THE ASTROPHYSICAL JOURNAL, 625:966–972, 2005 June 1

ELEVEN NEW DA WHITE DWARF VARIABLE STARS FROM THE SLOAN DIGITAL SKY SURVEY

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Received 2005 January 24; accepted 2005 February 23

ABSTRACT

We report the discovery of 11 new variable DA white dwarf (ZZ Ceti) stars. Candidates were selected by deriving temperatures from model fits to spectra obtained from the Sloan Digital Sky Survey (SDSS). We also find objects whose temperatures and gravities indicate they lie within the instability strip for pulsation but were not observed to vary. Although the temperatures are based on relatively low signal-to-noise ratio spectra, an impure strip is unexpected, which if confirmed, has implications for DA asteroseismology. This work brings the total number of published variable DA white dwarf stars to 82.

Subject headings: stars: oscillations — white dwarfs

Online material: color figures

1. INTRODUCTION

The relatively simple structure and behavior of white dwarf stars (WDs) make them ideal objects for astrophysical study. For the variable WDs, asteroseismology allows us a rare glimpse into the interior of a stellar object. WDs pulsate in three distinct instability strips along the H-R diagram. The extremely high gravity of these objects makes nonradial gravity modes energetically favorable (Winget 1998 and references therein). Of interest in this paper are the hydrogen atmosphere white dwarf stars (known as DAs), which pulsate at temperatures between approximately 11,000 and 12,000 K (Mukadam et al. 2004a). We previously believed that variability was a normal part of the evolution of a cooling WD (Fontaine et al. 1982; Bergeron et al. 2004), so these pulsating WDs (or DAVs) are otherwise normal stars caught during the brief period of evolution in which their temperatures allow pulsation. However, recent analysis by Mukadam et al. (2004b) has shown the presence of nonvariable stars within the strip, indicating either that the models used for fitting temperatures need refinement or that an additional third parameter determining the pulsation properties of these objects is present. This is an important concern in the application of the conclusions of DA asteroseismology to other DAs.

A hot subset of the variable DAs (known as hDAVs) were discovered to exhibit extreme stability in the period and phase of their pulsations (Stover et al. 1980; Kepler et al. 1982). Kepler (2005) showed that one such star, G117-B15A, has a period stability of $\dot{P} = (4.12 \pm 0.83) \times 10^{-15}$, a stability that rivals that of atomic clocks. Mukadam et al. (2003) constrained the stability of ZZ Ceti to better than $(5.5 \pm 1.9) \times 10^{-15}$.

With such a stable signal the presence of an orbiting planet can be inferred from variations in the observed arrival time of pulsations due to the reflex orbital motion of the star. The first limits on planetary mass companions to white dwarf stars were placed by Kepler et al. (1988). For this paper, our search for new variables was biased toward the hot edge of the strip where these stable pulsators, suitable for searching for planets, are to be found.

A key constraint on both the prior progress of asteroseismology and the search for planetary companions was the limited number of suitable stars available for study. For that reason, Mukadam et al. (2004a) performed a photometric search and discovered 35 new DAVs. This search is ongoing, and in this paper we report 11 new stars to make them available to the wider community. We refer the reader to Mukadam et al. (2004a) for a full description of this program.

2. OBJECT SELECTION AND OBSERVATION

The Sloan Digital Sky Survey (SDSS; Fukugita et al. 1996; Gunn et al. 1998; York et al. 2000; Hogg et al. 2001; Smith et al. 2002; Stoughton et al. 2002; Pier et al. 2003) is proving to be an impressive source of new WDs (Kleinman et al. 2004). We obtained candidate DAVs from both the Data Release 1 (DR1; Abazajian et al. 2003) and Data Release 2 (DR2; Abazajian et al. 2004) samples. Objects from DR1 were selected from the catalog of Kleinman et al. (2004) using temperature fits based on models published in Finley et al. (1997).

