CHARACTERIZING THREE CANDIDATE MAGNETIC CATACLYSMIC VARIABLES FROM SDSS: XMM-NEWTON AND OPTICAL FOLLOW-UP OBSERVATIONS

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ABSTRACT

In the latest in our series of papers on XMM-Newton and ground-based optical follow-up of new candidate magnetic cataclysmic variables (mCVs) found in the Sloan Digital Sky Survey, we report classifications of three systems: SDSS J144659.95+025330.3, SDSS J205017.84−053626.8, and SDSS J210131.26+105251.5. Both the X-ray and optical fluxes of SDSS J1446+02 are modulated on a period of 48.7 ± 0.5 minutes, with the X-ray modulation showing the characteristic energy dependence of photoelectric absorption seen in many intermediate polars (IP). A longer period modulation and radial velocity variation is also seen at around 4 hr, although neither data set is long enough to constrain this longer, likely orbital, period well. SDSS J2050−05 appears to be an example of the most highly magnetized class of mCV, a diskless, stream-fed polar. Its 1.57 hr orbital period is well constrained via optical eclipse timings; in the X-ray it shows both eclipses and an underlying strong, smooth modulation. In this case broadly phase-resolved spectral fits indicate that this change in flux is the result of a varying normalization of the dominant component (a 41 keV MEKAL plasma), plus the addition of a partial covering absorber during the lower flux interval. SDSS J2101+10 is a more perplexing system to categorize: its X-ray and optical fluxes exhibit no large periodic modulations; there are only barely detectable changes in the velocity structure of its optical emission lines; the X-ray spectra require only absorption by the interstellar medium; and the temperatures of the MEKAL fits are low, with maximum temperature components of either 10 or 25 keV. We conclude that SDSS J2101+10 cannot be an IP, nor likely a polar, but is rather most likely a disk accretor—a low-inclination SW Sex star.

Key words: novae, cataclysmic variables — stars: individual (SDSS J144659.95+025330.3, SDSS J205017.84−053626.8, SDSS J210131.26+105251.5) — stars: magnetic fields X-rays: stars

Online material: color figures

1. INTRODUCTION

The Sloan Digital Sky Survey (SDSS; York et al. 2000) has provided a wealth of new cataclysmic variables (CVs), the close binary systems with active accretion from a late main-sequence star to a white dwarf (reviewed in Warner 1995). Due to its sensitivity down to ~21 mag, SDSS is especially suited to the discovery of faint CVs with low accretion rates and short orbital periods. Included in the discoveries are dozens of systems with a noticeable emission line of He II, which is often a signature of a white dwarf with a high magnetic field. The highest field systems (polars) have no accretion disk, and the white dwarf spin is synchronized to the orbit. The intermediate polars ( IPs) usually have some outer disk, with magnetic curtains channeling the inner disk material to the magnetic poles of the white dwarf, which is spinning faster than the orbital timescale. Polars can be identified by circular polarization, cyclotron harmonics, and/or Zeeman splitting (review in Wickramasinghe & Ferrario 2000), while IPs are found through the detection of their spin and orbital periods. In addition, there is a class of high accretion rate disk systems with possible low magnetic field white dwarfs (Rodríguez-Gil et al. 2001) termed SW Sex stars that can also show strong He II lines in their optical spectra.

For the last few years we have used XMM-Newton to identify the nature of CVs with He II and to explore the nature of X-ray heating in these systems. Polars generally exhibit hard X-rays from the accretion shock and soft X-rays from the white dwarf surface heated by the hard X-rays. The ratio of soft to hard X-rays shows a dramatic change with magnetic field strength and accretion rate. The IPs are generally hard X-ray emitters with large absorption effects from the accretion curtains. Usually the spin period is much more pronounced in the X-ray than the optical. The SW Sex stars usually show no X-ray variation and are hard X-ray emitters with low absorption.

The three sources in this study are all about 18 mag in the SDSS g filter and were all identified as potential magnetic CVs in Szkody et al. (2003a). SDSS J144659.95+025330.3 (hereafter SDSS J1446+02) showed no polarization, and limited time-resolved spectra could not determine the orbital period. SDSS J205017.85−053626.8 (SDSS J2050−05) has the strongest He II line of the three objects, with a peak flux comparable to H β, and showed evidence of high and low states of mass transfer. A short span of time-resolved spectroscopy showed an orbital period near 2 hr. Follow-up high-speed photometry by Woudt et al. (2004) revealed brief (260 s), deep (1.5 mag) eclipses and determined a precise period of 1.57 hr. The third system, SDSS J210131.26+105251.5 (SDSS J2101+10), has very strong Balmer lines but did not show any velocity variation during 1.3 hr of time-resolved spectroscopy.
TABLE 1
OBSERVATION SUMMARY

