent a flux variation, breaking this hypothesis. All the motions must be parallel to the orbital plane. Wind originating from the disk has a velocity vector out of the orbital plane. All the velocity vectors rotate with the binary system. The last hypothesis is that the intrinsic line profile width at any point is negligible; saturation effects at large optical depths can widen the line profiles (Horne 1995).

The Doppler tomograms from the H\(\alpha\) and He\(\)i line profiles were obtained using the filtered back-projection method (Rosenfeld & Kak 1982) and are shown in Figure 3. The coordinate system is defined with the \(x\)-axis pointing from the primary to the secondary and the \(y\)-axis pointing in the direction of the secondary’s motion. Considering a Keplerian disk, the outer part of the tomogram (higher velocities) represents the inner region in the position space, and vice versa. The H\(\alpha\) and He\(\)i tomograms were calculated using 1888 independent spectra. A 70 km s\(^{-1}\) FWHM Gaussian convolution filter was applied to the H\(\alpha\) line, and a 120 km s\(^{-1}\) one was applied to the He\(\)i line. The tomogram resolution is a combination of the spectral resolution, convolution filter width, and phase sampling. As the V3885 Sgr masses and orbital inclination cannot be strictly determined, the marked positions on the tomograms are plotted just as a reference. Distinct values of orbital inclination and mass would produce a rescaling of the marked positions.

In the H\(\alpha\) tomogram (Fig. 3a) one can see that the most intense emission is located in the \((-V_x, +V_y)\) quadrants, and we could not affirm based only on this map whether this emission originated from the illuminated secondary or from the hot spot. It is not aligned with the position of the stellar centers or clearly over the stream trajectory. The stellar positions could move along the \(y\)-axis direction depending on the actual orbital inclination. An extended region in the \((-V_x, -V_y)\) and \((+V_x, -V_y)\) quadrants can also be seen, corresponding to disk regions opposite to the secondary star. In order to show more clearly these tomogram anisotropies, a radially symmetric disk image was subtracted from the maps (Fig. 3).

The He\(\)i tomogram (Fig. 3b) presents a ring shape when compared with H\(\alpha\), suggesting that the emission from the former is mostly produced in the disk itself. The spot in the \((-V_x, +V_y)\) quadrant on the He\(\)i map is approximately at the same location as the H\(\alpha\) map spot. The asymmetric component is more structured in He\(\)i than in H\(\alpha\), and clearly shows the enhanced emission in the \((+V_x, -V_y)\) quadrants.

Comparing the H\(\alpha\) and He\(\)i tomograms (Fig. 3), one can see that the He\(\)i emission is more intense in the \((+V_x, +V_y)\) quadrant and in the lower part of the \((-V_x, -V_y)\) quadrant. The origin of such behavior is still unclear. It can also be seen that the H\(\alpha\) emission is more intense than that of He\(\)i in the \((-V_x, -V_y)\) quadrant. The emission from the \((+V_x, -V_y)\) quadrant in both lines can be explained if the stream does not hit the disk in the

![Image](https://example.com/image.png)
(-V_x, +V_y) quadrant, but it flies above the disk, reaching the disk in the (+V_x, -V_y) quadrant, before the point of minimum approach to the primary. Therefore, part of the stream material is not incorporated into the disk in the hot spot region but follows a free particle trajectory above the disk until it reaches the (+V_x, -V_y) quadrant. This hypothesis is plausible if one recalls that the accretion disk geometry is not flat, and so the height in the disk’s outer rim is greater than in the central regions, and, in addition, the primary gravity has an increasing vertical component for smaller radii.

The consistency of the Doppler maps was verified by comparing trailed spectra generated from the projection of the maps at many orbital phases and the trailed spectra generated from the observed line profiles (Fig. 4). The comparison between the phase maps suggests a reasonable consistency of the tomographic reconstructions. A significant difference between the maps is related to the sharp and low-velocity feature seen in the observed phase maps. This feature appears once per orbit in the observations, while it is spread into two features on each orbit in the projected map. As the tomography algorithm considers all the structures to be visible all the time, this sharp emission should be related to the illuminated face of the secondary star (see discussion in § 3.5).

