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A SECOND STELLAR COLOR LOCUS: A BRIDGE FROM WHITE DWARFS TO M STARS

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ABSTRACT

We report the discovery of a locus of binary stars in the Sloan Digital Sky Survey (SDSS) $g-r$ versus $u-g$ color-color diagram that connects the colors of white dwarfs and M dwarfs. While its contrast with respect to the main stellar locus is only ∼1 : 2300, this previously unrecognized feature includes 863 stars from the SDSS Data Release 1 (DR1). The position and shape of the feature are in good agreement with predictions of a simple binary star model that consists of a white dwarf and an M dwarf, with the components' luminosity ratio controlling the position along this binary system locus. SDSS DR1 spectra for 47 of these objects strongly support this model. The absolute magnitude–color distribution inferred for the white dwarf component is in good agreement with the models of Bergeron et al.

Subject headings: binaries: general — Galaxy: stellar content — stars: statistics — white dwarfs

Online material: color figures

1. INTRODUCTION

Modern large-scale, accurate photometric surveys offer an unprecedented view of stellar populations. Here we discuss a population of unresolved binary stars that account for fewer than 10^{-3} of stars detected by the Sloan Digital Sky Survey (SDSS; York et al. 2000). Despite this low occurrence frequency, the sample presented here is sufficiently large (∼1000 stars) to characterize their broadband optical properties.

1.1. *Sloan Digital Sky Survey*

The Sloan Digital Sky Survey (Abazajian et al. 2003 and references therein) is revolutionizing stellar astronomy by providing homogeneous, deep ($r < 22.5$ mag) photometry in five passbands (u, g, r, i, and z; Fukugita et al. 1996; Gunn et al. 1998; Hogg et al. 2001; Smith et al. 2002) that is accurate to 0.02 mag (Ivezić et al. 2003). Ultimately, up to 10,000 deg^2 of sky in the northern Galactic cap will be surveyed. The survey sky coverage will result in photometric measurements for over 100 million stars and a similar number of galaxies. Astrometric positions are accurate to better than 0$''$.1 per coordinate (rms) for point sources with $r < 20.5$ mag (Pier et al. 2003), and the morphological information from the images allows robust star-galaxy separation to $r \sim 21.5$ mag (Lupton et al. 2003).

Here we report the results of a color-based search for binary stars in the recent SDSS Data Release 1,[10] which includes 53 million unique objects detected in 2099 deg^2 of sky.

1.2. *The Stellar Locus in the SDSS Photometric System*

The effective temperature is the dominant parameter that determines the position of the majority of stars in optical color-color diagrams constructed with broadband filters (Lenz et al. 1998 and references therein). The effective temperature range results in a well-defined stellar locus in color-color diagrams (for more details, see Finlator et al. 2000 and references therein).

2. THE LOCUS OF BINARY STARS

An unresolved binary star may have colors that place it either inside or outside the locus. If the luminosity of one star is much greater than that of the other, the more luminous star determines the system colors. However, even if the luminosities are comparable, the system colors may still fall close to the locus of single stars in color-color diagrams in which the locus resembles a straight line (e.g. the $i-z$ versus $r-i$ diagram). Thus, to select unresolved binary systems by their colors, the most promising diagrams are those in which the locus is curved, such as the $g-r$ versus $u-g$ and $r-i$ versus $g-r$ color-color diagrams. The curvature in these diagrams is the result of saturation of the $u-g$ and $g-r$ colors due to the strong molecular absorption bands that first appear at type ∼M0.

Figure 1 shows the $g-r$ versus $u-g$ color-color diagram for ∼1.99 million stars with $u < 20.5$, extracted from the public SDSS Data Release 1 (DR1) database. This magnitude limit ensures that the accuracy of the u-band magnitudes is better than 0.1 mag (for $u < 18$, the photometric accuracy is 0.02 mag; Ivezić et al. 2003). The most prominent feature is the main stellar locus. Because of the large number of stars in DR1, we are able to demonstrate the existence of a second stellar locus clearly visible just above the main stellar locus. The number of stars in this previously unreported feature is a factor of ∼2300 smaller than in the main locus (using color cuts listed in § 3). Thus, accurate multiband

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[10] See http://www.sdss.org.