| UT Date       | Observatory | UT Time   | Characteristics | Comments                        |
|---------------|-------------|-----------|----------------|---------------------------------|
| 2002 May 11   | SO Bok (2.3 m) | ...       | r = +0.38%     | 3 ks exposure, spectropolarimetry |
| 2003 Apr 27   | APO         | 05:43–09:47 | ...          | 23 × 600 s spectra             |
| 2003 May 7    | NOFS        | 06:39–11:34 | ~V = 17.9     | Open filter photometry          |
| 2004 Jan 30   | XMM-Newton EPIC-pn | 04:17–05:32 | 0.2 counts s⁻¹| Only 3.0 ks live time²,³       |
|               | XMM-Newton EPIC-MOS1/2 | 03:55–05:18 | 0.1 counts s⁻¹| Only 4.5 ks live time²,³       |
|               | XMM-Newton OM | 04:03–08:10 | B = 18.3      | 13.9 ks duration               |
|               | NOFS        | 09:13–13:18 | ~V = 18.2     | Open filter photometry          |
| 2005 Jan 12   | XMM-Newton EPIC-pn | 06:22–08:09 | 0.20 counts s⁻¹| 5.6 ks live time               |
|               | XMM-Newton EPIC-MOS1/2 | 06:00–08:14 | 0.10 counts s⁻¹| 7.7 ks live time               |
|               | XMM-Newton OM | 06:08–08:16 | B = 18.2      | 5.6 ks duration               |

| UT Date       | Observatory | UT Time   | Characteristics | Comments                        |
|---------------|-------------|-----------|----------------|---------------------------------|
| 2003 May 29   | MMT         | ...       | r = +1.06%     | 1.2 ks exposure, spectropolarimetry |
| 2003 May 30   | MMT         | ...       | r = −0.23%     | 2.4 ks exposure, spectropolarimetry |
| 2004 May 14   | SO Bok (2.3 m) | ...       | r = −0.31%     | 1.2 ks exposure, spectropolarimetry |
| 2004 Oct 18   | XMM-Newton EPIC-pn | 10:13–13:17 | 0.67 counts s⁻¹| 8.7 ks live timeb               |
|               | XMM-Newton EPIC-MOS1/2 | 09:50–13:22 | 0.21 counts s⁻¹| 12 ks live time               |
|               | XMM-Newton OM | 06:08–08:16 | B = 18.4      | 8.4 ks duration               |
| 2004 Oct 21   | NOFS        | 01:33–04:34 | ~V = 18.0     | Open filter photometry          |

| UT Date       | Observatory | UT Time   | Characteristics | Comments                        |
|---------------|-------------|-----------|----------------|---------------------------------|
| 2003 May 29   | SO Bok (2.3 m) | ...       | r = +0.03%     | 1.6 ks exposure, spectropolarimetry |
| 2003 Sep 22   | SO Bok (2.3 m) | ...       | r = −0.10%     | 1.6 ks exposure, R-band imaging polarimetry |
| 2004 May 14   | APO         | 10:47–11:04 | ...          | 1 ks spectrum                 |
| 2004 May 19   | NOFS        | 08:01–11:35 | ~V = 18.9     | Open filter photometry          |
| 2004 May 19   | XMM-Newton EPIC-pn | 16:57–18:13 | 0.64 counts s⁻¹| 4.1 ks live timeb               |
|               | XMM-Newton EPIC-MOS1/2 | 16:35–18:18 | 0.23 counts s⁻¹| 6.1 ks live time               |
|               | XMM-Newton OM | 16:43–18:20 | B = 19.0      | 5.5 ks duration               |

² The open-filter photometry from NOFS has an estimated equivalent V zero point, while for spectra the flux density at ~5500 Å is used. The XMM-Newton count rates are average values for each observation for a single detector.

³ The live time of the X-ray CCD detectors refers to the sum of the GTIs, less any dead time. It is typically much less than the difference of observation start and stop times.

The XMM-Newton data obtained on these three sources, combined with additional photometry, spectroscopy, and spectropolarimetry, have allowed us to determine that SDSS J1446+02 is an IP and SDSS J2050−05 is a likely polar, while SDSS J2101+10 escapes an easy classification but appears most likely to be an SW Sex star. Our observations and results are described below.

2. OBSERVATIONS

2.1. X-Ray

Table 1 summarizes our X-ray and optical observations. SDSS J1446+02 was observed twice by XMM-Newton, as the 2004 January 30 observation was badly affected by high charged-particle background throughout, and the X-ray exposures were curtailed after only a few kiloseconds. Since the X-ray instrumentation (comprising three X-ray telescopes, backed by the two MOS and one pn EPIC CCD cameras; Turner et al. 2001) was set as the prime instrument, an automatic reobservation was triggered. However, the 2004 optical data from XMM-Newton’s optical monitor (OM; Strüder et al. 2001) were good throughout the scheduled ~13 ks observation. In the second observation, on 2005 January 12, good data were obtained from all three EPIC spectroimagers, but this time the OM only succeeded for two out of an expected four exposures. We note that for both observations no useful data were available from the two Reflection Grating Spectrographs (RGSs; den Herder et al. 2001) arrayed in the optical path of the MOS detectors, as the source is too faint to furnish adequate signal in the dispersed spectra. The initial visits made to SDSS J2050−05 and SDSS J2101+10 were highly successful, with only a little background flaring in the last 3 ks of the 12 ks observation of SDSS J2050−05 and none affecting that of SDSS J2101+10. Useful data were therefore obtained from EPIC imaging and the OM, although once again neither target was bright enough for the RGS.