Objects from DR2 (which do not appear in Kleinman et al. 2004) with spectra were also selected. DA stars near the DA instability strip are easily identifiable because of their very broad Balmer lines caused by their very high surface gravity and by the fact that the Balmer lines are maximally broad near the temperature range of the instability strip (Fontaine et al. 2003). For each spectrum in the database we measured the equivalent widths of the Hβ and Hγ lines over the wavelength region given in Table 1. Objects in the range $40 < \mathrm{H}\beta < 65$ and $20 < \mathrm{H}\gamma < 45$ were selected and a color cut of $0.2 \leq (u - g) \leq 0.7$, $-0.4 \leq (g - r) \leq 0.05$, and $9.5(u - g) - (g - r) > 4.14$ was used to further trim the sample. The third cut removes DAs with Balmer lines of appropriate equivalent width but on the hotter side of the curve of growth (≈15,000 K). The temperatures and gravities of the selected DAVs were found by fitting to a grid of temperature models as described in Kleinman et al. (2004).

Objects were observed and reduced as described in Mukadam et al. (2004a). Each object was observed for 2 hr on the 2.1 m Otto Struve telescope at McDonald Observatory using the Argos prime focus CCD camera (Nather & Mukadam 2004). Individual exposure times were between 5 and 15 s, depending on the brightness of the target, and readout times were negligible because of

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TABLE 1

Wavelengths Used to Calculate Equivalent Width of Balmer Lines

Line	Center (Å)	Width (Å)
Hβ	4861.3	324
Hγ	4340.5	214

the use of a frame transfer buffer. If an object showed signs of variability it was reobserved on a later night for confirmation. Faint objects or those observed under poor conditions may appear to show variability, so a second run is required to confirm variability. If an object did not appear to pulsate, it was not reobserved. Many DAVs present closely spaced modes that can destructively interfere, effectively hiding a mode for periods longer than 2 hr. However, the aim of this survey is to find as many pulsators as possible with the telescope time available, not to conduct a complete search of the sample, and so stars that did not appear to vary were not reobserved.

The CCD images were flat-fielded and light curves extracted using IRAF's weighted aperture *appphot* package.[5] We subtract the contribution from sky photons and divide by a combination of reference stars to remove small cloud variations.

We discovered 11 new DAVs and 26 stars that were not observed to vary. A journal of observations of the new pulsators appears in Table 2. Light curves and Fourier transforms of the new pulsators are shown in Figures 1 and 2. Table 3 lists the observed periods and amplitudes of pulsation. The high number of nonvariables is due to an unsuccessful attempt to use a different method to measure the stellar temperatures. Our instability strip is similar to that discovered in Mukadam et al. (2004a), which is to be expected, as we are using the same temperature fitting technique.

3. CHARACTERISTICS OF THE INSTABILITY STRIP

A plot of the location of the new variables within the instability strip is shown in Figure 3. A table of the properties of the variables is presented in Table 4 and those stars not observed to vary in Table 5. The term "nonvariable" is fraught with danger, as a star may be exhibiting destructive interference between two closely spaced modes while being observed, or it may merely be pulsating with too low an amplitude to be detected. For this reason, we prefer to use the term "not observed to vary" (NOV).

The uncertainties in Figure 3 and Tables 4 and 5 are the formal least-squares fit errors. In an effort to determine the extent of external errors in DAV temperature fits, Fontaine et al. (2003) compared the measured effective temperature of a number of DAs in the region of the instability strip as measured from two independently observed and reduced spectra of each object. They conclude that the external errors, due primarily to different flux calibrations, were ~200 K. It should be noted that paper uses spectra with signal-to-noise ratios (S/Ns) of greater than 80 pixel^{-1}, while our faintest star, SDSS J173712 ($g = 19.2$) has an S/N of less than 8. Mukadam et al. (2004b), using similar spectra from the Sloan survey that are observed and reduced in a consistent manner, estimate an uncertainty in $T_{\rm eff}$ of less than 300 K for the fainter stars and 200 K for the brighter stars.

