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A CENSUS OF AM CVN STARS: THREE NEW CANDIDATES AND ONE CONFIRMED 48.3-MINUTE BINARY

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ABSTRACT

We present three new candidate AM CVn binaries, plus one confirmed new system, from a spectroscopic survey of color-selected objects from the Sloan Digital Sky Survey. All four systems were found from their helium emission lines in low-resolution spectra taken on the Hale telescope at Palomar, and the Nordic Optical Telescope and the William Herschel Telescope on La Palma.

The ultra-compact binary nature of SDSS J090221.35+381941.9 was confirmed using phase-resolved spectroscopy at the Keck-I telescope. From the characteristic radial velocity 'S-wave' observed in the helium emission lines we measure an orbital period of 48.31 ± 0.08 min. The continuum emission can be described with a blackbody or a helium white dwarf atmosphere of $T_{eff} \sim 15,000$ K, in agreement with theoretical cooling models for relatively massive accretors and/or donors. The absence in the spectrum of broad helium absorption lines from the accreting white dwarf suggests that the accreting white dwarf cannot be much hotter than 15,000 K, or that an additional component such as the accretion disk contributes substantially to the optical flux.

Two of the candidate systems, SDSS J152509.57+360054.5 and SDSS J172102.48+273301.2, do show helium absorption in the blue part of their spectra in addition to the characteristic helium emission lines. This, in combination with the high effective temperatures of $\sim 18,000$ K and $\sim 16,000$ K suggests both two be at orbital periods below ≈ 40 min. The third candidate, SDSS J164228.06+193410.0, exhibits remarkably strong helium emission on top of a relatively cool ($T_{eff} \sim 12,000$ K) continuum, indicating an orbital period above ~ 50 min.

Subject headings: stars: individual: (SDSS J090221.34+381941.9, SDSS J152509.57+360054.5, SDSS J164228.06+193410.0, SDSS J172102.48+273301.2) – binaries:close – white dwarfs – novae, cataclysmic variables – accretion, accretion discs

1. INTRODUCTION

The AM CVn stars form a small class of interacting binaries, consisting of white dwarf accretors with degenerate or semi-degenerate helium-transferring companion stars. AM CVn stars exist in ultra-compact configurations, with observed orbital periods, P_{orb}, ranging from 65 min down to 10 min (below the orbital period minimum for hydrogen-rich donors, see Nelemans 2005, for a recent review). Two ultrashort-period candidates, V407 Vul (Cropper et al. 1998) and HM Cnc (Israel et al. 2002), possibly extend the P_{orb}-distribution further down to 5.3 min.

AM CVn stars are of interest for binary stellar evolution theory as they form the end-product of several evolutionary scenarios (e.g., Nelemans et al. 2001; Podsiadlowski et al. 2003) and can potentially produce rare, subluminous, SN Ia-like explosions (SN .Ia, Bildsten et al. 2007). They are also the strongest known sources that can be detected as gravitational-wave emitters with the future *Laser Interferometer Space Antenna* (*LISA*; see e.g., Nelemans et al. 2004; Stroeer et al. 2005; Roelofs et al. 2007c).

Our understanding of the physics of these systems has increased significantly over the last few years (e.g., Deloye et al. 2005; Bildsten et al. 2006; Deloye et al. 2007), while observationally, the Sloan Digital Sky Survey (SDSS, York et al. 2000) has been instrumental. Pre-SDSS, only $\sim$10 AM CVn binaries were known (Roelofs et al. 2005), and the extreme heterogeneity of this already small sample made a census of the Galactic population of AM CVn stars impossible. The SDSS-I (Data Release 5) provided a substantially more homogeneous sample of 6 new AM CVn stars, allowing for a local space density measurement, limited by the still small size of the sample (Roelofs et al. 2007c).

Noting that the AM CVn stars occupy a relatively sparsely populated region in color space where the spectroscopic completeness down to $g = 20.5$ in the SDSS database is only $\sim$20 %, we started an extensive spectroscopic survey program at a number of observatories world-wide to resolve the 'hidden' population of AM CVn stars in the SDSS photometry. The aim of this project is to significantly increase the total known population of AM CVn stars and, more importantly, enlarge the homogeneous sample of these sources. Ultimately, the space density of AM CVn stars, and further population characteristics such as their orbital period distribution, will allow comparisons with predictions from theoretical models, and will allow better modeling of the Galactic gravitational-wave foreground signal seen by *LISA*.

Details of our spectroscopic follow-up program, in particular the sample selection criteria, and the first (peculiar) new AM CVn star (SDSS J080449.49+161624.8) were described in Roelofs et al. (2009). A complete cata-

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log of sources, and a detailed AM CVn population study, will be presented when the spectroscopic survey program is complete. Here, we give a status update after the first year and present four new discoveries, including a detailed spectroscopic study of one confirmed new AM CVn star.

