HS 2325 + 8205—An Ideal Laboratory for Accretion Disk Physics

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Received 2011 December 9; accepted 2012 January 30; published 2012 February 29

ABSTRACT. We identify HS 2325 + 8205 as an eclipsing, frequently outbursting, dwarf nova with an orbital period of $P_{orb} = 279.841731(5)$ minutes. Spectroscopic observations are used to derive the radial velocity curve of the secondary star from absorption features and also from the H$\alpha$ emission lines, originating from the accretion disk, yielding $K_{sec} = K_{abs} = 237 \pm 28$ km s$^{-1}$ and $K_{em} = 145 \pm 9$ km s$^{-1}$, respectively. The distance to the system is calculated to be $400(+200,-140)$ pc. A photometric monitoring campaign reveals an outburst recurrence time of $\sim 12–14$ days. The combination of magnitude range (17–14 mag), high declination, and eclipsing nature and frequency of outbursts makes HS 2325 + 8205 the ideal system for “real-time” studies of the accretion disk evolution and behavior in dwarf nova outbursts.

1. INTRODUCTION

Dwarf novae are a subclass of nonmagnetic (or weakly magnetic) cataclysmic variables (CVs; see, e.g., Warner [1995] for a comprehensive review), in which a white dwarf primary accretes matter via an accretion disk, formed by material transferred through the $L_1$ point from a Roche lobe-filling (near) main-sequence secondary. The defining trait of dwarf novae are quasi-periodical brightness changes of several magnitudes, commonly known as “dwarf nova outbursts.” It is widely accepted that outbursts can be understood within the framework of the disk instability model (see, e.g., Smak [1984]; Cannizzo [1993]; Osaki [1996]; Lasota [2001] for reviews of the topic).

Within the disk instability model, accretion disks undergo outbursts if the mass transfer rate is below a critical value, $\dot{M}_{crit}$. Above the CV orbital period gap$^{14}$ accretion rates are usually larger than $\dot{M}_{crit}$ and, as a result, only about one-third of nonmagnetic systems are dwarf novae. The situation is completely different below the period gap, where dwarf novae dominate the CV population (Shafter 1992).

Dwarf novae provide the best environment to develop and test our understanding of accretion disk structure and dynamics, which is relevant to a wide range of objects, such as low-mass X-ray binaries (Dubus et al. 2001), active galactic nuclei (Burderi et al. 1998), and young stellar objects (Bell & Lin 1994).

Of particular interest in this context are eclipsing dwarf novae. In these systems, the physical properties of the binary (such as the mass ratio, the inclination angle, the masses and temperatures of the component stars, and the radial structure of the accretion disk) can be determined to high precision, through studies of the eclipse features of the white dwarf, the bright spot (formed in the region where the mass-transferring stream meets the accretion disk), and accretion disk components (see, e.g., Wood et al. 1989; Littlefair et al. 2006b; Southworth et al. 2009).

HS 2325 + 8205 (R.A.: $23^h26^m50.4^s$, Dec.: $+82^\circ22^\prime12^\prime$) [J2000], henceforth HS 2325) was one of the systems identified in a dedicated search for CVs (Aungwerojwit et al. 2005) within the Hamburg Quasar Survey (Hagen et al. 1995). Photometric observations soon revealed the eclipsing nature of the system and also frequently occurring outbursts. An interesting historic note is that Morgenroth (1936) mentioned short-term variability of HS 2325, which corresponding was included in the New

$^{14}$The orbital period range of 2 hr $\leq P_{orb} \leq$ 3 hr, where only a small number of CVs are found.
2. OBSERVATIONS

We obtained photometric and spectroscopic data on HS 2325 using both large-aperture (>1 m) and small-aperture telescopes. Table 1 summarizes the observations conducted with the former. A brief account on data reduction follows.