TABLE 2

Journal of Observations

Run	Object Name	UTC Date	Start Time	Exp. (s)	Length
A0752	SDSS J001836.11+003151.1	2003 Nov 19	03:05:56	15	02:05:45
A0762	SDSS J001836.11+003151.1	2003 Nov 21	04:18:46	15	02:05:00
A0794	SDSS J001836.11+003151.1	2003 Dec 1	00:55:45	10	04:42:00
A0701	SDSS J004855.17+152148.7	2003 Sep 4	08:10:40	15	01:40:00
A0706	SDSS J004855.17+152148.7	2003 Sep 5	09:09:51	15	01:52:15
A0860	SDSS J075617.54+202010.2	2004 Mar 18	01:54:49	10	03:08:20
A0864	SDSS J075617.54+202010.2	2004 Mar 19	02:03:04	10	04:55:00
A0831	SDSS J081828.98+313153.0	2004 Jan 19	03:57:18	10	03:26:40
A0849	SDSS J081828.98+313153.0	2004 Mar 1	01:58:28	10	02:51:20
A0836	SDSS J091312.74+403628.7	2004 Jan 20	07:43:18	10	01:44:20
A0866	SDSS J091312.74+403628.7	2004 Mar 20	02:03:26	10	05:00:10
A0861	SDSS J100238.58+581835.9	2004 Mar 18	05:11:27	10	03:06:40
A0870	SDSS J100238.58+581835.9	2004 Mar 24	05:05:08	10	01:23:00
A0635	SDSS J100718.26+524519.8	2003 May 6	02:42:38	15	03:51:15
A0869	SDSS J100718.26+524519.8	2004 Mar 24	02:01:27	15	01:45:45
A0833	SDSS J105449.87+530759.1	2004 Jan 19	09:45:01	10	03:19:30
A0867	SDSS J105449.87+530759.1	2004 Mar 20	07:14:37	10	02:45:50
A0862	SDSS J135531.03+545404.5	2004 Mar 18	08:25:51	15	02:03:00
A0873	SDSS J135531.03+545404.5	2004 Mar 25	09:25:52	15	02:43:00
A0880	SDSS J135531.03+545404.5	2004 May 14	02:58:42	15	05:09:00
A0430	SDSS J215905.52+132255.7	2002 Dec 8	00:53:08	15	01:53:00
A0673	SDSS J215905.52+132255.7	2003 Jul 2	09:22:30	15	01:43:45
A0670	SDSS J221458.37−002511.7	2003 Jul 1	08:37:02	10	02:36:20
A0692	SDSS J221458.37−002511.7	2003 Sep 2	04:35:53	10	03:59:50
A0723	SDSS J221458.37−002511.7	2003 Oct 25	01:15:40	10	04:18:30
A0761	SDSS J221458.37−002511.7	2003 Nov 21	00:54:57	10	03:15:30
A0783	SDSS J221458.37−002511.7	2003 Nov 28	01:01:22	10	02:55:00

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[5] IRAF 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 (NSF).