For the extraction of spectra and light curves from the XMM-Newton data we used the tools available in the Science Analysis System (SAS9), version 6.5.0, with calibration files current to 2005 December 15, and followed the standard protocol as given by the ESA XMM-Newton Web site and the ABC guide10 from the US Guest Observer Facility. In all cases we produced new event list files from the observation data files to incorporate the latest calibration updates and then filtered them with the standard canned expressions. We defined circular source extraction regions (radii of 480 and 360 pixels for the MOS and pn camera, respectively) centered on the centroid of the source, enclosing ~80% of the energy to optimize the signal-to-noise ratio. Simple annular

⁹ Available from http://xmm.vilspa.esa.es/external/xmm_sw_cal/sas.shtml.

¹⁰ See http://heasarc.gsfc.nasa.gov/docs/xmm/abc/abc.html.
background-extraction regions were defined on the same central MOS chip for those two cameras; for the pn CCD we used adjacent rectangular regions at similar detector $Y$ locations to the target. We also reprocessed the OM data with rmfchain, extracting light curves using more appropriate (for our relatively faint targets) source aperture and background regions to maximize the signal-to-noise ratio. We also chose binning to match that of the ground-based photometry, and finally, to aid comparison, converted count rates to $B$ magnitudes.

The SAS task evselect performed the extractions of both X-ray spectra and light curves for source and background. For SDSS J1446+02 and SDSS J2050—05 further time filtering was applied to the event lists prior to spectral extraction to excise intervals of high X-ray background; the revised good time intervals (GTIs) were generated by setting limits on the count rate in hard (>10 keV) light curves for the entire detector. We also restricted acceptable events to singles in the pn CCD (pattern = 0) but up to quadruples in the MOS (pattern $\leq 12$) to further improve energy resolution. In contrast, in extracting light curves only the standard GTIs were invoked, and we kept both singles and doubles for the pn CCD (pattern $\leq 4$) to maximize both light curve coverage and signal-to-noise ratio. For SDSS J2101+10 we also restricted the energy range to below 2.5 keV, at which energy the source contributions dominate. SAS tasks rmfgen, arfgen, and backscal generated appropriate redistribution matrix (rmf) and ancillary response files (arf) and calculated the relative scaling of source to background.

The final steps in data reduction used general-purpose utilities in the FTOOLS software suite: grrppha grouped the spectral bins and associated various files ready for spectral analysis in XSPEC, cmatch created background-subtracted light curves and combined the two MOS light curves, while earth2sun applied a correction to the time stamps for the solar system barycenter.

2.2. Optical

Ground-based photometry was obtained for all three sources using the US Naval Observatory Flagstaff Station (NOFS) 1 m telescope and a 2048 $\times$ 2048 CCD. An open filter was used that had close to a $V$ response, and the magnitudes were calibrated from separate nights of all-sky photometry with Landolt standards. Light curves were made by using differential photometry with respect to comparison stars in each field and the magnitudes measured using IRAF routines. For SDSS J1446+02, 4 hr of photometry began about 1 hr after the XMM-Newton observation ended on 2004 January 30. No data were obtained for the second observation, but an additional 5 hr of photometry from 2003 May 7 was used to establish the optical period. For SDSS J2050—05, 3 hr of photometry were obtained 3 days after the XMM-Newton observations, while the 3.5 hr of observations for SDSS J2101+10 took place 5.5 hr prior to the start of XMM-Newton coverage. In all cases, the ground-based measurements agreed with the OM in showing the systems were all in their normal state of accretion.

In order to determine the orbital period for SDSS J1446+02, 4 hr of time-resolved spectra were obtained on 2003 April 27. The Double Imaging Spectrograph was used on the 3.5 m telescope of the Apache Point Observatory (APO). Twenty-three 10 minute blue and red spectra were obtained with a 1.5” slit, covering the regions 4200–5100 and 6300–7200 Å with a resolution of about 2 Å. IRAF routines were used to calibrate the spectra for wavelength and flux using standards from the night. Velocities were measured for the prominent emission lines using the centroid (“e”) routine in the IRAF splot package; a double-Gaussian method (Shafter 1983) was tried as well. A single spectrum of SDSS J2101+10 was also obtained at APO five nights before the XMM-Newton observation. The Balmer and He II strengths are very similar to the SDSS spectrum shown in Szkody et al. (2003a).

Circular spectropolarimetry was also performed for the three systems in a search for evidence of magnetic fields. The CCD spectropolarimeter SPOL was used (Schmidt et al. 1992) on the Steward Observatory (SO) 2.3 m Bok telescope and the 6.5 m MMT, as indicated in Table 1. All measurements of SDSS J1446+02 and SDSS J2101+10, and two of the three on SDSS J2050—05, yielded spectrum-averaged values $|\nu| = |V/I| < 0.4\%$. Each result is well within $3\sigma$ of zero and thus consistent with being unpolarized. However, a third epoch on SDSS J2050—05, obtained on 2003 May 29 in good observing conditions at the MMT, yielded $|\nu| = +1.06\%$. The signal-to-noise ratio of this data is sufficient to reveal that the circular polarization rises continuously from $v \sim 0$ at ~$4200$ Å to $v \sim 3\%$ beyond $\lambda = 8000$ Å. This and other evidence for polarization by cyclotron emission in SDSS J2050—05 is discussed in § 4.2.