The outline of the paper is as follows. In § 2 we summarize the observations and data reduction. We present the new AM CVn candidates as well as the spectral and timing analysis of the confirmed system in § 3. Our conclusions are given in § 4.

2. OBSERVATIONS AND DATA REDUCTION

Low-resolution, low-signal-to-noise ratio spectra of objects in our color-selected sample have been obtained on a multitude of telescopes. To date, almost half of our sample of ≈1500 candidates has been completed (see Fig. 1 for a concise summary of the current statistics). Two of the systems presented here (SDSS J172102.48+273301.2, hereafter SDSS J1721, and SDSS J152509.57+360054.5, hereafter SDSS J1525) were identified as helium-emission-line objects from spectra taken at the 2.6-m Nordic Optical Telescope (NOT) on La Palma, Spain, with the ALFOSC spectrograph fitted with the grism #11 (see Table 1). Slits with $0\rlap{.}''9$ and $1\rlap{.}''3$ width were used for SDSS J1721 and SDSS J1525, respectively, offering resultions of R$\sim$ 210 and R$\sim$ 145 at 5200 Å. The third object, SDSS J164228.06+193410.0 (hereafter SDSS J1642) was identified in a spectrum taken at the 4.2-m William Herschel Telescope (WHT), also on La Palma, equipped with the new Auxiliary-port Camera (ACAM) and the 400V holographic grism, providing an effective resolution $R \sim 450$ at 6000 Å. This set-up was also used to obtain confirmation spectra of the two objects discovered at the NOT. The NOT and WHT spectra were corrected for Galacitic foreground extinction assuming that the AM CVn stars are on average located behind the Galactic Plane dust screen (Roelofs et al. 2009).

The identifying spectrum of SDSS J090221.35+381941.9 (hereafter SDSS J0902) was taken at the Hale 5-m telescope at Palomar Observatory equipped with the Double-Beam Spectrograph (DBSP; Oke & Gunn 1982). A $1\rlap{.}''5$ slit and the 300/3990 and 316/7500 gratings were used, achieving a spectral resolution on the blue and red sides of R$\sim$ 540 (4000 Å) and R$\sim$ 700 (6000 Å), respectively.

Follow-up phase-resolved spectroscopy of SDSS J0902 was obtained on 2009 Jan 26 and 27 using the Low-Resolution Imager and Spectrograph (LRIS; Oke et al. 1995) at the 10 m Keck-I telescope (see Table 1). Similar to DBSP, LRIS is a dual-beam instrument. We used the 600/4000 grism and 600/7500 grating for the blue and red arms, respectively, with the light split by a dichroic at $\approx$ 5600 Å. The blue arm data were binned on the chip by factors of 4 each in spatial and dispersion direction. This allowed a reduction of the overhead due to CCD readout from 42 s (unbinned) to 27 s. All LRIS observations were performed with a long slit of $1\rlap{.}''5$ width and the atmospheric dispersion corrector in place. Typical seeing was about $1\rlap{.}''2$ resulting in an effective spectral resolution of about 4.5 Å FWHM at 4500 Å, or 300 km s^{-1}. The red arm data were binned 2 × 2 providing readout times of 34 s (compared to 72 s unbinned) and a resolution of 4.4 Å

TABLE 1
LOG OF SPECTROSCOPIC OBSERVATIONS.

SDSS …	UT Date	Set-up	Exposures
J090221.35+381941.9	2009-01-01	P200/DBSP	1×910 s
	2009-01-26	Keck-I/LRIS	20×240 s
	2009-01-27		$^{\dagger}45 \times 180$ s
J152509.57+360054.5	2009-05-26	NOT/ALFOSC	1×600 s
	2009-06-25	WHT/ACAM	1×900 s
J164228.06+193410.0	2009-06-23	WHT/ACAM	2×400 s
J172102.48+273301.2	2009-05-25	NOT/ALFOSC	1×600 s
	2009-06-19	WHT/ACAM	1×600 s

†43 exposures on the red side.

at 6000 Å (≈ 220 km s^{-1}).

All data were reduced with standard IRAF routines, and spectra were extracted using an optimal (variance-weighted) method. Spectro-photometric flux calibration was carried out with spectra of the standard star Feige 34 (Oke 1990) taken each night. Correction for Galactic foreground extinction of E(B–V)=0.024 mag (Schlegek et al. 1998) was applied.

3. RESULTS

3.1. *Identification Spectra of the New AM CVns*

The extracted spectra of all four objects are shown in Figure 2. The prominent neutral He emission lines are clearly recognized in all of them, most notably He I 5876, 6678 & 7065. This, and the absence of hydrogen in the spectra suggests that all four objects are likely new members of the class of AM CVn stars, although further observations are needed to confirm their ultra-compact binary nature beyond question.