Emissivity profiles in velocity space can be obtained directly from the Doppler tomograms. This was done using Doppler tomograms for H\textalpha\ and He i centered at the primary’s position (Fig. 3b). The emissivity profiles are similar to line profiles, but they are free from the projection of intrinsically high velocity emission that may appear at lower velocity in the line profiles. In order to produce the velocity profiles, the intensity along each concentric ring centered at the primary was represented by its mode. With this procedure, we verified that the H\textalpha\ tomogram is more homogeneous than the He i one, with the mode, median, and mean yielding similar results.

Doppler tomograms are always plotted in velocity space, but one can transform the maps to position space, assuming a Keplerian velocity regime. One problem that could occur in this transformation arises from the fact that the disk’s most internal regions (seen in the line far wings) are brighter and carry the larger uncertainties in the inversion process. To study the disk emissivity profiles, the
emission at a given radius was estimated, obtaining the disk radial emissivity profiles for both H\alpha and He\textsc{i} (Fig. 3a). This value is calculated as the mode along each ring, because it is less susceptible to local variations due to the disk emission anisotropies. To obtain the absolute radial emissivity profiles, we used a distance to the system equal to 110 \pm 23 pc from the Hipparcos parallax (Perryman et al. 1997) and a color excess of $E(B-V)$ of 0.02 (Bruch & Engel 1994). The profiles are shown in Figure 5. The radial emissivity profiles may be fitted by power laws, $I_{\text{H\alpha}} \propto r^{-2.1}$ and $I_{\text{He\textsc{i}}} \propto r^{-2.5}$. In this system the He\textsc{i} emission seems more concentrated in the inner disk regions than the H\alpha emission. The obtained radial emissivity indexes are similar to those obtained for V841 Oph by Diaz & Ribeiro (2003). Radial emissivity profiles were also obtained from Doppler maps for CU Vel (Mennickent & Diaz 1996), V347 Pup (Diaz & Hubeny 1999), RR Pic (Diaz & Ribeiro 2003), and U Gem during outburst (Marsh & Horne 1990).

3.4. Flickering Tomography

We have explored until this point the “stationary” line emission from V3885 Sgr. The line emission intrinsic variability can be conveniently studied using the tomographic reconstruction of the flickering emission. In the flickering tomography method (Diaz 2001), we start by calculating the variances of the observed line profiles in each phase bin. Then the intrinsic line variability is isolated from the instrumental, orbital, and secular components. The instrumental component of the variance is calculated as a combination of the Poisson noise and a Gaussian readout noise. The orbital component contribution is considered negligible, since the data are sampled into small phase bins. The secular component is the remaining long-term variability of the system. The effect of such a component was found to be negligible by replacing the long-term average profiles by profiles computed from individual runs. Doppler tomograms are calculated from these intrinsic variance line profiles mapping the line emission variability in the system. The flickering tomography method is very demanding on the amount of collected data and also sensitive to the time sampling.

Pure photon and readout noise were removed from the data using the empirical noise model described above. However, residual noise from other sources (such as continuum subtraction and differential calibration errors) are still present in the variance data. A total of 1863 spectra from our original data set were used in the flickering tomography study. Some spectra were not used in this analysis because they deteriorate the statistics on the quantities calculated with these data. The flickering tomography could only be performed with the H\alpha line, which are more intense than the He\textsc{i} one. In Figure 6 we show the average of all spectra used in the flickering tomography and the average rms spectrum already.
corrected from instrumental, orbital, and secular effects. The flickering line profile defined as above is single peaked. The rms increases with the emission intensity, but not as expected from pure photon noise. It can be seen that the flickering and the flux line profiles present slightly distinct intensities in the blue-side continuum region. The rms flickering intensity relative to the average line intensity obtained in this work is larger than that observed in the nova-like V442 Oph (Diaz 2001).

The Hα flickering Doppler tomogram is shown in Figure 7. The filter used to produce this map was set to 100 km s$^{-1}$ FWHM, and the final tomogram resolution is estimated as 130 km s$^{-1}$. The positions marked in the tomogram from top to bottom are, as in the flux Doppler tomograms, the secondary center of mass, the internal Lagrange point L1, the system’s center of mass, and the center of mass of the primary. As the orbital inclination and masses cannot be strictly determined, the stellar positions are plotted just as a reference.

![Fig. 5.](image)

![Fig. 6.](image)

![Fig. 7.](image)
At least two regions of enhanced variance can be identified: (1) the \((-V_X, +V_Y)\) quadrant near the line that connects the stellar centers and (2) the \((+V_X, -V_Y)\) quadrant. Comparing this variance tomogram with the flux tomogram (Fig. 3), one can see that the region of higher emissivity has a different shape and is significantly shifted in velocity.