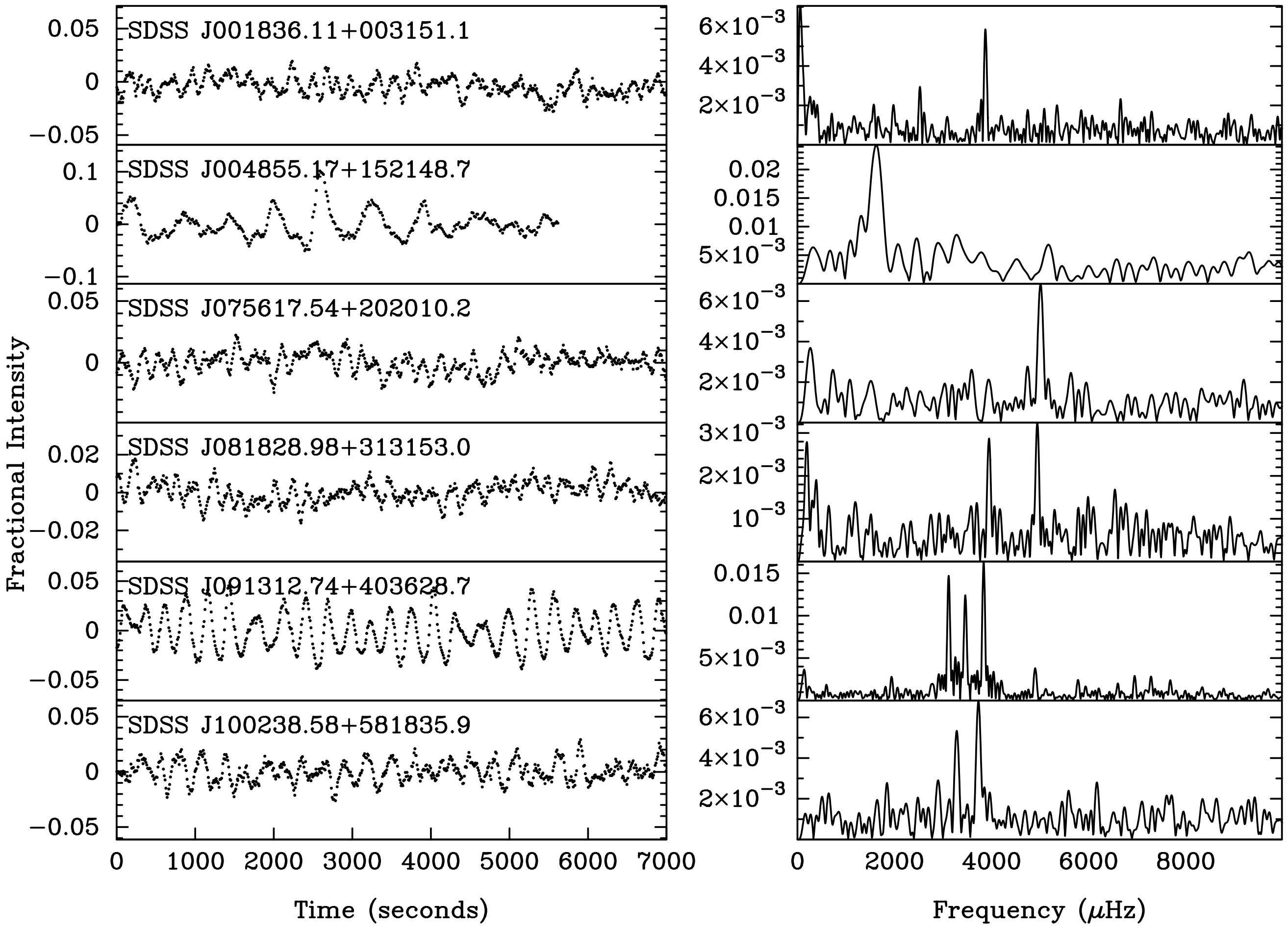

FIG. 1.—Two hr portions of light curves for the new pulsators. The light curves have been boxcar-smoothed by seven points to emphasize the pulse shapes. The Fourier transforms in the right column are of the unsmoothed data and may be taken from longer data sets.