3.2. *Phase-Resolved Spectroscopy of SDSS J0902*

Phase-resolved spectroscopy is the technique of choice for measuring the orbital period of AM CVn binaries, for which photometry does typically not yield stable orbital period signals. In AM CVn stars, the emission lines in a spectroscopic time series are commonly observed to vary in the form of a sinusoidal "S-wave". In analogy with the bright spots seen in hydrogen-rich cataclysmic variables, this S-wave is caused by the impact region where the infalling accretion stream hits the accretion disk edge, providing an emission-line source that is fixed in the binary frame. In order to search for a similar signature in our data of SDSS J0902, we combined the strongest helium lines from both nights of Keck-I/LRIS observations. We focused on the blue side of LRIS where the signal-to-noise is highest.

Roughly following the approach of Nather et al. (1981) we divided the combined lines into red and blue wings and calculated the ratio of the fluxes in both wings for each individual spectrum. A Lomb-Scargle periodogram of the flux ratios is shown in Figure 3. The maximum power is found at 29.8 cylces per day, corresponding to a period of 48.3 min. The periodogram shows the next two strongest peaks at the usual ±1 cycle per day aliases (see inset of Figure 3), which are caused by the relatively short observing baseline on two consecutive nights.

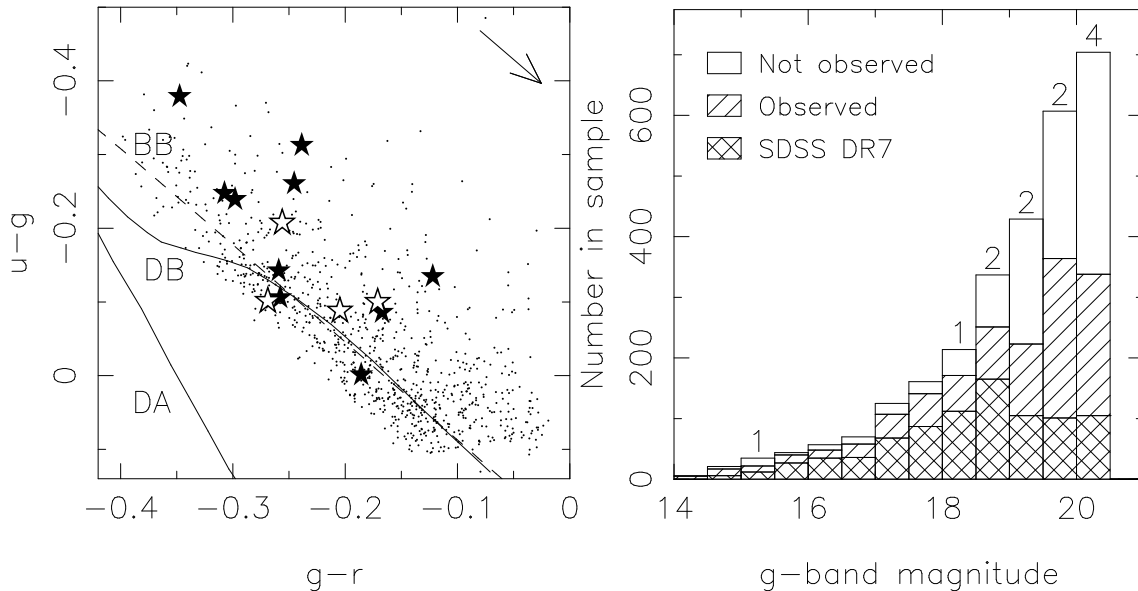Phase-folding the individual spectra of both nights on

FIG. 1.— Photometric colors (left, de-reddened) and spectroscopic completeness (right, not de-reddened) of our sample. Left, stars indicate known AM CVn stars with SDSS photometry; open stars are the four new systems presented here (SDSS J0902, J1525, J1721, J1642 from left to right). The dots denote our candidate population up to DR7. Blackbody (BB), helium-atmosphere (DB) and hydrogen-atmosphere (DA) white dwarf cooling curves are indicated. The arrow shows the reddening vector for a g-band extinction of 0.2 mag. Right, numbers above bins give the number of AM CVns in our spectroscopy or the DR7 spectroscopic database. Two systems with DR7 photometry have not been observed spectroscopically by us or the SDSS. The brightest system is the well studied source GP Com.

a period of 48.3 min produces the trailed spectrum shown in Figure 4. A clear sinusoidal S-wave with a velocity amplitude of $\approx 700\,\mathrm{km\,s^{-1}}$ is found. The observing baseline on the second night (see Table 1) is long enough and the S-wave signal is strong enough that we can obtain a unique trace of the S-wave signal throughout the two-night baseline of our Keck run, without losing count of the orbital cycles. To accurately track the phase of the S-wave signal, we back-projected the spectra into a Doppler tomogram (Marsh & Horne 1988), transforming the S-wave emission into a localized emission 'bright spot' (Figure 5). Fine-tuning of the phase-folding period to eliminate the phase drift of the bright spot gives an orbital period $P_{\mathrm{orb}} = 48.31 \pm 0.08$ minutes. The error on the orbital period is obtained from an estimate of the bright-spot phasing accuracy due to statistical and systematic errors, as discussed in Roelofs et al. (2007d).