2.1. Photometry

We obtained time-series photometry of HS 2325 during 17 nights throughout the period of 2003 to 2007 using 1.2–2.5 m telescopes (Table 1). These observations were reduced with the pipeline described in Gänsicke et al. (2004), which employs bias-subtraction and flat-fielding in the standard fashion within MIDAS and uses SEXTRACTOR (Bertin & Arnouts 1996) to perform aperture photometry. Sample light curves are shown in Figure 1.

HS 2325 has been found to vary in brightness between the ∼17th and ∼14th magnitudes. Eclipses are shallow and maintain an almost constant depth during the rise to outburst. The eclipses in the bright state exhibit a symmetric U shape, which is typical for an accretion-disk-dominated system. During quiescence the eclipse morphology becomes more complicated and reveals several breaks in slope. In addition to eclipses, the light curve of HS 2325 displays two further features: short-term, random, out-of-eclipse variations, known as “flickering” (e.g., Bruch 2000) and an “orbital hump,” which is a brightening just before the start of the eclipse attributed to the bright spot coming into view (e.g., Krzeminski 1965).

![Sample light curves of HS 2325](image)

**FIG. 1.**—Sample light curves of HS 2325. *Top:* Filterless KY observations from 2003 September 5 (ID01), with the system on the rise to outburst. *Middle:* Filterless KY observations from 2004 July 27 (ID06), with the system in an intermediate state. *Bottom:* Filterless NOT observations from 2005 September 15 (ID13), with the system in quiescence.
An intensive 1.5-month-long photometric campaign was conducted in 2009 to characterize the outburst behavior of HS 2325, using small-aperture (11–14 inch) telescopes. The data were reduced with AIP4WIN and MAXIMDL, and the resulting light curve is shown in Figure 2.

2.2. Spectroscopy

Spectroscopic observations during the system’s quiescence were obtained at the 2.4 m Hiltnor telescope at MDM Observatory on Kitt Peak, Arizona. The modular spectrograph and a SITe 20482 pixel CCD yielded 2 Å pixel\(^{-1}\) and from 4210 to 7500 Å, but with decreased sensitivity toward the ends of the wavelength range. The spectral resolution was \(\approx 3.5\) Å full width at half-maximum (FWHM). Reductions were performed mostly with standard IRAF routines, but we used an original implementation of the optimal extraction algorithm detailed by Horne (1986) to compute one-dimensional spectra from the two-dimensional images. For wavelength calibration, we used a dispersion curve derived from lamp exposures in twilight, and we corrected for nighttime drifts using the \(\lambda 5577\) sky line. We observed standard stars in twilight whenever the sky appeared clear, and we used these observations to flux-calibrate the data. The scatter of the standard stars typically suggests that the flux calibration is uncertain by several tenths of a magnitude, probably due to uncalibrated losses at the spectrograph slit. The mean quiescent spectrum is shown in Figure 3. The flux level of the observed spectrum implies a \(V\)-band magnitude near 17.0, subject to the calibration uncertainties.

3. ORBITAL PERIOD AND EPHEMERIS

Mideclipse times (given in Table 2) were determined by visually cross-correlating each eclipse profile with its mirror image with respect to time. This was found to produce more robust results than fitting a parabola to the eclipse minimum: in particular, for the light curves with poor time resolution. We adopted the duty cycle (exposure plus readout time) of the corresponding observations as a conservative estimate of the uncertainty in the mideclipse times.

Fitting a linear ephemeris to the mideclipse times gives

\[
T_0(\text{HJD}) = 2,452,888.42554(3) + 0.194334535(3) E, \tag{1}
\]

with mideclipse times calculated on a UTC timescale, i.e., an orbital period of \(P_{\text{orb}} = 279.841731(5)\) minutes.