The ratio of the rms flickering tomogram and the flux tomogram was calculated (Fig. 5) in order to verify whether the flickering is dependent on the line flux of the originating region. The high-velocity regions of the resulting image were also excluded, because the flux tomograms are more noisy and present values near zero. The resulting relative tomogram was then limited to intrinsic velocities below \(\approx 400\) km s\(^{-1}\). The ratio between the tomograms does not present bright regions as do the flux and variance tomograms. However, the relative flickering map is not flat, but regions of lower intensity and a higher intensity near the center of the image can be seen. From this it can be concluded that the flickering can vary with the region of the disk in which the flickering is formed, and that the flickering rms activity may be independent of the flux intensity of its originating region. In addition, the flickering in V3885 Sgr is not uniformly distributed in the disk. This behavior was also observed in V442 Oph by Diaz (2001).

In order to obtain flickering activity profiles, variance tomograms centered in the primary were also calculated, excluding the high-noise peripheral regions. Following the same method used for the calculation of the emission profiles, the median along concentric rings centered on the primary was calculated. These emissivity profiles as a function of velocity are shown in Figure 8. The median was used as the statistical criterion because it proved to be more robust than the average or mode, avoiding the emissivity profile being affected by the high-noise regions. One can see from Figure 8 (top) that the average flickering at a given velocity (or radius in a Keplerian disk) is roughly correlated with the disk emissivity for absolute velocities higher than approximately 300 km s\(^{-1}\). These profiles have different behavior when compared with those found for V442 Oph, for which both the emissivity profiles and the ratio of the tomograms presented a depression at lower velocities. In V3885 Sgr such behavior is not observed.

3.5. Flickering Simulations

Simulations of accretion disks including a stochastic variability component were made, aiming to perform a better analysis of the flickering tomogram. The simulations were performed assuming a Keplerian accretion disk, with a line emissivity profile given by a radial power law. For each “exposure,” a synthetic line profile was generated, considering the presence of noise with a given S/N. Over each synthetic line profile, the contributions of isolated emission sources in the disk can be included to simulate the hot spot and/or the boundary layer. The synthetic flux and flickering tomograms were generated with the resulting line profiles.

The flickering activity was modeled as a series of flares at random positions inside a restricted region of the disk, or at the secondary’s illuminated face. The flickering mean frequency and amplitude were given as a function of the total line profile flux. These are the main simulation parameters. The flickering flares were included in the simulation as having instantaneous rise and exponential decay.

Aiming to verify whether the flickering is produced in the accretion disk, a tomogram of a Keplerian disk was simulated using the V3885 Sgr orbital period and probable masses. Comparing this tomogram with the observed flickering tomogram, one can verify that the position of the most intense flickering feature (hereafter C1) does not match the accretion disk in the tomogram (Fig. 9a). The simulations show that the absolute velocity of the flickering C1 source is not consistent with the velocities found in any Keplerian disk contained within the primary Roche lobe, or with a tidally limited disk. However, the possibility of the C1 feature originating in a non-Keplerian disk cannot be excluded at all. The absolute ballistic velocities at the hot spot impact region \((v_{\text{stream}} \approx 280\) km s\(^{-1}\)) at the tidal disk radius; see Fig. 7) are large when compared with the C1 absolute velocity \((\approx 130\) km s\(^{-1}\)), as expected from the gas accelerating in the white dwarf’s potential well. If the actual disk radius were smaller than the tidal radius, such a difference would be even larger. These two arguments suggest that C1 is not the result of line flickering at the hot spot or outer disk and they are independent of the adopted orbital phase.

The next step is to test the hypothesis that the C1 feature originated in the secondary’s illuminated face. Synthetic flickering tomograms were computed with flickering flares from the secondary’s inner face, and these maps were compared with the observed flickering tomograms (Fig. 9b). We can verify a fairly good agreement between these two reconstructions. This simulation was repeated considering different values of stellar masses and orbital inclination given by the mass diagram, and the position agreement between the flickering feature C1 and the inner face of the secondary star in the tomogram remained.

There are at least two possibilities to explain the observation of line flickering at the companion star: first, the variability could be due to the illumination effect by flickering events produced at the accretion disk; second, it could be due to fast chromospheric activity of the secondary. Below we examine these two possibilities.