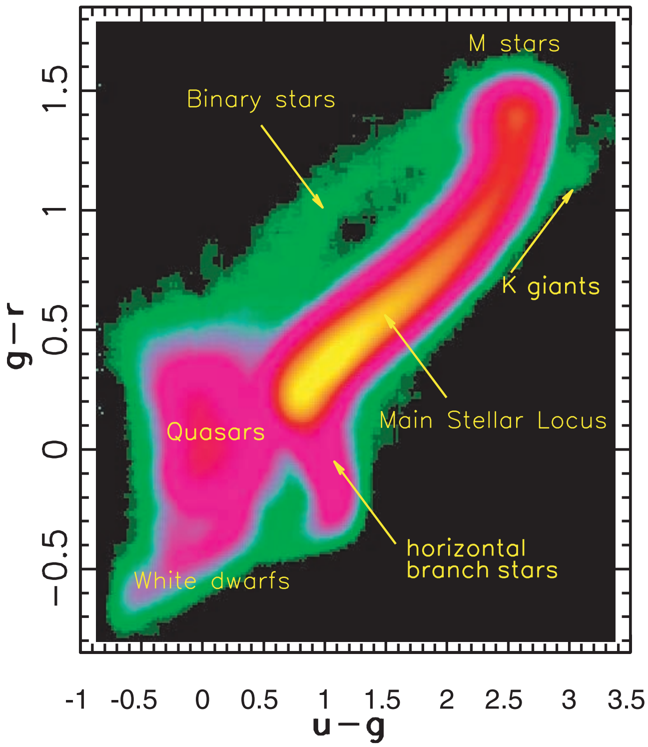

FIG. 1.—Number density, displayed on a logarithmic scale, of ∼1.99 million stars with $u < 20.5$ from SDSS Data Release 1 in the $g-r$ vs. $u-g$ color-color diagram (increasing from green to red to yellow). The most prominent features are the main stellar locus and the clump of low-redshift ($z < 2.3$) quasars, as marked. Other notable features include the locus of white dwarfs, horizontal branch stars (also including blue stragglers and RR Lyrae stars), and solar-metallicity K giants. The fainter feature colored green (*above and to the left of the main locus*) is the locus of ∼1,000 binary stars. The properties of this locus are consistent with a distribution of M dwarf–white dwarf pairs with varying luminosity ratios. The root-mean scatter of stars about this locus is only ∼0.1 mag.

photometry (u band in particular) for a sufficiently large number of stars was required to detect such a low-contrast feature.

The second stellar locus is consistent with binary systems that include an M dwarf and a white dwarf. We demonstrate that this simple model provides a satisfactory explanation for the position of the second stellar locus, hereafter the "bridge" (from M dwarfs to white dwarfs). We also show that the available SDSS spectra for a subsample of bridge stars support this interpretation.

3. M DWARF–WHITE DWARF MODEL

The bridge of stars in the $g-r$ versus $u-g$ color-color diagram appears to connect the positions of M stars and hot blue stars with MK spectral type around B. In order to produce a locus of stars that is not coincident with the main stellar locus, the luminosities of the two components must be comparable. The possibilities are an M dwarf–white dwarf pair or an M giant–blue giant/supergiant pair. The latter systems cannot dominate the sample, because the sky density of the selected stars (0.40 deg^{-2}) is too high, given the faint magnitudes and high latitudes probed by SDSS (see Majewski et al. 2003 for a nearly complete census of M giants in the Galaxy).

We generate model colors for binary systems by assuming SDSS colors for single M dwarf and white dwarf stars and parametrize the system colors by the luminosity ratio of the two components (in practice, we use the r-band flux fractions). For

