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Supporting Online Material for

A Brown Dwarf Mass Donor in an Accreting Binary

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Supporting Online Material

1 Materials and Methods: Observations and analysis

SDSS 103533.03+055158.4 (hereafter SDSS 1035) was observed on the nights of 4^{th}, 5^{th}, 7^{th} and 8^{th} of March 2006 using ULTRACAM on the 4.2-m William Herschel Telescope at the Isaac Newton Group of Telecopes, La Palma. ULTRACAM is a CCD camera designed to provide imaging photometry at high temporal resolution in three different colours simultaneously *(S1)*. ULTRACAM mounts at the Cassegrain focus and provides a 5 arcminute field on its three 1024x1024 CCDs (i.e. 0.3 arcseconds/pixel). Incident light is first collimated and then split into three different beams using a pair of dichroic beamsplitters. Because ULTRACAM employs frame-transfer chips, it can achieve negligible dead-times between exposures. Observations were obtained simultaneously in the Sloan $u'g'r'$ colour filters, using exposure times of 3.98s with a dead-time of 25ms. Data reduction was carried out using the ULTRACAM pipeline data reduction software. Observations of a standard star close to SDSS 1035 were used to correct for variations in seeing and transparency between data points. All the data were corrected to zero airmass using the nightly extinction coefficients measured by the Carlsberg Meridian Telescope on La Palma.

2 A parameterized model of the eclipse

To determine the system parameters we used a physical model of the binary system to calculate eclipse light curves for each of the various components. This model assumes that the eclipse is caused by the secondary star, which completely fills its Roche lobe. System parameters derived via this method have been shown to give consistent results with other methods commonly employed in cataclysmic variables *(S2)*. We fit the model to all the observed eclipses, which were phase-folded and binned into groups of 5 data points.

The 10 parameters that control the shape of the light curve are as follows:

1. The mass ratio, q.
2. The white dwarf eclipse phase full-width at half-depth, $\Delta\phi$.
3. The outer disc radius, R_{d}/a.
4. The white dwarf limb-darkening coefficient, U_{w}.
5. The white dwarf radius, R_{w}/a.
6. The bright-spot scale, S/a. The bright-spot is modelled as a linear strip passing through the intersection of the gas stream and disc. The intensity distribution along this strip is given by $(X/S)^2 e^{-X/S}$, where X is the distance along the strip.

7. The bright-spot tilt angle, θ_{B}, measured relative to the line joining the white dwarf and the secondary star. This allows adjustment of the phase of the peak of bright spot emission.
8. The fraction of bright-spot light which is isotropic, f_{iso}.
9. The disc exponent, b, describing the power law of the radial intensity distribution of the disc.
10. A phase offset, ϕ_0.

The AMOEBA algorithm (downhill simplex) was used to adjust all parameters bar U_{w}, to find the best fit. A linear regression was used to scale the four light curves (for the white dwarf, bright-spot, accretion disc and secondary) to fit the observed light curves in each passband. The excellent agreement between model and data gives us confidence that our simple model accurately describes the system. However, the model is a poorer fit to the data after eclipse. This is most likely because the accretion disc in SDSS 103533.03+055158.4 is optically thin, allowing the bright spot to remain visible when on the far side of the accretion disc. Such an effect is not included in our simple model. To limit the effects that the poor fit to post-eclipse data may have on the resulting system parameters we excluded the regions shown in red (light grey) in Figure 1 of the main paper from the fit. In order to estimate the errors on each parameter once the best fit had been found, we perturbed one parameter from its best fit value by an arbitrary amount (initially 5 per cent) and re-optimised the rest of them (holding the parameter of interest, and any others originally kept constant, fixed). We then used a bisection method to determine the perturbation necessary to increase χ^2 by 1, i.e. $\chi^2 - \chi^2_{\mathrm{min}} = \Delta\chi^2 = 1$. The difference between the perturbed and best-fit values of the parameter gave the relevant 1σ error. The errors generated by this method were checked against errors provided by a bootstrapping technique. Two-hundred bootstrapped lightcurves were generated by selecting, at random and with replacement, data points from the original lightcurve. For points that are not selected we set the associated error bar to infinity and thereby effectively remove these points from the fit. Points which are selected multiple times have their error bars divided by the square root of the number of times they are selected. Each bootstrapped lightcurve is fit by the process described above, and the standard deviation of the distribution of best-fit model parameters gives an estimate of the error. Parameter and error estimates from both methods are wholly consistent, giving us confidence in our error determinations. As a further check of the robustness of our results, we performed a search for alternative solutions, by performing the fitting procedure from 250 randomly selected starting positions. The simulation found no other set of model parameters consistent with our data. We are thus confident that the model parameters and their errors presented here are both unique and accurate.