4. SECONDARY SPECTRAL TYPE AND RADIAL VELOCITY ANALYSIS

As is typical for quiescent dwarf novae, the Balmer lines in emission are the most prominent features in the spectrum of HS 2325, with equivalent widths of \(\approx 30\) and \(\approx 54\) Å for H\(\beta\) and H\(\delta\), respectively. He \(\text{i}\) emission is detected at 4921, 5015, and 5876 Å, and Fe \(\text{ii}\) is detected at \(\lambda 5169\) (the features at \(\lambda\lambda 4921\) and 5015 may also be blended with Fe \(\text{ii}\)). The absorption bands of an M dwarf companion are conspicuous. To quantify the M dwarf contribution, we subtracted library spectra of M dwarfs classified by Boeshaar (1976), taken with the same instrument, and varied the spectral type and scaling until the M dwarf features were canceled as well as possible. The lower two
traces in Figure 3 show the decomposition that was (at least subjectively) the best. From this exercise, we estimate that the companion is of type M3.0 ± 0.75 subclasses and that its flux corresponds to $V = 19.0 ± 0.4$ (external error, including calibration uncertainties). The spectral type-period relation of Smith & Dhillon (1998; eq. [4]) in their article for $P > 4$ hr yields $\text{Sp}^2 = M_{1.5}$ for the derived orbital period of $P_{\text{orb}} = 4.664$ hr, which is a value broadly consistent with our estimate of M3.0 ± 0.75, as the rms scatter of the spectral type-period relation is three subclasses for $P > 4$ hr (Smith & Dhillon 1998).

We measured radial velocities of the H$\alpha$ emission line using a double-Gaussian convolution method outlined by Schneider & Young (1980); the centers of the Gaussians were separated by 1280 km s$^{-1}$, and each individual Gaussian had a FWHM of 270 km s$^{-1}$, comparable with our spectral resolution. This emphasized the outer wings of the line profile. We also tried a range of separations and found that the radial velocity amplitude and phase were insensitive to this parameter. To measure the velocity of the M dwarf component, we used the cross-correlation program rvsao, written by Kurtz & Mink (1998). For the template, we used a velocity-compensated composite M dwarf spectrum, composed by summing the spectra of a large number of M dwarfs for which Marcy et al. (1987) tabulate precise velocities. The cross-correlation region was from 6000 to 6500 Å; this was for which Marcy et al. (1987) tabulate precise velocities. The orbital period $P_{\text{orb}}$ was held fixed to the value derived from eclipses. Because of the modest number of absorption velocities and their limited phase coverage, and because the absorption should trace the motion of the secondary star fairly well, we fixed $T_0$ to the mid-eclipse ephemeris when fitting the absorption velocities, but left it as a free parameter for the H$\alpha$ emission ones. The resulting velocities were $K_{\text{sec}} = K_{\text{abs}} = 237(28)$ km s$^{-1}$, $\gamma_{\text{abs}} = -19(20)$ km s$^{-1}$, $K_{\text{em}} = 145(9)$ km s$^{-1}$, and $\gamma_{\text{em}} = -42(6)$ km s$^{-1}$ for the absorption and emission lines, respectively, with the numbers in parentheses indicating the errors.

Figure 4 shows the emission and absorption velocities as a function of orbital phase, and Figure 5 shows a grayscale representation of the low-state spectra, as a function of phase. The upper panel of Figure 5 is scaled to emphasize the M dwarf absorption features and to show the structure in the He I $\lambda 5876$ line; the orbital motion of the M dwarf is clearly seen. The scaling of the lower panel brings out the complex structure in the H$\alpha$ emission.

