Two newly identified magnetic cataclysmic variables discovered in the Sloan Digital Sky Survey (SDSS), SDSS J155331.12+551614.5 and SDSS J132411.57+032050.5, have spectra showing highly prominent, narrow, strongly polarized cyclotron humps with amplitudes that vary on orbital periods of 4.39 and 2.6 hr, respectively. In the former, the spacing of the humps indicates the third and fourth harmonics in a magnetic field of \( \sim 60 \) MG. The narrowness of the cyclotron features and the lack of strong emission lines imply very low temperature plasmas and very low accretion rates, so that the accreting area is heated by particle collisions rather than accretion shocks. The detection of rare systems like these exemplifies the ability of the SDSS to find the lowest accretion rate close binaries.

Subject headings: novae, cataclysmic variables — stars: individual (SDSS J155331.12+551614.5, SDSS J132411.57+032050.5)

1. INTRODUCTION

The commissioning year of the Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002) showed that this survey is highly effective in finding new cataclysmic variables (Szkody et al. 2002). While previous surveys had primarily identified the brightest systems with the highest mass transfer rates, the SDSS photometry in five filters to well beyond the 20th magnitude (Gunn et al. 1998; Fukugita et al. 1996; Hogg et al. 2001; Pier et al. 2003; Smith et al. 2002) is able to find the population of low mass transfer rate, very short orbital period systems that are predicted to exist in close binary evolution models (Howell, Rappaport, & Polittano 1997). Included in this latter group are some systems that contain highly magnetic white dwarfs with field strengths of 6–240 MG, which are termed AM Her systems, or polars (see Warner 1995 for a review of all types of cataclysmic variables).

In the polars, the high field prevents the formation of an accretion disk by directing the ballistic flow of material transferred from the late-type secondary onto one or both magnetic poles of the white dwarf. Different regimes of accretion rate and magnetic field strength are predicted to result in quantitatively different accretion scenarios (Wickramasinghe & Ferrario 2000, hereafter WF00). At the highest specific accretion rates (100 g cm\(^{-2}\) s\(^{-1}\)), high-density blobs carry the mass and energy below the surface of the white dwarf. At intermediate-accretion rates (1 g cm\(^{-2}\) s\(^{-1}\), a standoff shock is formed above the surface, and the gas cools primarily by 10–30 keV thermal bremsstrahlung emission. As the accretion lowers by another factor of 100, the cooling becomes dominated by cyclotron emission until, at the lowest rates, a shock does not form at all, and the energy of the incoming ions is transmitted directly to the atmosphere of the white dwarf in what is termed a “bombardment solution” (Kuipers & Pringle 1982; Fischer & Beuermann 2001). The magnetic field also affects the results in that higher fields tend to produce weaker shocks and possibly more direct heating by blobs beneath the surface (Ramsay et al. 1994). Complicating this picture further is the fact that the accretion rate of polars can change sporadically. Typically, systems in high mass transfer states exhibit strong He II \( \lambda 4686 \) and Balmer emission lines, which dominate the optical spectrum, and strong X-ray and cyclotron emission. At low states of reduced or absent mass transfer, the line emission disappears (except for some narrow Balmer emission from the irradiated secondary star), the X-ray and cyclotron emission is much reduced or absent, and the photospheres of the white dwarf and late secondary are visible.

During low states, the magnetic field may be identified through Zeeman splitting in the photospheric spectrum, but for most systems, the field is determined in high states of accretion from the presence of cyclotron harmonics in the optical and near-IR. Cyclotron opacity is a rapidly
decreasing function of harmonic number, and the high harmonics are strongly angle-dependent, polarized, and broadened with increasing electron temperature (e.g., Chant-mugam 1980; Meggitt & Wickramasinghe 1982). For \( T \lesssim 10 \) keV, the wavelength of the harmonic number \( n \) is simply related to the magnetic field \( B; \lambda_n = (10, 700/n)(10^6/B) \) Å.