3. ANALYSIS AND RESULTS

3.1. X-Ray Spectral Fitting

The extracted spectra were binned at $>20$ counts bin$^{-1}$, to facilitate the use of $\chi^2$ statistics to find the best model fits. For all sources the background contributed less than 3% of the flux within the source aperture; hence, simpler fitting of background-subtracted spectra was deemed acceptable. At the very lowest energies the calibration of the EPIC detectors remains uncertain; following the latest guidelines, we restricted our fitting to $>0.2\$ keV for the MOS and $>0.15\$ keV for the pn CCD. In every case, we performed joint fits to the data from all three X-ray cameras simultaneously, where all model parameters were fixed apart from the relative normalization of the pn CCD relative to the MOS (which were assumed to be identical). In the cases for which we separated the data into two phase or time bins we then had six data sets. Starting from the case for which all relative normalizations, as well as other model parameters, were kept constant, we then allowed normalizations (but keeping the MOS-to-pn ratios constant) and then other model parameters like temperature to vary. $F$-testing to see whether the additional degrees of freedom were statistically warranted each time. The best fits that we present in figures and tables are those in which the model has the fewest free parameters (i.e., leaves the most degrees of freedom); any further freeing of parameters did not then significantly reduce the (reduced) $\chi^2$ values.

Furthermore, in finding the best-fit models we always started from the simplest single-emission component, solely absorbed by interstellar dust, with an initial value for $N_H$ as predicted by dust maps for the appropriate line of sight through the Galaxy. Typically, we used a single bremsstrahlung model or a model including explicit line emission (the XSPEC model MKAL) as expected for the optically thin thermally emitting plasma encountered in CVs. In all cases, these simplest models failed to provide a good fit; hence, we moved onto a variety of more complex combinations, e.g., multitemperature or two-temperature thermal plasmas, additional soft blackbody components (as emitted by the heated polar caps in polars), and the effects of local partial

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11 Available from http://heasarc.gsfc.nasa.gov/ftools.

12 IRAF (Image Reduction and Analysis Facility) 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.
covering absorption (i.e., due to obscuration by the accretion stream and/or curtain). We discuss the details of the best fits as we report the results of our various analyses for each target in turn.

3.2. SDSS J1446+02

3.2.1. Search for Periodicities

From our APO spectroscopy run on SDSS J1446+02 we generated radial velocity curves for the prominent emission lines. A least-squares sine fit to the velocities was then used to determine the systemic velocity, the semiamplitude, the orbital period, and the phase (based on the red-to-blue crossing). While the Hα, Hβ, Hγ, and He lines were all measured, there were large deviations with respect to the best-fit sine wave in all cases (total σ of the fit of 34, 46, 75, and 73 km s⁻¹, respectively); hence, we only consider the fit to the Hα curve in any detail (shown in Fig. 1). All lines gave a period solution near 4 hr, which is very close to the length of the data set. The Hα solution shown in Figure 1 is for a period of 3.8 ± 0.3 hr, K = 105 ± 11 km s⁻¹, and γ = −8 ± 5 km s⁻¹, with red-to-blue crossing (phase 0) at 7:30 UT on 2003 April 27. Because the period is so close to the length of the observation, it is not a robust determination, but useful in showing that the orbital period is not short (i.e., under 2 hr).

For SDSS J1446+02 we also possess four optical light curves (two from the ground and two from the OM) plus those from the EPIC X-ray cameras. To maximize the signal-to-noise ratio we summed the results from the two MOSs; however, since these are always of longer duration than the pn CCD, we did not combine pn and MOS data at this stage. We performed a Lomb-Scargle periodogram (Scargle 1982) analysis of each of our light curves. In every case a significant peak was found at a period of 49 minutes, which we identify as the spin period of the white dwarf. In addition, longer term variations were apparent in the optical light curves, with peaks corresponding to around 4 hr, close to the signal found in the time-resolved APO spectra. To determine the periods most accurately we used sinusoidal fitting to the longest 2003 May 7 NOFS light curve, with a sinusoid plus first harmonic model for the pulse and a simple sinusoid for the longer period variation. This yielded a period of 0.0338 ± 0.0004 days (48.7 ± 0.5 minutes) for the pulse and 0.165 ± 0.015 days (4.0 ± 0.4 hr) for the longer period, which we presume to be the orbital period of the system. Once again we caution that the 2003 May curve provides only 1.3 cycles coverage of our tentative orbital period, and it remains poorly constrained. Nevertheless, we then fitted the other three optical curves with sinusoids constrained to the pulse and orbital periods and subtracted the latter. In Figure 2 we show the two resulting NOFS light curves; the pulse profile is obvious in most cycles in the 2003 May curve, whereas in 2004 January there is far more scatter, especially away from minimum light. This may simply be due to varying amounts of flickering, perhaps indicative of small changes in accretion state. Lastly, we phase-folded (and binned) the light curves on the pulse period to examine its profile in greater detail. The binned results are shown (along with the X-ray) in Figure 3. The profile is clearly far from sinusoidal, having a relatively broad and flat-topped peak and a narrower V-shaped minimum.