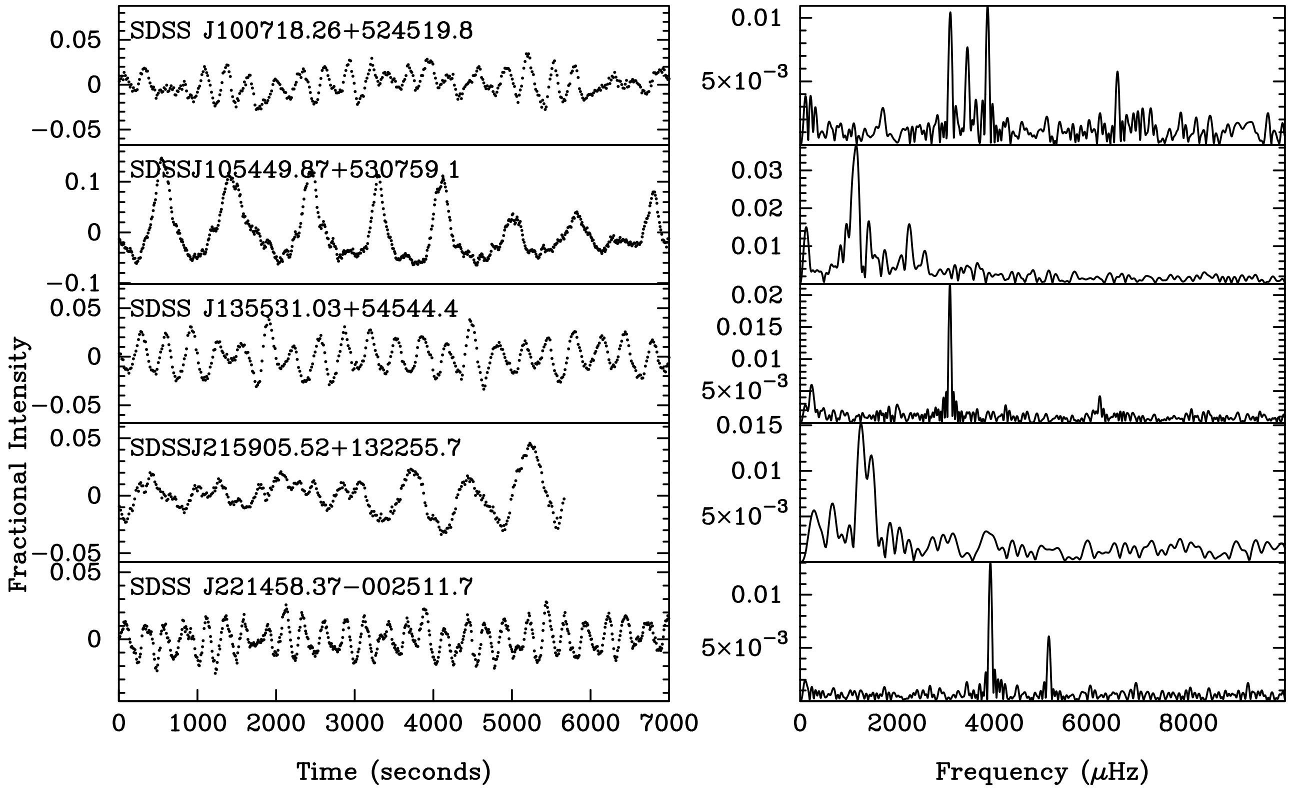

FIG. 2.—Same as Fig. 1, but for five additional pulsators.

TABLE 3

Observed Periods and Amplitudes

Object	Resolution (μHz)	Frequency (μHz)	Period (s)	Amplitude (%)
SDSS J001836.11+003151.1	59	3876	257.9	0.58
SDSS J004855.17+152148.7	145	1625*	615.3	2.48
SDSS J075617.54+202010.2	56	5011	199.5	0.68
SDSS J081828.98+313153.0	81	3947*	253.3	0.29
		4942	202.3	0.33
SDSS J091312.74+403628.7	56	3119*	320.5	1.47
		3462	288.7	1.24
		3841*	260.3	1.65
		4903	203.9	0.38
SDSS J100238.58+581835.9	89	3282	304.6	0.53
		3728	268.2	0.68
SDSS J100718.26+524519.8	72	3094*	323.1	1.04
		3446	290.1	0.77
		3863*	258.8	1.10
		6540	152.8	0.58
SDSS J105449.87+530759.1	101	1150*	869.1	3.74
		2248	444.6	1.60
SDSS J135531.03+545404.4	54	3086	324.0	2.18
SDSS J215905.52+132255.7	147	1248	801.0	1.51
		1462*	683.7	1.17
SDSS J221458.37−002511.7	65	3917	255.2	1.31
		5122	195.2	0.61