Within the above theoretical and empirical framework, observation of the soft and hard X-ray fluxes and of the optical spectral and cyclotron features can elucidate the magnetic field and accretion regime of identified polars. More than 80% of the \( \sim 65 \) known polars were discovered in the \textit{ROSAT} All-Sky Survey (RASS; Voges et al. 1999), with typical count rates for 15th–19th optical magnitudes in the range of 0.2–2.5 counts s\(^{-1}\) (Beuermann & Burwitz 1995). The selection criteria of high X-ray count rate and strong optical emission lines resulted in the discovery of polars in the intermediate-to-high specific accretion rate regimes. Recently, the deep objective prism plates of the Hamburg Quasar survey provided the identification of two polars with extremely low accretion rates (WX LMi = HS 1023+3900: Reimers, Hagen, & Hopp 1999; HS 0922+1333: Reimers & Hagen 2000), and the follow-up of faint \textit{ROSAT} sources yielded two more (RX J012851.9-233931: Schwopf, Schwarz, & Greiner 1999; RX J1007.5–2016: Reinsch et al. 1999). In this paper, we describe two new SDSS polars that are among the most extreme cases of the intriguing cyclotron-dominated systems at the lowest accretion rates. As only a small fraction of the eventual SDSS data have been examined, the survey should discover a modest-sized sample of these previously exotic stars.

2. OBSERVATIONS

The objects SDSS J155331.12+551614.5 and SDSS J132411.57+032050.5 (hereafter abbreviated as SDSS 1553 and SDSS 1324) were automatically selected for SDSS spectroscopy since their unusual SDSS colors \((r = 17.43, u-g = 1.52, g-r = 1.06, r-i = 0.40, \) and \( i-z = 1.00 \)) for SDSS 1553 and \( r = 20.44, g-r = 1.65, r-i = 0.21, i-z = 0.83, \) and \( u-g \approx 1.1 \) for SDSS 1324 with no reddening correction) fell far from the stellar locus and within the selection criteria for quasars (Richards et al. 2002). The SDSS spectra with ~3 Å resolution (Fig. 1) show strong broad cyclotron features at 4600 and 6200 Å in SDSS 1553 and at 5700 Å in SDSS 1324, together with the TiO band features of late-type main-sequence stars. Periodic photometric variability at different wavelengths (Fig. 2) was used to determine the orbital periods. Observations were obtained with the United States Naval Observatory (USNO) 1 m telescope using \( BVRI \) filters calibrated with Landolt standards, with the University of Washington Manastash Ridge Observatory (MRO) 0.76 m telescope with a 1024 \times 1024 pixel Ford Aerospace CCD using a filter similar to the Sloan \( r (\lambda_r \approx 6200 \) Å) and a Harris \( V \) filter, and with the Apache Point Observatory (APO) 3.5 m using the 2048 \times 2048 pixel StTe CCD system SPICam with the Sloan \( r \) filter. Follow-up spectroscopic observations were conducted on SDSS 1553 using the Double Imaging Spectrograph (DIS) on the APO 3.5 m telescope at low resolution (~12 Å) with a 1" slit, providing flux-calibrated data from 3800 to 10000 Å. These observations showed that the cyclotron features are highly variable throughout the orbital period (Fig. 3). Finally, to confirm the suspected magnetic nature of the objects, circular polarization observations were obtained with the CCD Spectropolarimeter SPOL on the 6.5 m MMT and on the Steward Observatory 2.3 m telescope (Figs. 4 and 5). SPOL was used with a low-resolution grating and a 1.1" slit, providing spectral coverage of ~4200–4800 Å at a resolution of ~15 Å. Observations for both objects are summarized in Table 1.