Before phase-folding the X-ray data we created five different energy-selected light curves in order to investigate any dependence of the pulse profile on energy. The final binned light curves shown in Figure 3 were constructed by summing the folded and binned results for all three X-ray cameras to maximize the signal-to-noise ratio. Perhaps not too surprisingly the profile of the X-ray pulse is very different from the optical, but it is noteworthy that the X-ray and optical are neither in phase nor antiphased. Instead, the peak of the X-ray roughly leads that of the optical by ~0.3 in phase. The X-ray pulse is also energy-dependent, with the largest amplitude (and symmetrical peaked pulse) in the two lowest energy bins; the amplitude then decreases with energy, until above 5 keV there is no significant variation.

3.2.2. Spectral Variations with Phase

The variation in pulse amplitude with energy is exactly that which we would expect if obscuration by a local absorber is responsible. In fitting the X-ray spectra we first found a fit to the entire data set, but then applied this model separately to spectra phase-selected from the maximum (φ = 0.05–0.55) and minimum (φ = 0.55–1.05) flux intervals of the pulse profile. The details of the fits are given in Table 2. The model that has the best fit consists of a two-temperature thermal plasma (MEKAL), absorbed by a small Galactic column and also by a much larger variable partial-covering absorber. The fit to the combined spectrum achieved a barely acceptable reduced χ² = 1.1 for 134 degrees of freedom, although it does better than any other model. This model has a well-constrained cool plasma of kT = 130 ± 2 eV contributing unresolved soft emission-line structure plus a very hot component whose temperature pegged at 80 keV, the upper limit for the MEKAL model. Furthermore, the values of the Galactic and local columns were very poorly constrained. This is
probably an effect of trying to fit a highly phase-variable spectrum with a single model (even this fairly complex one). Indeed, after separating the data into "max" and "min" subsets, a joint fit to these spectra was a significant improvement (see Fig. 4).

There was not a significant change in the reduced $\chi^2$, but we were then able to find well-constrained values for the absorbing columns and a physically plausible temperature for the hottest MEKAL component of $kT = 58^{+15}_{-8} \text{keV}$. Once again the fit required a very cool MEKAL model to account for line structure in the 0.3–0.4 keV range, plus O vi emission at 0.56 keV; indeed, this parameter is now pegged at its minimum value of 81 eV, indicating that some problems still remain (but the need for a very cool plasma is less problematic than an unphysically hot one, given the physical conditions in the expected complex multi-temperature accretion column). In this fit the partial-covering absorber parameters for the max tended to zero; hence, we fixed them as such: the min interval as expected requires a thick column around $4 \times 10^{22} \text{cm}^{-2}$, with a 61% covering fraction. In our joint fit we found no statistical support for varying any of the normalization parameters; the change between max and min is entirely accounted for by the introduction of the thick partial-covering absorber. Therefore, the fully unabsorbed flux (0.01–10 keV) remains constant at $3 \times 10^{-13} \text{ergs cm}^{-2} \text{s}^{-1}$, whereas the effect of the absorption leads to clear energy-dependent changes in the observed fluxes: a drop of 60% (4.6×10$^{-13}$–1.8×10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$) in the softest 0.2–2.0 keV band, a decrease of only 30% (7.6×10$^{-13}$ to 5.6×10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$) in the 2.0–5.0 keV band, and no significant change in the flux above 5 keV.

3.3. SDSS J2050–05

The eclipses seen in the optical photometry of Woudt et al. (2004) are also very apparent in the X-ray light curves and in our B-band OM results. Their ephemeris is sufficiently precise that there is merely a 0.01 cycle uncertainty at the time of our XMM-Newton observations. Adding our own eclipse-center measurements, we are able to even further refine the ephemeris to

$$\text{HJD}_{\text{min}}(\text{TT}) = 2,453.296.29816(6) + 0.06542463(1) \times 13 \text{E days},$$

where the numbers in parentheses indicate the 1σ uncertainty in the last digit. Also, note that the time is given in Terrestrial time (UT = TT + 64.184 s at the present epoch).

Besides the eclipses, the X-ray light curves exhibit large amplitude but apparently irregular flaring behavior. We divided the X-ray data into two energy bins, above and below 1.6 keV, roughly encompassing the same count rates, then phase-folded the light curves; we plot them in Figure 5, where we also plot each cycle of data with a different symbol. Although this energy division is not physically motivated, it does roughly separate the energies severely affected by photoelectric absorption from those little affected (as can be seen in Fig. 6). We note, however, that the soft band does include contributions from physically distinct X-ray emission regions (the heated white dwarf surface and the accretion column), which should be borne in mind in any interpretations of the light curves. We see that the flaring does not repeat in each orbit, and that it is far more significant below 1.6 keV. The overplotted binned data (stepped line) bring out the average orbital modulations more clearly. At the higher energies there appears to be a broad peak, cut unevenly by the eclipse, whereas at lower energies the rise in flux to peak does not occur until phase 0. As we did for SDSS J1446+02, we undertook X-ray spectral fitting to both the complete data set, and two phase-selected intervals, here dubbed “peak” and “trough,” excluding the eclipse phase; these regions are also indicated in Fig. 5.