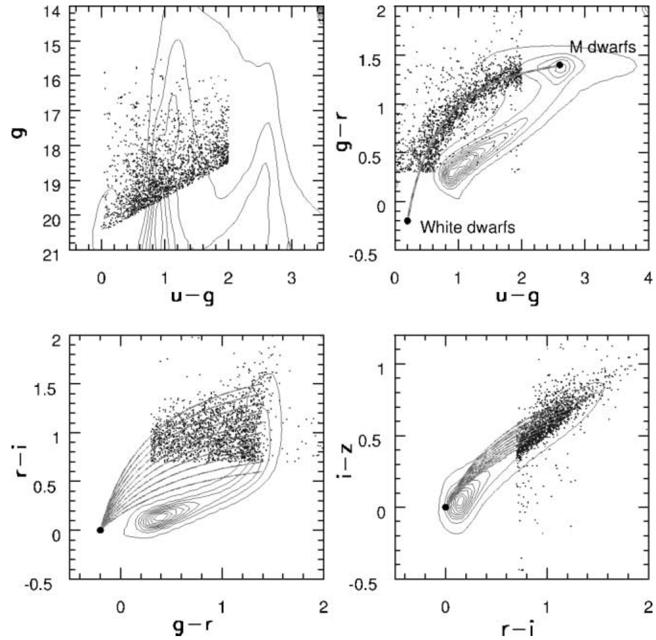

FIG. 2.—Comparison of a simple M dwarf–white dwarf pair model with the data. A representative distribution of all stars is shown by linearly spaced isopleths. The 863 stars from SDSS Data Release 1 selected by requiring $u < 20.5$, $u-g < 2$, $g-r > 0.3$, and $r-i > 0.7$ are shown by dots. The model predictions are shown by lines, where each corresponds to different $r-i$ and $i-z$ colors assumed for the M dwarf. The position along the line depends on the luminosity ratio of the two components. There is only one line in the $g-r$ vs. $u-g$ diagram (*top right*), because all M dwarfs have practically the same $u-g$ and $g-r$ colors (Finlator et al. 2000; Hawley et al. 2002). The observed data scatter around this line is presumably due to a distribution of white dwarf colors, photometric errors, and sample contamination by other types of source. [*See the electronic edition of the Journal for a color version of this figure.*]

the M dwarf, we adopt $u-g = 2.6$, $g-r = 1.4$, $r-i = 2(i-z)$, and $i-z = 0.3$ to 0.75, with a step of 0.05, and for the white dwarf, $u-g = 0.2$, $g-r = -0.2$, $r-i = 0$, $i-z = 0$. For more details about M dwarfs and white dwarfs discovered by SDSS, see Hawley et al. (2002), Harris et al. (2003), Raymond et al. (2003), and Kleinman et al. (2004). The model predictions are compared to the data in Figure 2, where the dots represent 863 "DR1 bridge stars" selected by requiring $u < 20.5$, $u-g < 2$, $g-r > 0.3$, $r-i > 0.7$, and that the processing flags BRIGHT, SATUR, and BLENDED are not set (the flag requirement selects unique unsaturated objects; see Abazajian et al. 2003). We corrected all colors for the interstellar reddening using the maps from Schlegel et al. (1998); typical corrections at the high galactic latitudes considered here are below 0.05 mag.

The agreement between this simple binary star model and the data is satisfactory. In particular, the model track closely follows the distribution of bridge stars in the $g-r$ versus $u-g$ color-color diagram and reproduces the observed range of colors in other diagrams. A noteworthy point is that the implied contribution of the white dwarf to the total r-band flux is at most 50% for practically all stars from the "DR1 bridge" sample (for equal r-band flux contributions, the model predicts $u-g = 0.40$ and $g-r = 0.33$).

4. SDSS SPECTRA

While the close agreement between the data and model predictions supports the hypothesis that the bridge stars are dominated by M dwarf–white dwarf pairs, further confirmation can