### 5. DISTANCE

We can estimate the distance to HS 2325 using the secondary star’s contribution to the spectrum and our knowledge of the orbital period $P_{\text{orb}}$. For a secondary star of mass $M_{\text{sec}}$ at a fixed $P_{\text{orb}}$, the Roche lobe radius $R_2$ is proportional to $M_{\text{sec}}^{1/3}$ and is almost independent of the primary mass $M_{\text{WP}}$ (Beuermann et al. 1998). We do not know $M_{\text{sec}}$, but we can estimate it using evolutionary models tabulated by Baraffe & Kolb (2000); these suggest that the secondary is between 0.23 and 0.56 $M_\odot$. At this $P_{\text{orb}}$, equation (1) of Beuermann et al. (1998) then implies $R_2 = 0.47 ± 0.07 R_\odot$. Beuermann et al. (1999) tabulate absolute magnitudes and radii for late-type dwarfs as a function of spectral class, which implies a surface brightness for each star. In the range of spectral type we see here, these correspond to
We have inspected version 7.12 (2009) of the Ritter & Kolb (R&K) catalog (Ritter & Kolb 2003) and compiled a list of UGem-type dwarf novae (UG) and Z Cam-type stars (ZC) that are found in the range of $4 \, \text{hr} < P_\text{orb} < 5 \, \text{hr}$. Only systems with confirmed UG/ZC status and with a quoted outburst recurrence period were considered. This left us with a list of 22 systems (out of the 39 listed in R&K in this $P_\text{orb}$ range). In this list, ZC systems dominate the short end of the outburst recurrence period distribution (11–18 days), while UG systems tend to have longer intervals between outbursts (16–150 days). Our inferred outburst recurrence period places HS 2325 in the ZC region. However, as there has been no recorded standstill (the hallmark of ZC systems), its identification as either a UG or a ZC remains ambiguous.

6. OUTBURST BEHAVIOR

We intensively monitored HS 2325 for about 50 days, starting from 2009 April 1 using small-aperture telescopes. Four outbursts have been recorded during this period, indicating a recurrence time of $\sim 12$–14 days. Prominent in Figure 2 is a “long” outburst, lasting $\sim 11$–12 days, followed by a seemingly “short” outburst. This could be a hint toward a bimodal distribution of the outburst duration, observed in many dwarf novae (see, e.g., Szkody & Mattei 1984; Ak et al. 2002). Further observations are required to establish a more accurate recurrence time and to check the consistency of the long and short outburst succession.

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7. ESTIMATES OF THE BINARY PROPERTIES

The standard treatment of eclipsing CVs (see, e.g., Wood et al. 1986, 1992; Littlefair et al. 2006a) involves the identification of the contact points of the white dwarf, the bright spot, and the accretion disk. The corresponding phase widths are then used to place firm (geometrical) constraints on the mass ratio $q$ and the inclination angle $i$ (e.g., Bailey 1979; Horne 1985) and to deduce information about the extent and location of the bright spot and the size of the accretion disk. Flickering can hinder attempts to identify the contact points. Averaging many light curves together is an often-applied solution (see, e.g., Copperwheat et al. 2010) for the case of IP Peg).

Although breaks in slope are seen in the light curve of HS 2325, the available data set is not of sufficient quality and time resolution to unambiguously identify the different
contact points. Hence, the exact eclipse geometry of HS 2325 remains unclear.

In an attempt to constrain the parameter space (albeit roughly), we have to rely on theoretical predictions and empirical evidence from the observed CV population, coupled with the limited information that can be extracted from the light curves.

Following the procedure outlined in detail in Dhillon et al. (1991), the radius of the accretion disk can be determined as a function of the binary separation, \( q \) and \( i \), for a given eclipse half-width at maximum intensity \( \Delta \phi \) (essentially timing the first and last contacts of eclipse and dividing by two). \( \Delta \phi \) was determined by eye to be \( \Delta \phi = 0.1 \pm 0.02 \). The large error is due to the fact that the exact beginning and end of the eclipse are uncertain because of flickering.

The left panel of Figure 6 shows the disk radius \( R_D \) (in units of the distance between the primary and the inner Lagrangian point, \( R_{L_1} \)) calculated using equations (3), (4), and (5) of Dhillon et al. (1991), for \( 0 \leq q \leq 1 \) and various inclination angles. The curves are bound above by the requirement that \( R_D \leq R_{L_1} \), and bound below by the requirement for a partial disk eclipse, satisfied if the disk radius is larger than the half-cord of the secondary (shown by the change in line color in the left panel of Fig. 6). This allows us to place a strict lower limit for the inclination angle to be \( i_{\text{min}} = 68^\circ \). However, the upper limit of \( i \) and the possible values of \( q \) remain unconstrained.