Notes.—We do not have the resolution in our data sets to resolve multiplets or closely spaced modes for most of these stars. Objects marked with an asterisk show evidence of amplitude variability between runs. The resolution quoted is reciprocal of the length of the run.

Our enlarged sample of DAVs has the same characteristics as the sample published in Mukadam et al. (2004a). Our survey emphasized the blue edge of the instability strip, which is why we found more pulsators hotter than 11,500 K than cooler. With this bias in mind, our new sample still supports the narrower strip found in Mukadam et al. (2004b). We note that two stars not observed to vary, SDSS J143249 and SDSS J012234, lie within the strip. It is possible that these objects are complex pulsators whose modes were destructively interfering for the time they were observed, or it may be simply that their amplitude was too low to be observed. If further observations address those concerns, these objects lend support to the arguments in Mukadam et al. (2004b) that the DA instability strip is impure.

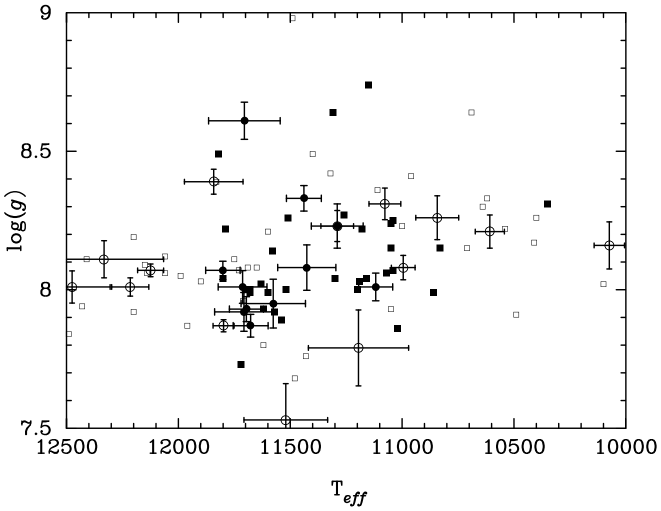

Fig. 3.—Distribution of effective temperatures and gravities of DAVs discovered in the SDSS. The filled shapes are pulsators, and open shapes are NOVs. Circles are stars reported in this paper, while squares are from Mukadam et al. (2004a). For clarity, error bars are only shown for objects reported in this paper; those in Mukadam et al. (2004a) are similar in size. [*See the electronic edition of the Journal for a color version of this figure.*]

This work is supported by a grant from the NASA Origins program, NAG5-13094 and performed in part under contract with the Jet Propulsion Laboratory (JPL) funded by the National Aeronautics and Space Administration (NASA) through the Michelson Fellowship Program. JPL is managed for NASA by the California Institute of Technology. We also acknowledge the support of the Texas Advanced Research Program under grant ARP-0543. Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, NASA, the NSF, the Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, the Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max Planck Institute for Astronomy (MPIA), the Max Planck Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, Princeton University, the United States Naval Observatory, and the University of Washington. We thank D. Schneider for his constructive criticisms of an early draft of this manuscript.