3.3. Average Spectrum of SDSS J0902

In order to generate an averaged, high signal-to-noise spectrum of SDSS J0902, we combined all LRIS exposures using optimal weights (Figure 6). As already indicated by the DBSP spectrum (Figure 2a), SDSS J0902 exhibits a blue continuum dominated by strong emission of neutral helium, typical for AM CVn stars. In addition, the LRIS spectrum reveals singly ionized helium ($\lambda 4685$) as well as weak components of Fe II $\lambda 5169$ and Si II $\lambda 6347 + 6371$. These features are commonly observed in AM CVn stars (e.g. Groot et al. 2001; Roelofs et al. 2006a), and are expected from a donor star with solar abundances of heavy metals (Marsh et al. 1991). We note the absence of significant DB white dwarf absorption (as seen in e.g., SDSS J1240-0159, Roelofs et al. 2005) underlying the helium emission lines. There are two known AM CVn stars with comparable orbital pe-

riod - GP Com ($P_{\mathrm{orb}} = 46.5$ min; Nather et al. 1981) and SDSS J1411+4812 ($P_{\mathrm{orb}} = 46 \pm 2$ min; Roelofs 2007). Overall the spectrum of SDSS J0902 is particularly reminiscent of that of SDSS J1411+4812 (Anderson et al. 2005). It shows similar metal lines and He line equivalent widths (e.g, He I 5876 $\mathrm{EW_{J0902}} = 79 \pm 3$ Å (see Table 2) vs. $\mathrm{EW_{J1411}} \approx 65$ Å; Anderson et al. 2005). In contrast, the high abundance of nitrogen in GP Com is not seen in SDSS J0902, which suggest that the CNO cycle is less prominent in the latter.

The He I emission lines, averaged as well as in single exposures, show the classical double-winged profile indicative of an accretion disk (Figure 7). In addition, we detect a third emission component near zero velocity, similar to that seen in many other AM CVn stars. This emission spike is thought to originate from (or very near) the surface of the accreting white dwarf, as suggested by observed radial velocity shifts consistent with the accretor's expected orbital motion in GP Com (Marsh 1999; Morales-Rueda et al. 2003). It is interesting to note that the He II emission line at $\lambda 4685$ (blended with He I $\lambda 4713$) has a Gaussian profile and a lower full-width at half-maximum (FWHM, $\approx 700\,\mathrm{km\,s^{-1}}$) than the He I lines ($\approx 1200\,\mathrm{km\,s^{-1}}$), suggesting that the He II line may largely consist of the central spike component.

An estimate of the continuum temperature of SDSS J0902 can be obtained by modeling the available photometric and spectroscopic data. A fit to the SDSS photometry taken in 2002 and the GALEX NUV measurement obtained in 2004 suggest a black body with effective temperature of $T_{\mathrm{eff}} \approx 15,100$ K (Figure 8a). A similarly good match is obtained using the helium white dwarf atmosphere models of Koester (2008) with $T_{\mathrm{eff}} \approx 14,000$ K.
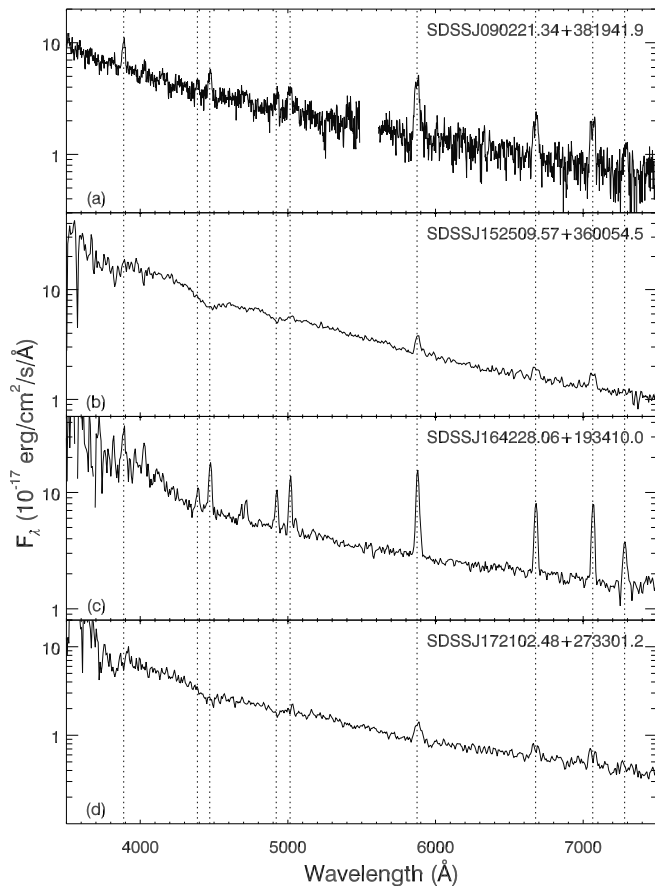
Fig. 2.— De-reddened low-resolution spectra of (a) SDSS J0902 (taken with P200/DBSP), (b) SDSSJ 1525, (c) SDSSJ 1642, and (d) SDSSJ 1721 (all taken with WHT/ACAM). The positions of the strongest HeI lines are indicated by the dotted vertical lines.
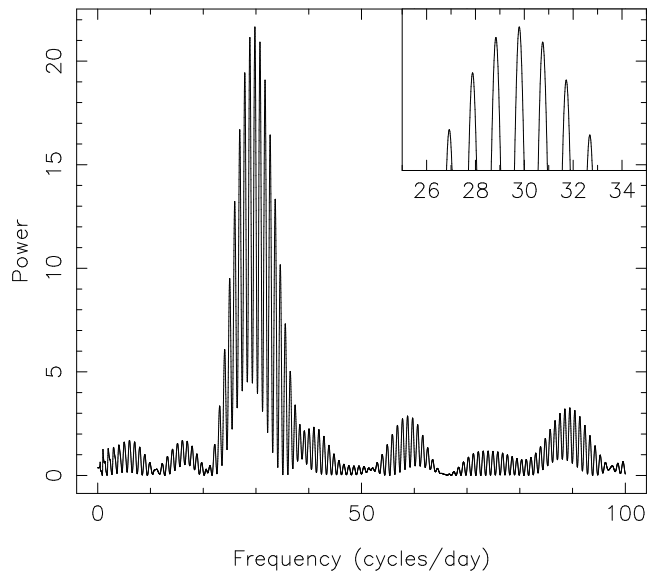