3. SDSS 1553

The nights of MRO and USNO photometry (Fig. 2) reveal periodic, highly modulated light curves. The spectrum (Fig. 1) indicates that the \( r, R, \) and \( V \) filter passbands are dominated by the strong 6200 Å harmonic, while the \( B \) filter contains the 4600 Å harmonic. The \( I \) band shows only a 0.15 mag modulation, which may be due to a harmonic near 9200 Å (see below). The best period determined from combining the five nights of \( r \) data is 0.18297 \pm 0.00004 days (4.39 hr), and Figure 2 shows the data phased on this period (with arbitrary zero phase using the first photometric data point at JD 2,452,164.73527). The sinusoidal shape of the light curve implies that we are seeing the geometrical change associated with the changing viewing angle of a magnetic pole. While the overall sinusoidal shape of the \( V, R, \) and \( r \) light curves suggests that the pole is not self-eclipsed by the white dwarf, i.e., \( i \) (angle of rotation axis to the line of sight) + \( \beta \) (angle between rotation axis and the magnetic pole) is less than 90°, the dip in the \( B \) light curve at phase 0.2 might indicate cyclotron beaming, so there could be a grazing eclipse of part of the accretion spot at phase 0.7.
With this period, we were able to phase the spectroscopic data into an orbital sequence (Fig. 3), which shows the changing amplitude of the cyclotron features. The spacing, the large amplitudes, and the narrow and asymmetric profiles of these features are all indicative of cyclotron emission at low electron temperatures (WF00). The hump locations are consistent with cyclotron harmonics $n = 3$ (6200 Å) and $n = 4$ (4600 Å) in a magnetic field near 58 MG. The narrow widths imply $T_e < 5$ keV. The circular polarization spectrum (Fig. 4) confirms this conclusion by showing that the features are highly polarized, and the large difference in polarization between the 6200 and 4600 Å features shows that the emission changes from marginally optically thick at $n = 3$ to thin at $n = 4$.

It is clear that SDSS 1553 has accretion characteristics that are unlike the majority of polars (WF00). We derived an upper limit of 0.04 counts s$^{-1}$ from the RASS, and this lack of strong X-rays supports a low accretion rate, while the lack of strong Balmer emission lines indicates a greatly reduced ionizing UV flux (Liebert et al. 1978). The weak and narrow Balmer emission may originate from the irradiated secondary, as is common in polars with low mass transfer (Schmidt, Stockman, & Margon 1981), but time-resolved spectropolarimetry at higher spectral resolution is needed to determine the exact viewing and magnetic geometry. While the cyclotron features of most polars show maximum strength when viewed perpendicular to the field lines and maximum circular polarization when viewed along the field lines, the angle dependence of the two is expected to be more similar at low optical depth and lower harmonic number (WF00). This is borne out, in part, in the low-$M$ system RX J1007.5–2016 (Reinsch et al. 1999), where the cyclotron features are at highest intensity when viewed along the field lines.
While many polars show temporary low accretion states, the cyclotron humps present during those low states still indicate high temperature and optical depth (e.g., VV Pup: Visvanathan & Wickramasinghe 1979). SDSS 1553 appears to belong to a rare group of polars with extremely low accretion rates ($\sim 10^{-13} M_\odot$ yr$^{-1}$), plasma temperatures ($< 5$ keV), and specific accretion rates ($10^{-3}$ g cm$^{-2}$ s$^{-1}$) as described by Schwope et al. (1999). These conditions place these polars within the bombardment solution of heating by particle collisions rather than shocks. SDSS 1553 and HS 0922+1333 (Reimers & Hagen 2000) appear to be the most extreme members of this group, based on their lack of X-rays and similarity of cyclotron features, while the others (WX LMi, RX J012851.9–233931, and RX J1007.5–2016) have some X-ray emission and/or weaker and broader cyclotron harmonics.

Using SDSS template stars of late spectral class (Hawley et al. 2002), the TiO band strengths were used to identify an M5 V star (to within one spectral class) in SDSS 1553. Using the mean $i$–$J$ color of $+2.73$ for M5 stars in the Early Data Release, together with an absolute $J$ magnitude of $+9.38$ and a measured Sloan $i$ of $+17.2$, we infer a distance modulus for SDSS 1553 in Sloan $i$ of $+5.1$, or a distance of 100 pc. However, it should be noted that several studies (Friend et al. 1990; Beuermann et al. 1998; Harrison et al. 2000) have found that the secondary stars in cataclysmic variables may not be like zero-age main-sequence stars.

Subtracting the M5 V secondary from the APO spectra reveals the expected n = 2 cyclotron harmonic near $\sim 9200$ Å. With the secondary as well as the large cyclotron features removed, the remaining flux was matched to the flux of DA white dwarfs at various temperatures (Hubeny & Lanz 1995), with a radius of $8 \times 10^8$ cm and a distance of 100 pc. This gave an upper limit of 10,000 K to the temperature of the underlying white dwarf, assuming no continuum contribution from the cyclotron emission. Polars with periods of greater than 3 hr generally have white dwarfs with temperatures of $\geq 20,000$ K (Sion 1999). Thus, it appears that SDSS 1553 contains a very cool white dwarf or, alternatively, its radius could be unusually small ($M \geq 0.6 M_\odot$). It is interesting that HS 0922+1333, with a period of 4.1 hr, also appears to contain a cool white dwarf (Reimers & Hagen 2000).