To verify the plausibility of the C1 flickering feature being observed in the secondary due to the reprocessing of the flickering from the disk, some basic quantities are calculated. The typical recombination timescale is given by equation (1) below, where
Ne is the electronic density and $\alpha_A$ is the recombination coefficient. An electron density $N_e \approx 3 \times 10^{12} \text{ cm}^{-3}$ is needed in order to observe flickering with a timescale of about 1 s:

$$\tau \approx \frac{1}{N_e \alpha_A} \approx \frac{3 \times 10^{12}}{N_e} \text{ s} \approx \frac{10^5}{N_e} \text{ yr.}$$ \hspace{1cm} (1)

The recombination volume needed to produce a given flux $F$ by recombination is given by equation (2), where $d$ is the distance to the source, $\nu$ the frequency of the emission, and $\alpha$ the recombination coefficient:

$$V = \frac{16\pi^2 d^2 F}{\nu \alpha N_e^2}.$$ \hspace{1cm} (2)

The flux of the C1 feature in the observed flickering tomogram was obtained by integrating the emission in the feature and subtracting the flux of the diffuse emission near it, yielding $F_{\text{C1}} = 3.6 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}$. In addition, a constraint on the electron density is needed. A lower limit could be obtained from the fact that forbidden lines are not observed in CVs; from this, the electron density must be higher than $\approx 10^9 \text{ cm}^{-3}$.

Using equation (2), the lower electronic density limit mentioned above gives a volume of $V \approx 10^{34} \text{ cm}^3$, which is even bigger than the secondary’s volume (Eggleton 1983), so the recombination process could not generate the given flux in an environment with $N_e = 10^9 \text{ cm}^{-3}$.

An upper limit to the average density can be obtained from the classical atmosphere models by Hubeny & Lanz (1995). The structure of a 10,000 K and log $g = 4.0$ atmosphere was simulated, resulting in an atmosphere thickness of $z = 4 \times 10^{10} \text{ cm}$, measured from $\tau_{\text{Ross}} = 10^{-3}$ down to $\tau_{\text{Ross}} = 1$. We scaled this atmosphere to $T = 5000 \text{ K}$ using the pressure scale height, obtaining an atmosphere thickness $z' = 1.2 \times 10^{8} \text{ cm}$ and a secondary’s surface gravity log $g_s \approx 4.6$. The surface gravity value for the secondary in V3885 Sgr is consistent with an isolated M0 V or M2 V star (Cox 2000). Starting from the Roche lobe radius and the obtained atmosphere thickness, the average electron density is calculated (eq. [2]) as $N_e \approx 1.4 \times 10^{12} \text{ cm}^{-3}$.

Using high time-resolution $V$-band data taken on a single run (A. Bruch 2006, private communication) we have calculated an average orbital light curve. The data comprise 12 orbital cycles and were binned into 40 phase bins using the orbital ephemeris proposed in this work. The average flux curve presents a maximum around phase 0.6, which is consistent with significant companion illumination effects in the optical continuum (Fig. 10). The possibility of the main line-flickering feature being associated with the hot spot instead of the secondary cannot be completely ruled out from the data at hand. However, it would imply a large (>0.2) spectroscopic phase shift. In this case the broadband light-curve peak could not be associated with the secondary star. On the other...
hand, the expected absolute gas velocities at the hot spot are quite uncertain but possibly larger than those measured for the flickering feature at $V_e \approx 0$.

From the arguments above, we suggest that the $C_1$ emission-line flickering observed in V3885 Sgr could be due to a radiative variable component produced by recombinant at the secondary’s illuminated surface. The calculation described above provides only orders of magnitude, while a detailed model considering an irradiated atmosphere is still needed to confirm this conclusion. The observation of flickering coming directly from the inner accretion disk is not possible via flickering tomography because the information from higher velocities is diluted at the outer border of the tomograms. The time delay in the recombinant process could affect significantly only the flickering at high frequencies. As we used an integration time of about 3 minutes in our data, only the low-frequency flickering component is mapped.