Fig. 3.— Lomb–Sargle periodogram of the flux ratios of the blue and red wings of the combination of the strongest HeI ($\lambda\lambda 3888, 4026, 4471, 4921, 5015$) emission lines in the blue side of the Keck-I/LRIS spectra of SDSS J0902. A zoom around the peak (inset) shows the typical aliases at ± 1 cycle per day.
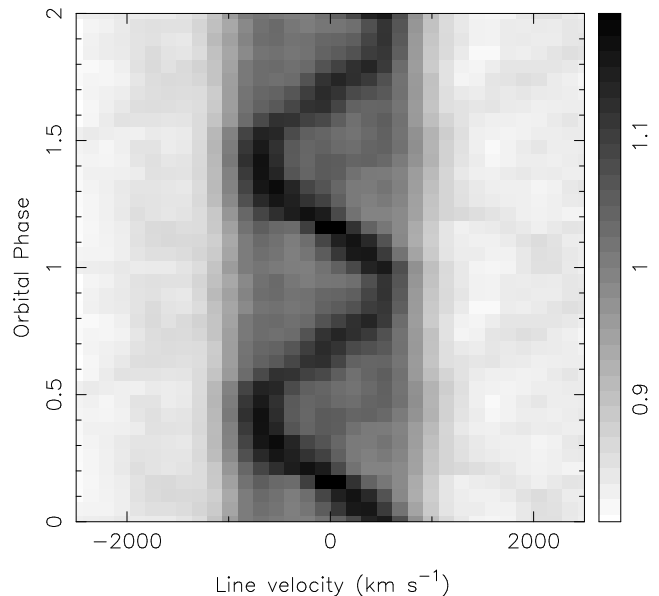

Fig. 4.— Trailed spectrum of the combined He emission lines in the blue arm spectra of SDSS J0902, phase-folded on the 48.31 min period. The zero-phase is arbitrary. The grey-scale indicates the relative flux densities. An arbitrary zero-phase of HJD=2454858.049150 has been used.

At the orbital period of SDSS J0902, the accreting white dwarf is expected to contribute a large fraction ($\approx 50\%$) of the continuum emission, if the mass transfer rate is not significantly higher than the equilibrium rate set by gravitational-wave radiation ($\approx 10^{-11}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$; Bildsten et al. 2006). This means that the accreting dwarf is expected to be the hottest component in the system. Interestingly, our temperature estimate is at the high end of expectations from theoretical models for the thermal evolution of the accreting white dwarf (Bildsten et al. 2006). These models predict temperatures in the range of 9,000 K to 15,000 K (for primary masses from $0.65\,\mathrm{M}_\odot$ to $1.05\,\mathrm{M}_\odot$) at orbital periods of ≈ 48 min.

Since a higher system mass leads to more accretion heating and shorter cooling time for the accretor at a give orbital period, the rather high continuum temperature in SDSS J0902 may point to a high accretor and/or donor mass. The absence of broad DB absorption lines, seen in other AM CVn stars (e.g. SDSS J1240; Roelofs et al. 2006b) suggests that the accretor cannot be much hotter than 15,000 K, if it contributes substantially to the optical flux as expected.