TABLE 4

Properties of New DAVs

MJD	Plate	Fiber	Designation	$T_{\rm eff}$	log g	Hβ	Hγ	$u - g$	$g - r$	g
52,203	0688	348	SDSS J001836.11+003151.1	11,696 ± 076	7.93 ± 0.045	52.66 ± 0.81	32.70 ± 0.59	0.452	−0.160	17.360
51,871	0420	388	SDSS J004855.17+152148.7	11,290 ± 116	8.23 ± 0.080	52.51 ± 1.58	37.41 ± 1.13	0.401	−0.109	18.676
52,941	1583	167	SDSS J075617.54+202010.2	11,713 ± 109	8.01 ± 0.059	54.92 ± 1.33	36.07 ± 0.98	0.465	−0.150	18.240
52,619	0931	321	SDSS J081828.98+313153.0	11,801 ± 077	8.07 ± 0.033	55.25 ± 0.80	38.65 ± 0.57	0.382	−0.185	17.381
52,668	1200	017	SDSS J091312.74+403628.8	11,677 ± 078	7.87 ± 0.041	53.90 ± 1.02	37.78 ± 0.71	0.495	−0.224	17.635
52,317	0558	573	SDSS J100238.58+581835.9	11,707 ± 131	7.92 ± 0.070	54.82 ± 1.32	36.83 ± 0.95	0.480	−0.201	18.264
52,400	0903	557	SDSS J100718.26+524519.8	11,426 ± 130	8.08 ± 0.082	56.47 ± 1.68	37.61 ± 1.19	0.414	−0.162	18.872
52,649	1010	629	SDSS J105449.87+530759.1	11,118 ± 076	8.01 ± 0.050	50.81 ± 1.02	37.85 ± 0.71	0.451	−0.156	17.922
52,797	1323	161	SDSS J135531.03+545404.5	11,576 ± 144	7.95 ± 0.088	52.32 ± 1.48	36.70 ± 1.05	0.398	−0.146	18.583
52,224	0734	419	SDSS J215905.52+132255.7	11,705 ± 160	8.61 ± 0.067	54.86 ± 1.75	37.52 ± 1.28	0.381	−0.193	18.873
51,791	0374	180	SDSS J221458.37−002511.7	11,439 ± 078	8.33 ± 0.046	52.41 ± 1.06	36.63 ± 0.77	0.334	−0.099	17.909