The possibility of the secondary being a flare star was also considered. Stellar flares are observed through all the main sequence, with the most intense flaring being dominant in the hotter stars (see Pettersen 1989 for a review). Stellar flares are observed mainly in cool stars, where the flares have smaller amplitude and are more frequent than those of hot stars. The mechanism proposed to explain the flare production involves the magnetic field of the star. The dynamo mechanism is enhanced by fast stellar rotation; for this reason it is expected that stars with higher rotation will show enhanced flare activity (Parker 1955). CVs, with their short orbital periods, are the perfect scenario for this kind of activity. Stellar flares were observed in Sloan Digital Sky Survey detached binary systems (Silvestri et al. 2006) and also in the magnetic CV AM Her during its low state (Kafka et al. 2005). Flickering and stellar flares present some differences: first, the flares appear as isolated outbursts, while flickering is a “continuous” phenomenon, and second, the timescales are distinct. AM Her has an orbital period of 3.8 hr (Young et al. 1981), which is shorter than the V3885 Sgr orbital period. Therefore, the secondary in AM Her has a higher rotation velocity to feed the dynamo and presents approximately one flare every 5.4 days (Kafka et al. 2005). As the less intense flares are more frequent, could the microflare phenomenon mimic line flickering? Robinson et al. (1995) observed 32 flare events in 2 hr of observing the microflaring dM8e star CN Leo. This represents a rate of 1 flare every 3.7 minutes, which is considerably lower than the frequency of flickering events.

The energies associated with the individual events in stellar flares and flickering in CVs are also distinct. The typical luminosity of a V3885 Sgr line-flickering event is calculated directly from the Doppler maps as $L \approx 4 \times 10^{32}$ ergs $s^{-1}$. Using a microflare timescale of $\tau \approx 5$ s (Robinson et al. 1999) and an energy range of $10^{25}$–$10^{28}$ ergs (Parker 1988), a luminosity range of $(2 \times 10^{25})$–$(2 \times 10^{28})$ can be inferred for the microflare events. The microflare energy range is therefore well below the flickering energy. The flare energy in red stars is below $10^{32}$ ergs; this, combined with a typical timescale of 10 s, yields a luminosity below $10^{28}$ ergs $s^{-1}$. This latter value is also below the flickering flare energy found in the V3885 Sgr secondary star.

As the stellar flares are distinct from the flickering both in frequency and energy, this phenomenon does not seem to be the main cause of the $C_1$ emission-line flickering observed in V3885 Sgr.

4. DISCUSSION

The stellar masses are constrained within an interval of $0.3 M_\odot < M_1 < 0.9 M_\odot$ and $0.25 M_\odot < M_2 < 0.55 M_\odot$. The uncertainty in $K_1$ propagates to the derived mass ranges, so these ranges are just formal as well. This uncertainty does not include the fact that the measured $K_1$ velocity in CVs may not reflect the white dwarf orbital velocity. Hartley et al. (2005) constrained the primary mass between 0.55 and 0.8 $M_\odot$, which is in agreement with our mass interval. Concerning the orbital inclination, we conclude that the possible values for the system are between 45° and 75°. Cowley et al. (1977) used $60°$ as an upper limit for the value of the orbital inclination in their mass diagram. Haug & Drechsel (1985) assumed that the orbital inclination is between 60° and 80°. Hartley et al. (2005) pointed out that the orbital inclination must be higher than 65°. The uncertainty on this parameter remains high.

Regarding the morphology of Doppler reconstructions, an enhanced emission in the $(V_{\gamma} + V_e)$ quadrant was observed in both H$\alpha$ and He$\alpha$ tomograms. In both cases an enhanced emission in the $(+V_\gamma, -V_e)$ quadrant might be interpreted as originating from the impact of the gas stream that has not reached the disk in the $(V_{\gamma}, +V_e)$ quadrant. Emission from the same region was searched for by visually inspecting the Doppler tomogram atlas by Kaitchuck et al. (1994). The presence of enhanced emission in the $(+V_\gamma, -V_e)$ quadrant is seen in V1315 Aql (H$\beta$ and He$\alpha$ tomogram, IP Peg (H$\beta$), LX Ser (He$\alpha$), and DX UMa (H$\gamma$)). Of all these systems, only IP Peg is classified as a dwarf nova, while the other objects are classified as nova-like CVs. The orbital periods of all these systems are shorter than 5 hr. This effect may well be due to a selection effect, as the catalog has only four objects with orbital periods longer than 5 hr and 14 objects with periods shorter than 5 hr. High-S/N tomography studies of other CVs are needed to investigate whether there is any correlation between the orbital period or eruptive class and the presence of emission in the $(V_{\gamma}, -V_e)$ quadrant.