For the complete data set acceptable fits (see Table 3) were found for two-component models with Galactic absorption consistent with the maximum line-of-sight column, with an optically thin thermal component (hot bremsstrahlung or MEKAL plasma equally) plus a soft blackbody. However, the temperature of the hotter component is $\sim 80$ keV is higher than typically found in CVs. We then investigated the phase-selected spectra seeking a single model requiring the fewest varying parameters. The final model consists of a two-temperature thermal component plus a...
| Model                  | Reduced $\chi^2$ | Degrees of Freedom | $N_{\text{H}}$ ($\times 10^{20}$ cm$^{-2}$) | $N_{\text{H}}$ ($\times 10^{22}$ cm$^{-2}$) | Fraction | Emission Model Parameters |
|------------------------|------------------|-------------------|--------------------------------|--------------------------------|----------|--------------------------|
| Bremsstrahlung         | 1.5              | 139               | 6.4$^a$                         | $\ldots$                         | $\ldots$ | $kT = 200$ (pegged)     |
| Power law              | 1.11             | 136               | 1.4$^{+0.8}_{-1.0}$              | 0.8 $\pm$ 0.2                   | 0.41$^{+0.04}_{-0.07}$ | $\Gamma = 1.2 \pm 0.2$ |
| Multi-T MEKAL$^b$      | 1.14             | 137               | 1.6 $\pm$ 0.7                   | 1.3 $\pm$ 0.2                   | 0.64 $\pm$ 0.02 | $kT_{\text{max}} = 60$ keV (fixed$^d$), $\alpha = 1.0$ (fixed) |
| 2 T MEKAL              | 1.10             | 134               | 4$^{+4}_{-2}$                   | 0.9$^{+1.9}_{-0.2}$             | 0.47$^{+0.05}_{-0.04}$ | $kT_1 = 130^{+24}_{-3}$ eV, $kT_2 = 80^{+39}_{-5}$ keV |
| 2 T MEKAL$^d$          | 1.08             | 104               | 13$^{+2}_{-3}$                  | None (max), 4.4$^{+1.6}_{-0.8}$ (min) | None (max), 0.61 $\pm$ 0.03 (min) | $kT_1 = 81^{+4}_{-0.6}$ eV, $kT_2 = 58^{+22}_{-19}$ keV |

$^a$ This fit did not converge well; hence, no error estimates are available.  
$^b$ We used the XSPEC model CEMEKL, in which a fine grid of MEKAL models are co-added, with the emission measures following a power law in temperature with index $\alpha$ and up to $kT_{\text{max}}$; i.e., normalizations scale as $(T/T_{\text{max}})^{\alpha}$.  
$^c$ Here, $kT_{\text{max}}$ was fixed to a plausible value; free fit does not converge.  
$^d$ Joint fit to phase-selected maximum and minimum flux intervals.
soft blackbody with partial covering absorption. In the light of this success we also fitted the complete data set with the same model; in all cases we found physically plausible temperatures and absorption columns. The dominant contribution to the observed absorbed flux (98% in the 0.01–10 keV range) is from a hot MEKAL with $kT/25 \approx 40$ keV, but $F$-tests confirm the importance of the soft blackbody to provide the softest X-ray flux (at 93% confidence) and the cool MEKAL to account for significant unresolved line emission at $\lambda/24 \approx 1$ keV (98%). The change in the spectrum from peak to trough is in part due to increased partial covering absorption—the peak spectrum requires no absorption in excess of the Galactic column, while for the trough we find a 35% covering column with $N_H = 1.3 \times 10^{22}$ cm$^{-2}$—and also to a decrease by 25% in the normalization of the hot MEKAL plasma; the blackbody and cool MEKAL normalizations remain unchanged. The fully unabsorbed 0.01–10 keV flux amounts to $5 \times 10^{32}$ ergs cm$^{-2}$ s$^{-1}$, with 40% contributed by the soft blackbody. In Figure 6 we show the fits to the phase-selected spectra, together with a breakdown of the three components; for clarity we only show data from the pn CCD, although we used the pn CCD and the two MOS spectra when fitting.