The data are not good enough to determine the white dwarf limb-darkening coefficient, U_{w}, accurately. To find an appropriate limb-darkening coefficient, we obtained an estimate of the effective temperature and mass of the white dwarf from a first iteration of the method below, assuming a limb-darkening coefficient of 0.5. The mass and effective temperature was then used in conjunction with stellar atmosphere codes *(S3)* to generate angle-dependent white dwarf model spectra. To convert the spectra to observed fluxes the model spectra were folded through passbands corresponding to the instrumental response in each filter; the effects of the SDSS filter set, the ULTRACAM CCD responses and the dichroics used in the instrumental optics were taken into account. These fluxes were then fit as a function of the limb position in order to derive limb-darkening parameters appropriate for each band. A second iteration using these values for the limb-darkening parameter gave the final values for each parameter. Limb-darkening parameters of 0.37, 0.45 and 0.56 were found for the r'- g'- and u'-bands, respectively. Comparison of the limb-darkening parameters provided by different atmosphere models *(S3, S4)* suggests an uncertainty in $U_{\rm w}$ of ~ 5 percent. This corresponds to an uncertainty in $R_{\rm w}/a$ of ~ 1 percent, which was added in quadrature to the error in $R_{\rm w}/a$ provided by the fitting process.

Fitting of the model to the data provides estimates q, $\Delta\phi$ and $R_{\rm w}/a$. The orbital inclination i is determined from q and $\Delta\phi$, using geometrical arguments. Separate fitting of the g'- and r'-band light curves provided consistent estimates of q, i and $R_{\rm w}/a$. We measured weighted means of $q = 0.055 \pm 0.002$, $i = 83^{\circ}.1 \pm 0^{\circ}.2$ and $R_{\rm w}/a = 0.0140 \pm 0.0003$. The u'-band light curve does not possess sufficient signal-to-noise to constrain q, i and $R_{\rm w}/a$, but does allow a measurement of the u'-band flux of the white dwarf. This was combined with r'- and g'-band fluxes for the white dwarf component, to derive an effective temperature for the white dwarf. The signal-to-noise of our data is very high, and the white dwarf fluxes are likely to be dominated by systematic errors, which are typically of the order of 1 percent. We added systematic errors of 1 percent to our white dwarf fluxes to account for this. A white dwarf temperature of $T_w^{eff} = 10100 \pm 200\,{\rm K}$ is found by fitting the white dwarf colours to the predictions of white dwarf model atmospheres *(S5)*. A mass for the white dwarf can then be derived from Kepler's 3^{rd} Law, the orbital period, the mass ratio and a mass-radius relationship for the white dwarf. We adopted an appropriate mass-radius relationship for the white dwarf *(S6)*, which we corrected to the appropriate effective temperature found above. Comparison of different white dwarf models *(S5, S6, S7)*, and correction to different effective temperatures revealed that the dominant source of uncertainty in the white dwarf mass is the uncertainty in $R_{\rm w}/a$. The effect of the assumed hydrogen envelope mass was also investigated using appropriate models *(S7)*. Whilst lower envelope masses tend to give higher derived masses for the white dwarf, changes in the envelope mass of an order of magnitude, from $M_H/M_* = 10^{-4}$ to $M_H/M_* = 10^{-5}$, are needed to change the resulting white dwarf mass by more than the uncertainty arising from our measurement of $R_{\rm w}/a$. We therefore neglect this effect in our analysis. Once the white dwarf mass is known, the mass of the donor star follows from q and the radius of the donor star can be calculated, assuming the donor star fills its Roche Lobe. Since the uncertainty in the brown dwarf mass is dominated by the uncertainty in q it is relatively unaffected by the uncertainty in the white dwarf mass.

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