### Table 1
Summary of Observations

| SDSS | UT Date      | Observatory | Data     | Exposure (minutes × N) | Length (hr) |
|------|--------------|-------------|----------|------------------------|-------------|
| 1553 | 2001 Mar 23  | SDSS        | ugriz    | 1 × 1                  | 0.02        |
| 1553 | 2001 May 26  | SDSS        | Spectrum | 87 × 1                 | 1.5         |
| 1553 | 2001 Sep 2   | APO         | DIS spectra | 10–20 × 2  | 0.5         |
| 1553 | 2001 Sep 3   | APO         | DIS spectra | 10–15 × 3  | 0.6         |
| 1553 | 2001 Sep 4   | APO         | DIS spectra | 10–15 × 2  | 0.4         |
| 1553 | 2001 Sep 12  | MRO         | CCD filter $r$ | 5 × 5      | 5.0         |
| 1553 | 2001 Sep 12  | APO         | DIS spectra | 10 × 3      | 0.8         |
| 1553 | 2001 Sep 14  | MRO         | CCD filter $r$ | 5 × 10     | 5.0         |
| 1553 | 2001 Sep 15  | MRO         | CCD filter $r$ | 5 × 57     | 5.3         |
| 1553 | 2001 Sep 15  | USNO        | CCD $BVRI$ | 1–3 × 6     | 1.8         |
| 1553 | 2001 Sep 17  | MRO         | CCD filter $V$ | 5–10 × 30 | 3.9         |
| 1553 | 2001 Sep 18  | APO         | DIS spectra | 10 × 9     | 1.9         |
| 1553 | 2001 Sep 19  | APO         | DIS spectra | 10 × 13     | 2.4         |
| 1553 | 2001 Sep 20  | MRO         | CCD filter $r$ | 5 × 5      | 4.7         |
| 1553 | 2001 Sep 21  | MRO         | CCD filter $r$ | 5 × 9     | 0.8         |
| 1553 | 2001 Sep 21  | USNO        | CCD $BVRI$ | 1–3 × 7     | 2.1         |
| 1553 | 2001 Sep 25  | USNO        | CCD $BVRI$ | 1–3 × 8     | 2.1         |
| 1553 | 2002 Feb 7   | MMT         | SPOL     | 24 × 1     | 0.4         |
| 1324 | 2002 May 5   | SDSS        | ugriz    | 1 × 1      | 0.02        |
| 1324 | 2002 Mar 8   | SDSS        | Spectrum | 85 × 1     | 1.4         |
| 1324 | 2002 Mar 24  | APO         | CCD filter $r$ | 10 × 14    | 3.5         |
| 1324 | 2002 Mar 30  | APO         | CCD filter $r$ | 10 × 21     | 4.2         |
| 1324 | 2002 May 8   | SO          | SPOL     | 20 × 7     | 2.2         |
accretion rate system of all known so far. The spectrum (Fig. 1) is dominated by a large-amplitude, narrow cyclotron feature near 5700 Å and a second possible feature at 4250 Å. These could be the third and fourth harmonics in a field near 63 MG. The spectropolarimetry (Fig. 5) shows that the 5700 Å feature is highly circularly polarized. As in SDSS 1553, the $r$ light curve of SDSS 1324 (Fig. 6) shows a sinusoidal modulation of high amplitude (1.3 mag amplitude) on a roughly 2.6 hr timescale, likely indicating a large modulation of the cyclotron feature throughout the orbit. Once again, the underlying contribution from the white dwarf must be very small. We derive an upper limit of 0.02 counts s$^{-1}$ from the RASS, even lower than SDSS 1553.