TABLE 5

Table of Objects Not Observed To Vary

MJD	Plate	Fiber	Designation	$T_{\rm eff}$	log g	Hβ	Hγ	$u-g$	$g-r$	g	Limit (%)
51,900............	0390	455	SDSS J002049.39+004435.0	9160 ± 10	9.00 ± 0.003	25.60 ± 0.74	15.47 ± 0.55	0.238	0.058	16.797	0.1
52,203............	0688	164	SDSS J002309.03−003342.0	15,522 ± 81	8.01 ± 0.016	55.56 ± 0.49	38.94 ± 0.34	0.242	−0.300	16.280	0.1
51,879............	0419	098	SDSS J004610.37+133910.2	11,077 ± 71	8.31 ± 0.057	52.31 ± 1.24	33.07 ± 0.90	0.404	−0.132	18.040	0.2
51,871............	0420	591	SDSS J005703.73+151014.6	10,074 ± 68	8.16 ± 0.085	43.11 ± 1.76	23.76 ± 1.32	0.546	−0.063	18.850	0.4
52,209............	0696	476	SDSS J012234.67+003026.3	11,798 ± 47	7.87 ± 0.022	55.66 ± 0.61	34.94 ± 0.42	0.355	−0.073	17.286	0.2
52,178............	0702	448	SDSS J020851.65+005332.4	13,401 ± 150	7.77 ± 0.024	58.75 ± 0.64	38.40 ± 0.44	0.386	−0.270	16.960	0.2
51,869............	0406	385	SDSS J022108.67+004924.7	10,608 ± 65	8.21 ± 0.060	46.24 ± 1.57	35.73 ± 1.11	0.457	−0.124	18.632	0.2
51,816............	0410	501	SDSS J025709.00+004628.0	12,215 ± 83	8.01 ± 0.033	57.51 ± 0.84	38.97 ± 0.60	0.418	−0.206	17.387	0.2
52,203............	0710	548	SDSS J031111.38−000344.4	14,537 ± 197	8.32 ± 0.040	63.66 ± 0.93	37.63 ± 0.66	0.295	−0.200	17.870	0.3
51,929............	0413	074	SDSS J032302.85+000559.6	13,030 ± 158	7.98 ± 0.041	59.63 ± 0.89	42.24 ± 0.62	0.785	−0.220	17.436	0.4
51,901............	0414	273	SDSS J032510.84−011114.1	18,267 ± 86	7.59 ± 0.017	46.27 ± 0.74	30.97 ± 0.55	0.446	−0.191	17.073	0.3
51,901............	0414	454	SDSS J032619.44+001817.5	12,124 ± 58	8.07 ± 0.023	58.08 ± 0.87	38.25 ± 0.61	0.387	−0.207	17.420	0.6
51,810............	0415	206	SDSS J033200.49−005752.5	17,476 ± 109	7.77 ± 0.023	45.24 ± 0.78	32.68 ± 0.54	0.227	−0.299	17.062	0.2
52,370............	0771	225	SDSS J101218.09+610818.9	11,842 ± 131	8.39 ± 0.045	55.39 ± 1.01	36.78 ± 0.74	0.399	−0.188	17.733	0.2
52,378............	0838	144	SDSS J114132.99+042028.8	11,520 ± 187	7.53 ± 0.131	49.85 ± 1.31	36.37 ± 0.94	0.524	−0.222	18.186	0.5
51,984............	0498	234	SDSS J140004.68+643128.3	10,995 ± 53	8.08 ± 0.044	48.85 ± 1.05	36.05 ± 0.74	0.467	−0.206	17.671	0.3
52,024............	0536	318	SDSS J143249.11+014615.5	11,290 ± 73	8.23 ± 0.056	52.60 ± 0.96	38.12 ± 0.70	0.540	−0.170	17.484	0.2
52,045............	0594	478	SDSS J154545.35+032150.0	15,652 ± 272	7.97 ± 0.054	54.98 ± 1.67	36.45 ± 1.19	0.329	−0.242	18.753	0.3
52,395............	0818	476	SDSS J164248.61+382411.1	18,813 ± 204	8.40 ± 0.035	51.50 ± 1.20	34.64 ± 0.83	0.076	−0.322	17.952	0.3
52,438............	0820	516	SDSS J165815.53+363816.0	10,843 ± 96	8.26 ± 0.079	50.22 ± 1.98	30.05 ± 1.46	0.455	−0.119	19.162	0.5
52,017............	0366	629	SDSS J173712.95+584428.7	11,195 ± 224	7.79 ± 0.137	49.37 ± 2.14	37.36 ± 1.50	0.517	−0.182	19.266	0.3
52,224............	0734	348	SDSS J215532.95+123801.5	12,332 ± 266	8.11 ± 0.067	55.03 ± 1.34	38.07 ± 0.97	0.376	−0.223	18.338	0.2
52,518............	0737	226	SDSS J222223.04+123824.7	13,888 ± 142	7.58 ± 0.030	53.84 ± 0.87	40.60 ± 0.59	0.388	−0.235	17.63	0.1
52,263............	0740	601	SDSS J225211.51+143610.5	17,027 ± 219	7.86 ± 0.044	49.09 ± 1.25	32.85 ± 0.87	0.213	−0.286	18.148	0.2
52,251............	0744	273	SDSS J231152.20+142417.2	12,475 ± 170	8.01 ± 0.058	57.03 ± 1.30	39.03 ± 0.95	0.448	−0.227	18.251	0.3
52,553............	0647	126	SDSS J233742.20−104144.0	16,164 ± 109	7.89 ± 0.024	52.29 ± 0.79	36.73 ± 0.54	0.168	−0.293	17.188	0.3

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