3.4. SDSS J2101+10

With no previously known periods, either spin or orbital, our first step was to examine the light curves (see Fig. 7) for periodicities. Unfortunately, the XMM-Newton data span only $\sim 1.5$ hr, and even the NOFS light curve is only 3.5 hr long, limiting our sensitivity to any modulations with periods much in excess of 2 hr. Moreover, the variability in both X-ray and optical bands appears extremely complex. The longest curve, the NOFS optical, appears to show two distinct humps at around 0.87 and 0.94 [truncated HJD(TT)], but of course even here only two cycles are present. Running a phase dispersion minimization (PDM; Stellingwerf 1978) period-folding search on this light curve we find three signals, but the lowest frequency one is close to the...
| Model                  | Reduced $\chi^2$ | Degrees of Freedom | $N_H$ ($\times 10^{20}$ cm$^{-2}$) | $N_H$ ($\times 10^{22}$ cm$^{-2}$) | Fraction | $kT_{BB}$ (eV) | $kT$ (keV) |
|------------------------|------------------|--------------------|-----------------------------------|-----------------------------------|----------|---------------|------------|
| Bremsstrahlung ..........| 0.99             | 418                | 4.3 $\pm$ 0.3                     | ...                               | ...      | ...           | 166$^{+33}_{-20}$ |
| MEKAL ........................| 1.01             | 418                | 4.8 $\pm$ 0.3                     | ...                               | ...      | ...           | 80$^{+2}_{-5}$    |
| 2 $^7$ MEKAL ............| 1.00             | 416                | 7.4 $\pm$ 0.3                     | ...                               | ...      | ...           | (8.08$^{+0.4}_{-0.1}$) $\times 10^{-2}$, 80$^{+0.5}_{-0.1}$ |
| BB + MEKAL ...............| 0.99             | 416                | 5.7$^{4.0}_{-0.4}$                 | ...                               | ...      | 20$^{+8}_{-6}$ | 80$^{+2}_{-5}$    |
| BB + bremsstrahlung......| 0.98             | 416                | 5.6$^{4.0}_{-0.4}$                 | ...                               | ...      | 22$^{+10}_{-6}$ | 100$^{+10}_{-10}$ |
| 2 $^7$ MEKAL + BB .......| 0.99             | 412                | 5.1$^{4.0}_{-0.4}$                 | 1.4$^{0.8}_{-0.6}$ | 0.14$^{+0.45}_{-0.05}$ | 32$^{+1}_{-1}$ | 1.3$^{+1.3}_{-0.5}$, 59$^{+21}_{-15}$ |
| 2 $^7$ MEKAL + BB$^*$.....| 0.88             | 417                | 4.9$^{4.1}_{-0.7}$                 | None (peak), 1.3$^{0.4}_{-0.3}$ (trough) | None (peak), 0.35 $\pm$ 0.03 (trough) | 28$^{+13}_{-10}$ | 1.0$^{+0.2}_{-0.2}$, 41$^{+13}_{-13}$ |

a Joint fit to phase-selected peak and trough intervals.

**TABLE 3**

**X-RAY SPECTRAL FITS FOR SDSS J2050–05**
inverse of the data time span and is therefore unreliable. This leaves minima at around 13.5 days$^{-1}$ (107 minutes) and 26.4 days$^{-1}$ (55 minutes), which are close to being harmonically related to each other. In Figure 8 we show the PDM for the NOFS light curve and the light curve folded on the two candidate periodicities. The fold on the longer period confirms the repeatability of the aforementioned humps; only at phases (arbitrary) 0.25–0.5 do the two cycles agree. However, the fold is also somewhat double-humped, with possibly a second interval of higher flux at around 0.9, although here there is a large amount of scatter. Folding on 54 minutes, the points line up along an approximately sinusoidal curve, but again there is significant scatter about this mean at all phases. Furthermore, for this shorter period we can usefully interrogate the OM and MOS light curves; their PDMs are also plotted in Figure 8. No strong signals appear around 54 minutes.

Returning to Figure 7, in order to consider the NOFS periods further we have overplotted vertical bars to mark phase 0.0 and 0.5 of a 107 minute period, arranging the time axes for the XMM-Newton and NOFS observations to yield phase agreement (only four cycles elapse between the two sets of observations). We see that the repeatable NOFS humps agree in phase and approximate form with a hump in the OM light curve. However, at other phases agreement is lost; in particular, another peak precedes the major hump in the OM curve, possibly correlated with a similar X-ray peak, in fact. Ignoring the high-frequency flickering in the X-ray light curves, there is possibly a slower variation on the $\sim$100 minute timescale, although of course we have no way to test whether this behavior actually repeats.

In the absence of any decisive periods, we simply fitted models to the complete X-ray spectrum. These are detailed in Table 4. A range of emission components from a single fairly cool MEKAL model ($kT = 9$ keV) to a multitemperature version with $kT_{\text{max}} = 25$ keV provide adequate fits, all with a single absorbing component with $N_H \approx 8 \times 10^{20}$ cm$^{-2}$, consistent with the Galactic line-of-sight maximum. An example fit to the spectra is shown in Figure 9; the resulting unabsorbed 0.01–10 keV flux is $1.7 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$.

4. CLASSIFYING THE THREE SOURCES

4.1. Nature of SDSS J1446+02

All the observational evidence indicates that SDSS J1446+02 is a short-period IP. A classic signature of IPs is the presence of multiple periodicities in their light curves. For SDSS J1446+02 we find that both its optical and X-ray fluxes are strongly modulated...
at a short 49 minute period, and there is evidence for an additional optical modulation at 4 hr. This latter periodicity also appears in the Hα radial velocity curve. However, more extensive photometric and spectroscopic runs are needed to confirm these, and hence secure the determination of the orbital period. The identification of the 49 minute modulation with the spin period of an asynchronously rotating white dwarf is much more secure: the characteristic energy dependence of the X-ray flux period of an asynchronously rotating white dwarf is much more likely not a low accretion rate polar (Schwope et al. 2002; Szkody et al. 2003b; Schmidt et al. 2005), for which mass-transfer appears to occur not via Roche-lobe overflow but rather by efficient magnetic capture of the secondary star’s stellar wind.