5. CONCLUSIONS

Our photometry, spectroscopy, and polarimetry of the SDSS source SDSS 1553 have revealed a polar system with an orbital period of 4.39 hr. The spectrum is dominated by extreme-amplitude, highly polarized cyclotron harmonics near 6200 and 4600 Å, indicating a white dwarf magnetic field strength of 58 MG, and TiO features from an M5 V secondary star, indicating a distance of 100 pc. Similar cyclotron features and photometric variability in SDSS 1324 indicate a polar with an orbital period near 2.6 hr. The narrowness and extreme amplitude of the cyclotron features imply that these systems are in the regime of low plasma temperature and very low specific accretion rates (the bombardment solution), where the accreting area is heated by particle collisions and the accretion luminosity appears as cyclotron radiation. The low count rates in the RASS (<0.04 counts s$^{-1}$) support this view. With its ability to probe a wide variety of stellar systems, the SDSS is contributing to a less biased view of the conditions in polars, especially at low mass transfer rates.

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REFERENCES

Beuermann, K., Baraffe, I., Kolb, U., & Weichhold, M. 1998, A&A, 339, 518
Beuermann, K., & Burwitz, V. 1995, in ASP Conf. Ser. 85, Cape Workshop on Magnetic Cataclysmic Variables, ed. D. A. H. Buckley & B. Warner (San Francisco: ASP), 99
Chamnumg, G. 1980, ApJ, 241, 1122
Fischer, A., & Beuermann, K. 2001, A&A, 373, 211
Friend, M. T., Martin, J. S., Smith, R. C., & Jones, D. H. P. 1990, MNRAS, 246, 637
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Gunn, J. E., et al. 1998, AJ, 116, 3040
Harrison, T. E., McNamara, B. J., Szkody, P., & Gilliland, R. L. 2000, AJ, 120, 2649
Hawley, S. L., et al. 2002, AJ, 123, 3409
Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., & Gunn, J. E. 2001, AJ, 122, 2129
Howell, S. B., Rappaport, S., & Politano, M. 1997, MNRAS, 287, 929
Hubeny, I., & Lanz, T. 1995, ApJ, 439, 875
Kuijpers, J., & Pringle, J. E. 1982, A&A, 114, L4
Liebert, J., Stockman, H. S., Angel, J. R. P., Woolf, N. J., Hege, K., & Margon, B. 1978, ApJ, 225, 201

$\text{Sloan}_{r}$ SDSS1324

Fig. 6.—APO light curve of SDSS 1324 in a Sloan $r$ filter on 2002 March 30, showing a modulation at a period near 2.6 hr. Magnitudes were obtained relative to comparison stars on each frame and have uncertainties of 0.03 (at 20.5 mag) to 0.1 (at 22 mag).

12 The SDSS Web site is located at http://www.sdss.org/.

Meggitt, S. M. A., & Wickramasinghe, D. T. 1982, MNRAS, 198, 71
Pier, J. R., et al. 2003, AJ, in press
Ramsay, G., Mason, K. O., Cropper, M., Watson, M. G., & Clayton, K. L. 1994, MNRAS, 270, 692
Reimers, D., & Hagen, H.-J. 2000, A&A, 358, L45
Reimers, D., & Hagen, H.-J., & Hopp, U. 1999, A&A, 343, 157
Reinsch, K., Burwitz, V., Beuermann, K., & Thomas, H-C. 1999, in ASP Conf. Ser. 157, Annapolis Workshop on Magnetic Cataclysmic Variables, ed. C. Hellier & K. Mukai (San Francisco: ASP), 187
Richards, G. T., et al. 2002, AJ, submitted
Schmidt, G. D., Stockman, H. S., & Margon, B. 1981, ApJ, 243, L157
Schwope, A. D., Schwarz, R., & Greiner, J. 1999, A&A, 346, 861
Sion, E. M. 1999, PASP, 111, 332
Smith, J. A., et al. 2002, AJ, 123, 2121
Stoughton, C., et al. 2002, AJ, 123, 485
Szkody, P., et al. 2002, AJ, 123, 430
Visvanathan, N. V., & Wickramasinghe, D. T. 1979, Nature, 281, 47
Voges, W., et al. 1999, A&A, 349, 389
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press)
Wickramasinghe, D. C., & Ferrario, L. 2000, PASP, 112, 873 (WF00)
York, D. G., et al. 2000, AJ, 120, 1579