3.4. SDSS J1525, SDSS J1642, and SDSS J1721

The two objects with the weakest emission lines, SDSS J1525 and SDSS J1721, turn over to a helium absorption-line spectrum in the blue, quite like the first Sloan-discovered AM CVn star, SDSS J1240 (Roelofs et al. 2005). Black body and helium white dwarf atmosphere model fits to their SDSS and GALEX photometry (Figure 8b,d) suggest temperatures of $T_{\mathrm{eff}} = 17,000 - 18,500\,\mathrm{K}$ and $T_{\mathrm{eff}} = 15,000 - 15,900\,\mathrm{K}$ for SDSS J1525 and SDSS J1721, respectively. This, together with the broad helium absorption lines in the spectra indicates orbital periods below ≈ 40 min (Nelemans

SDSS...	FUV$_{AB}$	NUV$_{AB}$	u	g	r	i	z	A(g)	$-EW_{HeIλ5876}$ (Å)
J090221.35+381941.9	[a]20.61(29)	20.35(17)	20.16(5)	20.23(2)	20.47(3)	20.59(5)	20.79(21)	0.09	79(3)
J152509.57+360054.5	20.01(15)	19.53(3)	19.64(3)	19.82(2)	20.06(2)	20.31(3)	20.40(12)	0.06	20(3)
J164228.06+193410.0	...	21.11(31)	20.29(5)	20.28(2)	20.37(2)	20.42(3)	20.61(19)	0.29	105(3)
J172102.48+273301.2	20.67(23)	20.26(14)	20.02(4)	20.06(2)	20.23(2)	20.35(3)	20.25(11)	0.12	30(6)

NOTE. — Photometry and g-band extinction are given in magnitudes. Numbers in parentheses indicate the errors in the corresponding number of last digits.

[a]Visual inspection of the GALEX All-sky Imaging Survey image AIS_85_sg82 puts doubts on the GR5 catalogued detection, as confirmed by the non-detection in a second visit (AIS_85_sg72).
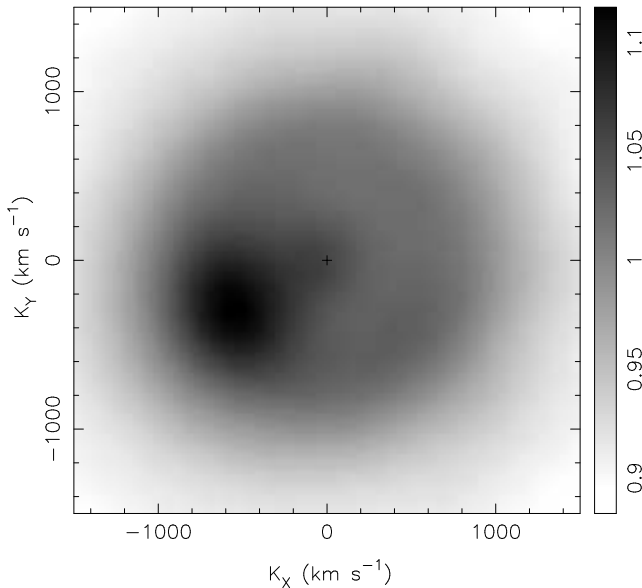

FIG. 5.— Linear back-projection Doppler tomogram of the combined SDSS J0902 He emission lines in the blue arm spectra taken with Keck-I/LRIS, projected on the 48.31 min period. The grey-scale indicates the relative flux densities. Zero-phase as in Figure 4.

2005). The relatively low temperature of the latter surprises given that similarly broad helium absorption lines in both systems (see Figure 2). We matched the white dwarf atmosphere models to the spectral range aodunr the 4921 Å absorption line and found a best fit temperature of 18,000 K in both sources. The apparent discrepancy for SDSS J1721 suggests that another component e.g., the accretion disk, contributes signifcantly to the continuum emission.

The third source, SDSS J1642, shows remarkably strong helium emission lines, comparable to CE 315, the system with the longest orbital period (65.1 ± 0.7 min; Ruiz et al. 2001). The absence of helium absorption and the low effective temperature of $\approx 12,000$ K (Figure 8c) suggest that SDSS J1642 may be of long orbital period (> 50 min) where the accretor is expected to dominate the optical flux.

4. CONCLUSIONS

We have presented four proposed new AM CVn stars, and time-resolved spectroscopy confirming beyond doubt the ultra-compact binary nature of one of them,

SDSS J090221.35+381941.9. This increases the total count of new systems to five, after completing the spectroscopic follow-up fo approx. half of the 1500 candidates in our sample. Based on the present sample completeness (Figure 1) we expect close to 8 more AM CVn stars among the remaining candidates. This already indicates a lower space density than predicted earlier (Roelofs et al. 2007a), btu a detailed population study will be presented in a separate paper after the follow-up program has been completed.