In support of the above interpretation the X-ray spectra of SDSS J2050—05 are fitted well by a two-temperature thermal plasma model (MEKAL), but, in addition, the data require a soft blackbody component. In this case, the two MEKAL components have temperatures of 1 and 41 keV respectively, once again likely indicating the limits of the range of temperatures present in the optically thin emitting plasma, both quite typical for polars. The blackbody has a temperature of about 30 eV, again within the observed range for polars. In the peak region, this cool blackbody component, arising from the heated surface of the white dwarf, contributes about 40% of the unabsorbed 0.01–10 keV flux.

In terms of the energy balance, assuming an X-ray albedo for the body component, arising from the heated surface of the white dwarf, contributes about 40% of the unabsorbed 0.01–10 keV flux. In terms of the energy balance, assuming an X-ray albedo for the body component, arising from the heated surface of the white dwarf, contributes about 40% of the unabsorbed 0.01–10 keV flux. In terms of the energy balance, assuming an X-ray albedo for the body component, arising from the heated surface of the white dwarf, contributes about 40% of the unabsorbed 0.01–10 keV flux. In terms of the energy balance, assuming an X-ray albedo for the body component, arising from the heated surface of the white dwarf, contributes about 40% of the unabsorbed 0.01–10 keV flux.
Such pre-eclipse energy-dependent dipping structure is seen in many other eclipsing polars, e.g., EP Dra, HU Aqr, and UZ For (Ramsay et al. 2004; Schwope et al. 2001; Sirk & Howell 1998). In the high-quality soft X-ray light curves of HU Aqr there is one broad dip centered on phase 0.7 and a narrower feature at around 0.9. These are interpreted as arising from the accretion column obscuring the nearby heated photosphere of the white dwarf, while the more distant accretion stream accounts for the sharper dip; indeed, the width and azimuth of this dip can be related to the geometry of the region where the stream threads onto the white dwarf’s magnetic field. Unfortunately, given the quality of our own data (both lacking the high signal-to-noise ratio and afflicted with the flaring), we cannot identify the dipping components and hence cannot probe the accretion flow in greater detail. Of course, from our spectral fitting we know that the soft flux arises from both the white dwarf and various parts of the accretion column, which would further complicate a more detailed analysis.

4.3. Nature of SDSS J2101+10

Although originally identified as a candidate mCV, given the strength of its high-excitation optical emission lines the follow-up observations of SDSS J2101+10 we have presented do not seem to confirm this classification. We find no strong modulation of its X-ray flux, quite unlike any polar (e.g., SDSS J2050−05). The X-ray spectrum also does not require any absorption in excess of the estimated Galactic column, effectively ruling out a typical IP. The X-ray emission is describable by a variety of thermal plasma (MEKAL) models, although with a noticeably lower temperature (kT ≈ 10, or at most 25, keV) than is found in most mCVs or, indeed, in our fits to SDSS J1446+02 or SDSS J2050−05. This cooler plasma is in fact far more typical of disk-accreting systems. Only the SW Sex stars show He ii with strength comparable to the magnetars; both the lack of absorption in the line profiles and their barely detectable radial velocities could be accounted for by a low inclination to our line of sight.

5. CONCLUSIONS

We have reported on observations allowing classification of three new SDSS CVs showing prominent He ii: SDSS J1446+02, SDSS J2050−05, and SDSS J2101+10. Each represents a different class of CV, known to exhibit such high-excitation emission lines.

SDSS J1446+02 is a clear example of an IP. We find two periodicities at about 4 hr and 49 minutes, arising respectively from the orbit and the asynchronously spinning white dwarf. The X-ray spectrum comprises a multitemperature thermal plasma, with a maximum of 60 keV, modulated by phase-dependent local absorption. This likely originates from obscuration by the accreting column formed by the accreting material as it flows between the disrupted disk and the magnetic poles of the white dwarf.

SDSS J2050−05 represents the most highly magnetized of the three, a fully spin-orbit synchronized polar, with an orbital period of 1.57 hr. In this case no disk forms, and all accretion is channeled along the field lines to a single dominant pole. Owing to its high inclination, there is a phase interval when the accretion stream obscures the X-ray emitting region, but most of the modulation on the spin/orbit appears consistent with simply its changing aspect. The X-ray emission has two components. The dominant one is characteristic of the postshock bremsstrahlung-cooled optically thin plasma of the accretion column, here with temperatures ranging from 1 to 40 keV; this also heats the surface of the white dwarf, leading to additional soft blackbody (30 eV) emission.

In SDSS J2101+10 we suggest that the combination of high accretion rate and lower magnetic field strength allows disk-mediated accretion but also the formation of He ii emission lines in the optical spectra; i.e., if it were at higher inclination it would appear as a classic SW Sex star. Its X-ray spectra indicate a rather cool thermal plasma (~10 keV) more typical of disk systems and an unobscured line of sight, inconsistent with an IP. From only weak modulation of its X-ray and optical light curves (unlike a polar) we suggest an orbital period in the 100 minute range.

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