Using the mass function

\[
f(M_{\text{WD}}) = \frac{(M_{\text{WD}} \sin i)^3}{(M_{\text{WD}} + M_{\text{sec}})^2} = \frac{P_{\text{orb}} R_{\text{sec}}^3}{2\pi G} \leq M_{\text{WD}}, \tag{2}
\]

we can transform a given \((q, i)\) pair to a unique \((M_{\text{WD}}, M_{\text{sec}})\) pair. The right panel of Figure 6 shows equation (2) calculated for \( i_{\text{min}} = 68^\circ \) and \( i_{\text{max}} = 90^\circ \), over a wide range in secondary mass, \( 0.1 \leq M_{\text{sec}}[M_\odot] \leq 0.6 \). Allowed \((M_{\text{WD}}, M_{\text{sec}})\) pairs are located between the two dash-dotted curves.

We can further narrow down the parameter space by making two assumptions:

1. The secondary follows the mass-period relation of Smith & Dhillon (1998); their equation (8) (power-law fit) yields \( M_{\text{sec}} = 0.43 \pm 0.07 \, M_\odot \), while their equation (9) (linear fit) yields \( M_{\text{sec}} = 0.48 \pm 0.07 \, M_\odot \) (Fig. 6, right panel, dashed horizontal lines). An average of these values is in perfect agreement with the value of \( M_{\text{sec}} = 0.45 \, M_\odot \) predicted by the revised model track of Knigge et al. (2011) for this orbital period.

2. The radial velocity variation of the emission lines tracks the motion of the white dwarf, so \( K_{\text{em}} = K_{\text{WD}} = 145 \pm 9 \, \text{km} \, \text{s}^{-1} \) and, therefore, \( q = K_{\text{WD}}/K_{\text{sec}} = 0.61 \pm 0.08 \) (Fig. 6, right panel, dotted lines).
While the latter is a frequently adopted assumption in CV research, it has to be viewed with a certain amount of caution (see, e.g., Shafter 1983 and Thorstensen 2000). An encouraging fact in the case of HS 2325 is that the phase of the emission lines is consistent with the eclipse ephemeris. The constraint on \( q \) imposes a narrower range of inclination angles: \( 70^\circ \leq i \leq 81^\circ \) (Fig. 6, left panel, dashed vertical lines). If these assumptions are indeed correct, then the allowed \((M_{WD}, M_{sec})\) pairs are indicated as the gray shaded area in the right panel of Figure 6.

8. DISCUSSION AND CONCLUSIONS

In this article, we identified HS 2325 + 8205 as an eclipsing, frequently outbursting, dwarf nova above the CV orbital period gap and presented our photometric and spectroscopic data. We used these data to measure the orbital period and the radial velocity of the secondary star, as well as to provide initial estimates on the binary parameters. With the photometric data at hand, it remains unclear whether the white dwarf is fully eclipsed or not. The shallow eclipse depth could suggest that it is not eclipsed at all. High time resolution and signal-to-noise ratio data at quiescence are needed in order to unambiguously identify the eclipse geometry.

The short outburst cycle of \( \sim 12–14 \) days makes HS 2325 a plausible Z Cam-type candidate. If confirmed, it will be one of the known eclipsing Z Cam system, after EM Cyg (e.g., North et al. 2000 and references therein) and AY Psc (e.g., Gülsecen et al. 2009 and references therein). While the latter is a frequently adopted assumption in CV research, it has to be viewed with a certain amount of caution (see, e.g., Shafter 1983 and Thorstensen 2000). An encouraging fact in the case of HS 2325 is that the phase of the emission lines is consistent with the eclipse ephemeris. The constraint on \( q \) imposes a narrower range of inclination angles: \( 70^\circ \leq i \leq 81^\circ \) (Fig. 6, left panel, dashed vertical lines). If these assumptions are indeed correct, then the allowed \((M_{WD}, M_{sec})\) pairs are indicated as the gray shaded area in the right panel of Figure 6.

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