SDSS J0902 is the second confirmed AM CVn star found in our ongoing spectroscopic survey of color-selected candidates from the Sloan Digital Sky Survey, after SDSS J0804 (Roelofs et al. 2009), and has an orbital period of $P_{orb} = 48.31 \pm 0.08$ min. With an apparent temperature of $T_{eff} \approx 14,000$ K, its optical/UV spectrum is at the high end of expectations from theoretical cooling models, assuming gravitational-wave driven evolution. This is becoming a common observational feature and may suggest large component masses in many AM CVns, or angular momentum losses additional to gravitational radiation.

At g=20.23 mag$_{AB}$, SDSS J0902 is near the faint magnitude limit of our sample. Our successful follow-up shows that phase-resolved spectroscopy of faint systems can be obtained at 8–10 m class telescopes within a modest amount of time, thanks to the strong S-wave signals typical of the emission-line AM CVn stars. Similar observations of the other new candidates are encouraged to confirm their ultra-compact binary nature and build up the orbital period distribution, which holds valuable information about the Galactic population as a whole and the physics governing its evolution (e.g. Deloye et al. 2007).
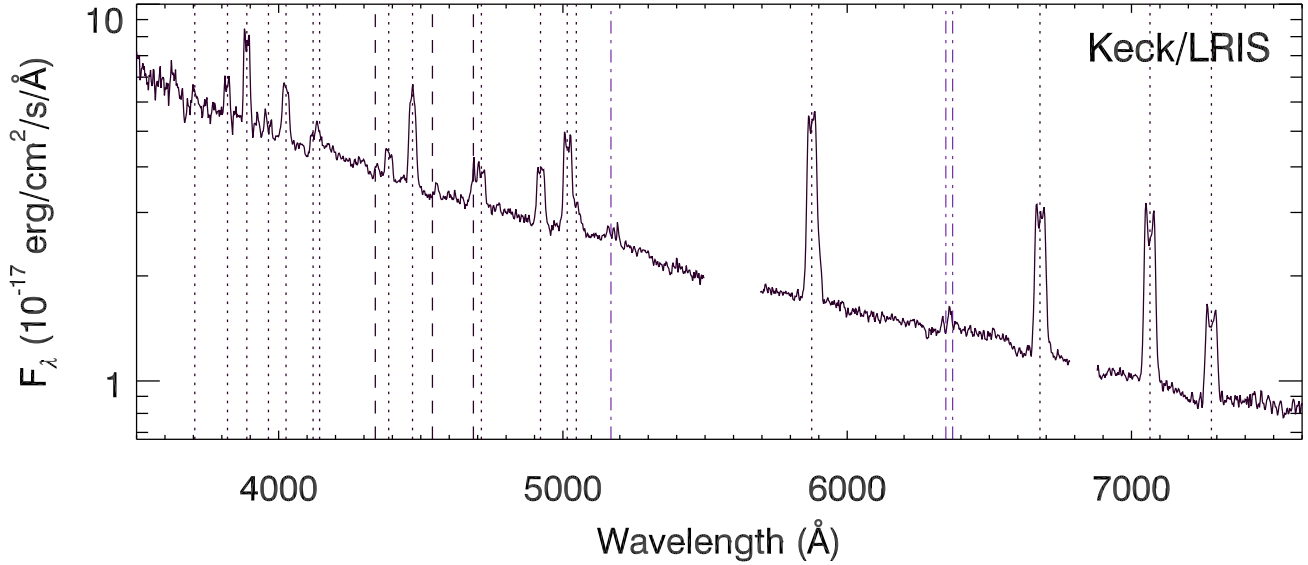
FIG. 6.— Average Keck-I/LRIS spectrum of SDSS J0902. Dotted and dashed lines mark the He I and He II emission features, respectively. The locations of Fe II ($\lambda5169$) and Si II ($\lambda6347, 6371$) in emission are indicated by the dash-dotted lines.
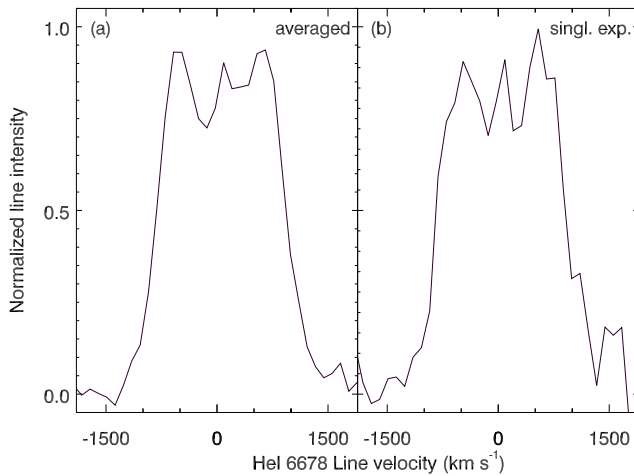

FIG. 7.— Profile of the HeI 6678 emission line in (a) the averaged spectrum of SDSS J0902 and (b) in a single 180 s exposure.