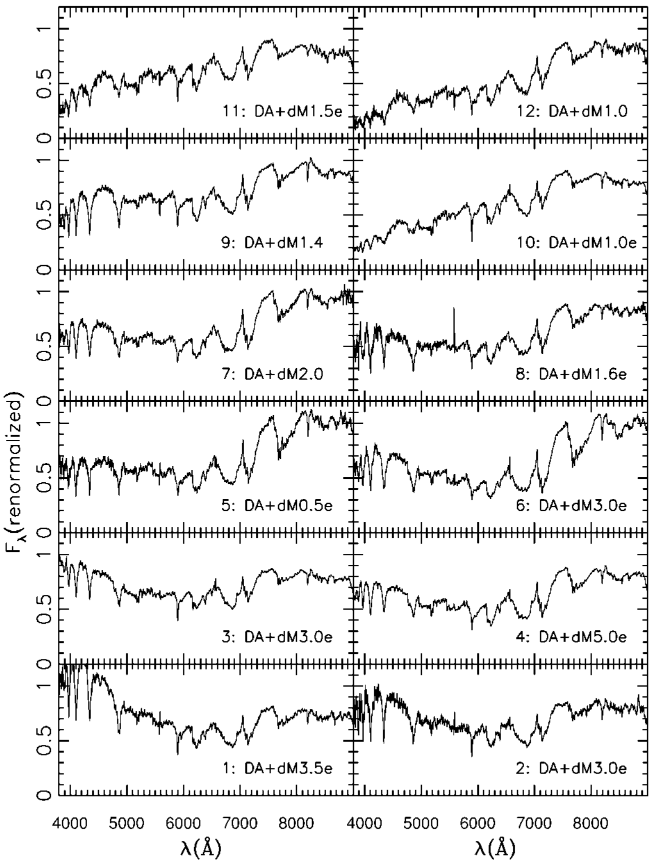

FIG. 3.—SDSS spectra for a subsample of stars whose SDSS colors are consistent with an M dwarf–white dwarf binary system. In all the systems shown, the red half of the spectrum is typical of an M dwarf, while the blue half is consistent with a white dwarf spectrum, with tentative spectral types as marked (accurate to within one to two subtypes). Spectra are approximately ordered by the M dwarf to white dwarf flux ratio in the r band. Note the prominent Hα emission for star 6. The feature at ∼5577 Å is due to the night sky. [*See the electronic edition of the Journal for a color version of this figure*.]

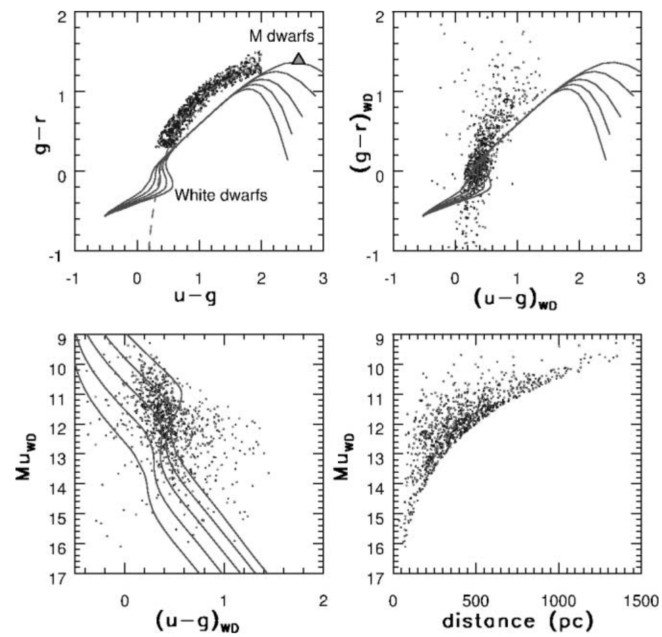

FIG. 4.—Comparison of data with Bergeron et al. (1995) white dwarf models. The symbols in the top left panel display the $g-r$ vs. $u-g$ color distribution for bridge stars, and the lines are white dwarf models with $\log g =$ (7, 7.5, 8, 8.5, 9). For a given $g-r$ color, the models with larger $\log g$ have bluer $u-g$ color (the temperature range is from 1500 to 10^5 K). The top right panel is analogous to the top left panel, except that the symbols show the color distribution for the white dwarf component. The bottom left panel compares the color-magnitude distribution for the white dwarf component with the model predictions (for a given $u-g$ color, $\log g$ decreases with the luminosity). The white dwarf absolute magnitude–distance distribution is shown in the bottom right panel. [*See the electronic edition of the Journal for a color version of this figure*.]

be gained by examining the available SDSS spectra. Stars are selected by various criteria for SDSS spectroscopic observations, and we postpone a detailed analysis of the selection statistics to a forthcoming publication. Here we simply report the results of a visual examination of 47 "bridge" stars from the DR1 sample for which SDSS spectra are available. The spectra are obtained through 3″ fibers and span the wavelength range 3800–9200 Å, with a spectral resolution of $\lambda/\Delta\lambda \sim 1800$.

Out of 863 stars in the sample, spectra are available for 47. The visual inspection of spectra indicates that 45 are consistent with an M dwarf–white dwarf interpretation (the remaining two are G stars; both are close to the color-selection boundary, and one belongs to a complex blended source). We display a representative sample of spectra in Figure 3. A preliminary comparison with the M dwarf spectral sequence (Hawley et al. 2002) indicates that M dwarfs in the binary systems discussed here are dominated by types M5 and earlier, as is the case for single M dwarfs in this magnitude-limited sample. This conclusion is also supported by the distribution of their $r-i$ and $i-z$ colors (the median $r-i$ color is ∼1.0; see the lower left panel in Fig. 2).