While the H$\beta$ and H$\gamma$ Doppler maps presented by Hartley et al. (2005) have a ring signature, our H$\alpha$ Doppler map is filled at low velocities. The obtained radial emissivity indexes for both H$\alpha$ and He$\alpha$ lines are similar to the ones obtained for V841 Oph by Diaz & Ribeiro (2003). Concerning the absolute intensities, V3885 Sgr is approximately 4 times fainter in the Balmer emission lines than V841 Oph.

V3885 Sgr is the second object targeted for a flickering tomography study; the first object was V442 Oph (Diaz 2001). The flickering variance tomogram presents two regions of higher variability in the $(+V_\gamma, +V_e)$ and $(V_{\gamma} - V_e)$ quadrants, which are not in the same location as the regions of higher emission. In the V442 Oph variance tomogram (Diaz 2001), the region of most intense emission is in the $(+V_\gamma, +V_e)$ and $(+V_\gamma, -V_e)$ quadrants. The ratio between flickering and flux tomograms for V3885 Sgr and V442 Oph also presents different behavior. For V442 Oph there is a region of low intensity near the center, while for V3885 Sgr the lowest intensity regions are not centered. In both cases it is verified that the flickering can vary with the position within the disk. The intrinsic distribution of the flickering as a function of the velocity also presents a distinct behavior for both systems. The flickering distribution along the V3885 Sgr disk appears to be nonhomogeneous, as observed in V442 Oph. A future study concerning methods for qualifying the significance of features in flickering maps is planned.

Comparing the flickering tomogram with simulations, we have associated one of the sources of emission-line flickering with the secondary star. As far as we know, this is the first detection of flickering at the companion star in CVs. Previous eclipse-mapping studies have restricted the continuum flickering sources to the accretion disk in UU Aqr (Bortoletto 2006) and to the accretion disk and the gas stream in V2051 Oph (Baptista & Bortoletto 2004). Using the flickering tomography method we are not able to observe the flickering originating in the inner parts of the accretion disk because the information at high velocities is spread at the
outer radii of the Doppler map. In addition, the S/N in the line wings is usually low. According to our simulations, the brightest line- flickering source in V3885 Sgr is associated with the secondary star. One mechanism that may be proposed to explain this behavior is the flickering in the UV continuum from the accretion disk being reprocessed on the illuminated face of the secondary star. As the internal part of the accretion disk rotates faster than the disk’s outer parts, the magnetic reconnection in the internal disk could be a mechanism to produce the high-frequency flickering (Geetsema & Achterberg 1992). Flickering in the UV can be produced in the inner hot disk, resulting in an illumination effect in the optical region. The illumination of the atmosphere of the companion star results in both heating and ionization. Recombination in the optically thin atmosphere results in a low fraction of the illumination energy being from emission lines (Strittmatter 1974). Hartley et al. (2005) presented evidence of illumination of the secondary star in V3885 Sgr based on a narrow emission component superposed on the lines and emission from the illuminated face of the secondary star in the H/β and H/γ Doppler maps. We present photometric data that support the scenario of an illuminated companion star. In our opinion, it would be much more difficult to argue in favor of the hot spot being responsible for the C1 feature. The absolute velocity for the hot spot would be too low, and it would require a large phase shift (>0.2).

5. CONCLUSIONS

We present the analysis of an extensive spectroscopic observation of V3885 Sgr. A long-term ephemeris was determined for V3885 Sgr, with orbital period \( P_{\text{orb}} = 0.20716071(22) \) days and spectroscopic conjunction \( E_0 = 51.942.08371(46) \) MHJD. The radial velocity semiamplitudes and the mass ranges derived by Hartley et al. (2005) are confirmed by our measurements.

Using flickering tomography, it was verified that the flickering intensity can vary within the disk. From the V3885 Sgr flickering tomogram’s emissivity profiles, one can see that the flickering is most intense in low-velocity regions. From the flickering tomography studies of V3885 Sgr and V442 Oph, one can conclude that the line flickering in CVs may have a nonhomogeneous distribution along the disk. Additional flickering tomography studies of other systems are needed to confirm this conclusion. Comparing synthetic flickering tomograms with observed ones, we concluded that the most intense line-flickering source could not originate in a Keplerian accretion disk defined by the V3885 Sgr mass interval and orbital period. The main flickering source might be associated with the secondary star, and the origin of such a feature might be the flickering in the UV continuum produced in the accretion disk being reprocessed at the illuminated face of the companion star.

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