Herschel Telescope, La Palma; and the *GALEX* public archive. We are grateful to D. Koester for kindly making available his white dwarf atmosphere models.

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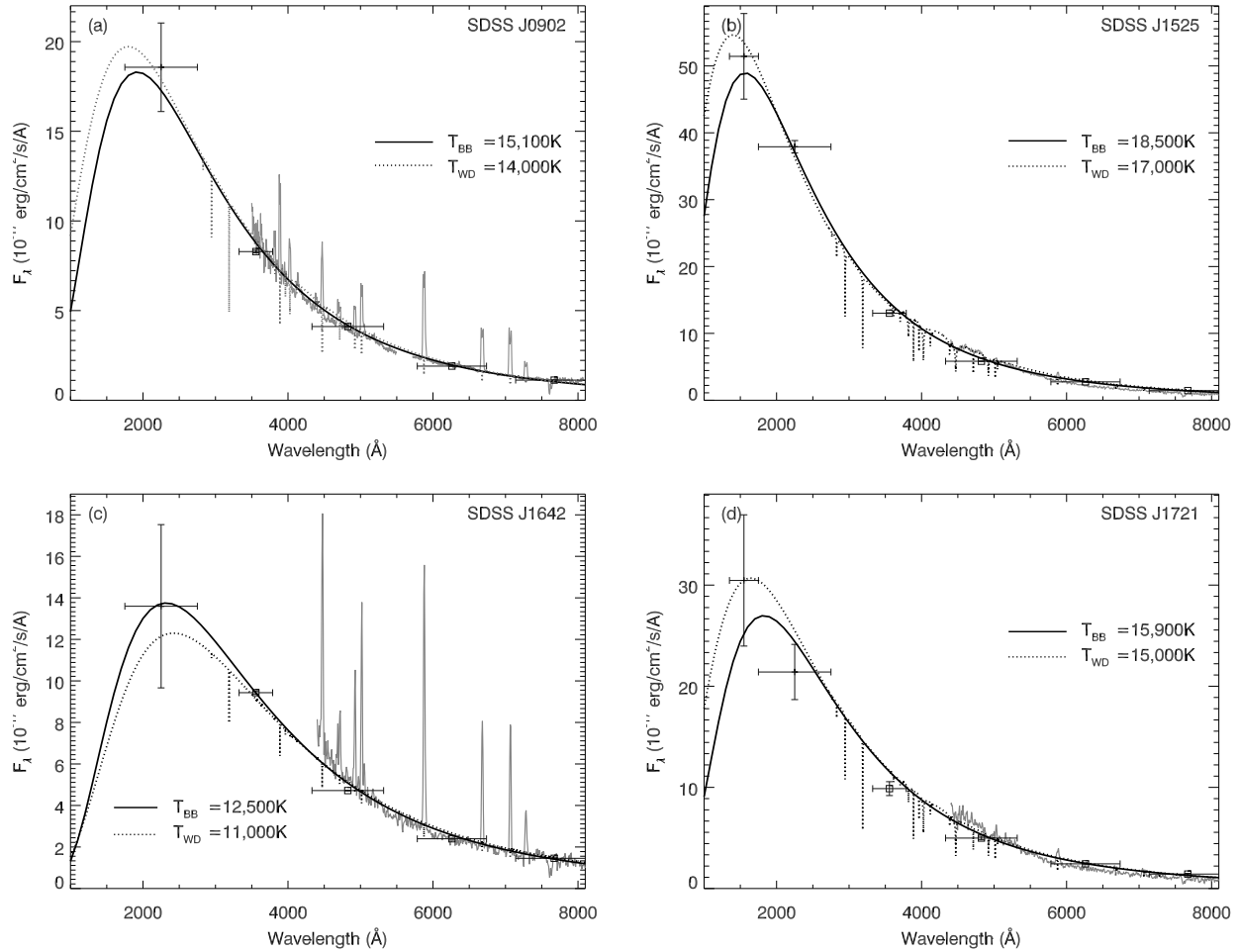
FIG. 8.— Flux-calibrated spectra together with photometry from GALEX GR5 (crosses) and SDSS DR7 (empty squares, see Table 2) for the four new AM CVn candidates. The photometry and specroscopy have been corrected for Galactic foreground extinction. The solid and dotted lines indicate black bodies and helium white dwarf atmosphere models of Koester (2008) with surface gravity log $g = 8$, respectively. The effective temperatures are noted in the panels. Spectrosopic observations of SDSS J0902 (panel a), SDS J1525 (b), and SDSS J1721 (d) have been obtained under non-photometric conditions resulting in considerable uncertainties in the absolute flux calibration. Thus, the spectra have been scaled to the SDSS photometry for visualiziation purpose.

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