We visually compared all spectra to the atlas of white dwarf spectra by Wesemael et al. (1993). About half belong to the DA class, and about one-third can be tentatively classified as subdwarfs. Other classes that are probably present in the sample include DB, DZ, and DQ. We note that SDSS spectra are of sufficient quality to allow determination of the white dwarf temperature and the M dwarf chromospheric activity (via Hα emission), as demonstrated by Raymond et al. (2003). Such an analysis will be presented in a forthcoming publication.

5. COMPARISON WITH WHITE DWARF MODELS

The models discussed in § 3 indicate that the white dwarf contribution to the i- and z-band fluxes is practically negligible. Hence, the absolute i-band magnitude for the M dwarf component (M_i) and, therefore, distances can be obtained using the M_i versus $i-z$ color-magnitude relation from Hawley et al. (2002). With an estimate for distance, the absolute u-band magnitude for the white dwarf component can be determined and compared to model cooling curves. Two additional parameters that can be derived from the data are the $u-g$ color for the white dwarf component and the components' r-band flux (or luminosity) ratio. In this analysis, we further constrain the sources to be very close (0.15 mag) to the "bridge" by requiring $P_2 < 0.5\ P_1^2 + 0.15$ and $P_2 > 0.2\ P_1^2 - 0.15$, where $P_1 = -0.5\ (u-g) - (g-r) + 1.5$ and $P_2 = 0.7\ (u-g) - (g-r) + 0.2$.

Using this approach, we find a median $M_i \sim 9$ for the M dwarf component, with a root-mean scatter of 1 mag. The corresponding median distance is ∼400 pc. The derived white dwarf parameters are compared to models by Bergeron et al. (1995) in Figure 4. As shown in the top right panel, the estimated white dwarf colors agree well with the model predictions. For example, only 7% of the sample have $g-r$ color that is inconsistent with models by more than 0.5 mag (15% for 0.3 mag). Similarly, fairly good agreement is obtained for the luminosity–color distribution displayed in the bottom left panel. Models with $7 < \log g < 8.5$ bracket the majority of data points, in agreement with the analysis of isolated white dwarfs with SDSS spectra (Kleinman et al. 2004). About 20% of the data points have $u-g$ color for a given absolute magnitude that are too red by about 0.5 mag (or equivalently, for a given $u-g$ color, absolute magnitude is too bright by ∼2 mag). This discrepancy could be due to sample contamination by other types of source (e.g., single M dwarfs) or to the effects of photometric errors on the determination of $u-g$ color for the white dwarf component in systems dominated by the M dwarf component.

The white dwarf absolute magnitude–distance distribution is shown in the bottom right panel of Figure 4. Since the sample presented here is an unbiased, *u*-band flux-limited sample (with the adopted *u*-band magnitude limit, the other four SDSS magnitudes for all stars in the sample are comfortably brighter than the corresponding SDSS completeness limits), it would be straightforward to determine the white dwarf luminosity function and the number density (assuming that the components are not strongly interacting). However, the unresolved binary stars discussed here are heavily biased toward systems with components that have similar luminosities, and it is not trivial to account for this effect. Furthermore, a robust knowledge of the behavior of M dwarf spectral energy distributions in SDSS bands, among other things, is needed for a reliable derivation of the selection function. Unfortunately, models for these low-temperature stars are very inaccurate (see, e.g., Finlator et al. 2000), and the analysis of SDSS spectral observations is only beginning to take place. Hence, a detailed analysis of M dwarf and white dwarf luminosity functions in unresolved binary systems will be presented in a future publication.

6. CONCLUSIONS

The accurate multiband SDSS photometry for a large number of stars allowed detection of a new feature in the broadband optical color-color diagrams: a "bridge" of stars well separated from the main stellar locus connects the positions of M dwarfs and white dwarfs. The bridge characteristics are consistent with a binary system that includes an M dwarf and a white dwarf, with the system's position on the bridge determined by the components' luminosity ratio. This conclusion is strongly supported by SDSS spectra for 47 such systems.

The distance to these systems can be estimated in a straightforward way, because a photometric parallax relation for M dwarfs can be applied to *i*- and *z*-band measurements, where the contribution from the white dwarf is negligible. With a known system distance, the white dwarf luminosity-color distributions can be determined and compared to models. We find that models by Bergeron et al. (1995) are in good agreement with the data.

This work analyzed only about a quarter of the data that will be obtained by the SDSS. Thus, the color-selection method presented here will eventually yield ∼4000 unresolved M dwarf–white dwarf binary systems.

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[11] The SDSS Web site is http://www.sdss.org.

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