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 stars in the SDSS $g-r$ vs. $u-g$ 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 SDSS Data Release 1. The position and shape of the feature is 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.

1. Introduction

1.1. Sloan Digital Sky Survey

The Sloan Digital Sky Survey (SDSS; Azebajian et al. 2003, and references therein) is revolutionizing stellar astronomy by providing homogeneous and deep ($r < 22.5$) photometry in five passbands (u, g, r, i, and z, Gunn et al. 1998) 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 arcsec per coordinate (rms) for point sources with $r < 20.5^m$ (Pier et al. 2003), and the morphological information from the images allows robust star-galaxy separation to $r \sim 21.5^m$ (Lupton et al. 2001).

Here we report the results of a color-based search for binary stars in the recent SDSS Data Release 1 (see www.sdss.org), which includes 53 million unique objects detected in 2099 deg^2 of sky.

1.2. The Stellar Locus in 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 broad-band filters (Lenz et al. 1998, and references therein). The effective temperature range results in a well-defined locus in color-color diagrams, as shown in Figure 1 (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 color may still fall close to the locus of single stars in color-color diagrams where the locus resembles a straight line (e.g. the $i-z$ vs. $r-i$ diagram, see the bottom right panel in Figure 1). Thus, to select unresolved binary systems by their colors, the most promising diagrams are those where the locus is curved, such as $g-r$ vs. $u-g$ and $r-i$ vs. $g-r$ 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 which first appear at type $\sim$M0.

Figure 2 shows the $g-r$ vs. $u-g$ color-color diagram for $\sim$1.99 million stars from the public SDSS Data Release 1 (DR1) database with $u < 20.5$. This magnitude limit ensures that the accuracy of the u 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 stellar locus discussed in Figure 1. Due to 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 $\sim$2,300 smaller than in the main locus (using color cuts listed in the next Section). Thus, accurate multi-band 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 than 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 $g-r$ vs. $u-g$ 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

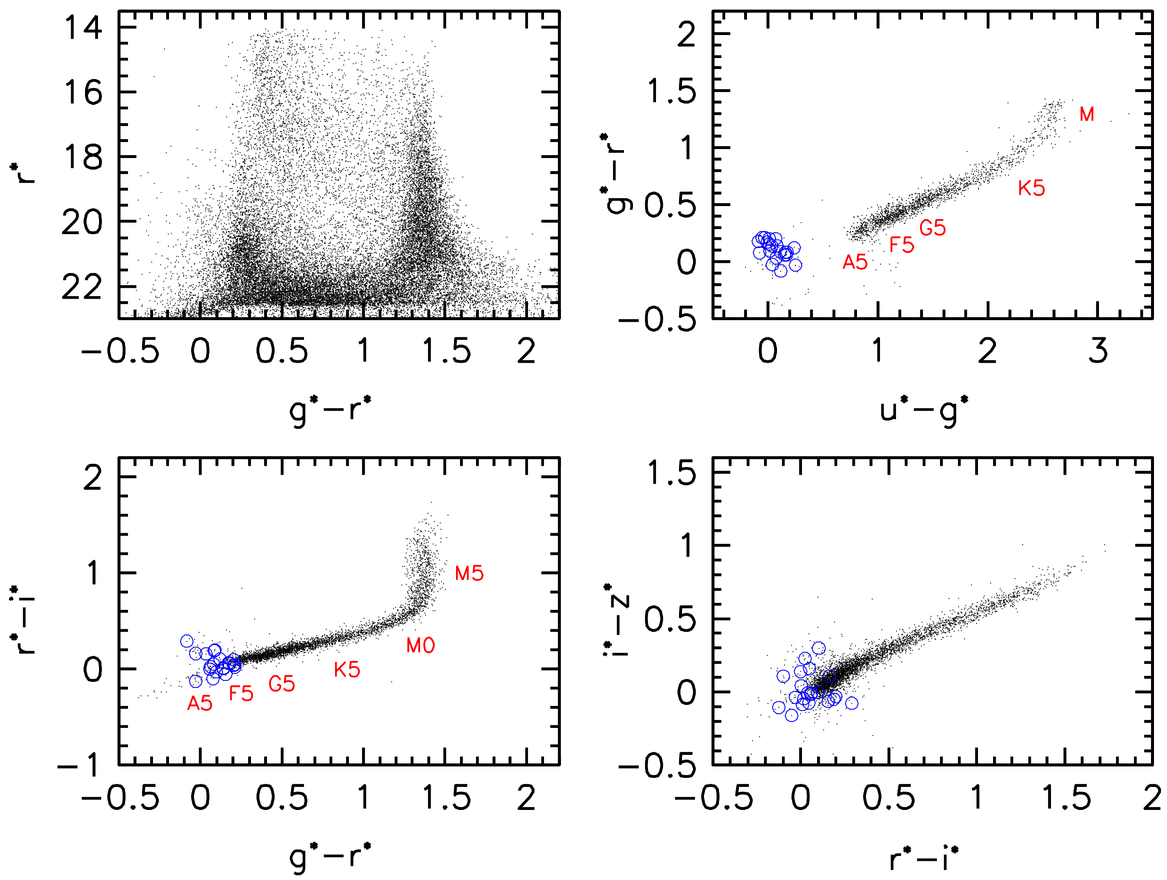

Fig. 1.— The SDSS color-color and color-magnitude diagrams which summarize photometric properties of unresolved sources, marked as dots (adopted from Finlator et al. 2000, when SDSS photometric system was still marked by an asterisk). The top left panel displays the r vs. $g-r$ color-magnitude diagram for ∼25,000 high-latitude objects observed in 3 deg^2 of sky (for more details see Finlator et al. 2000). The three remaining panels show color-color diagrams for objects brighter than 20^m in each of the 3 bands used to construct each diagram (red is always towards the upper right corner). The locus of "normal" stars (dominated by main sequence stars) is clearly visible in all three diagrams, and the positions of several spectral types are indicated next to the locus in the $u-g$ vs. $g-r$ and $r-i$ vs. $g-r$ color-color diagrams. For completeness, point sources that have $u-g$ and $g-r$ colors similar to low-redshift QSOs ($u-g<$ 0.4, -0.1 $< g-r<$ 0.3, $r-i<$ 0.5), and are brighter than the limit for quasars in the SDSS spectroscopic survey ($i<$ 19), are marked by open circles.

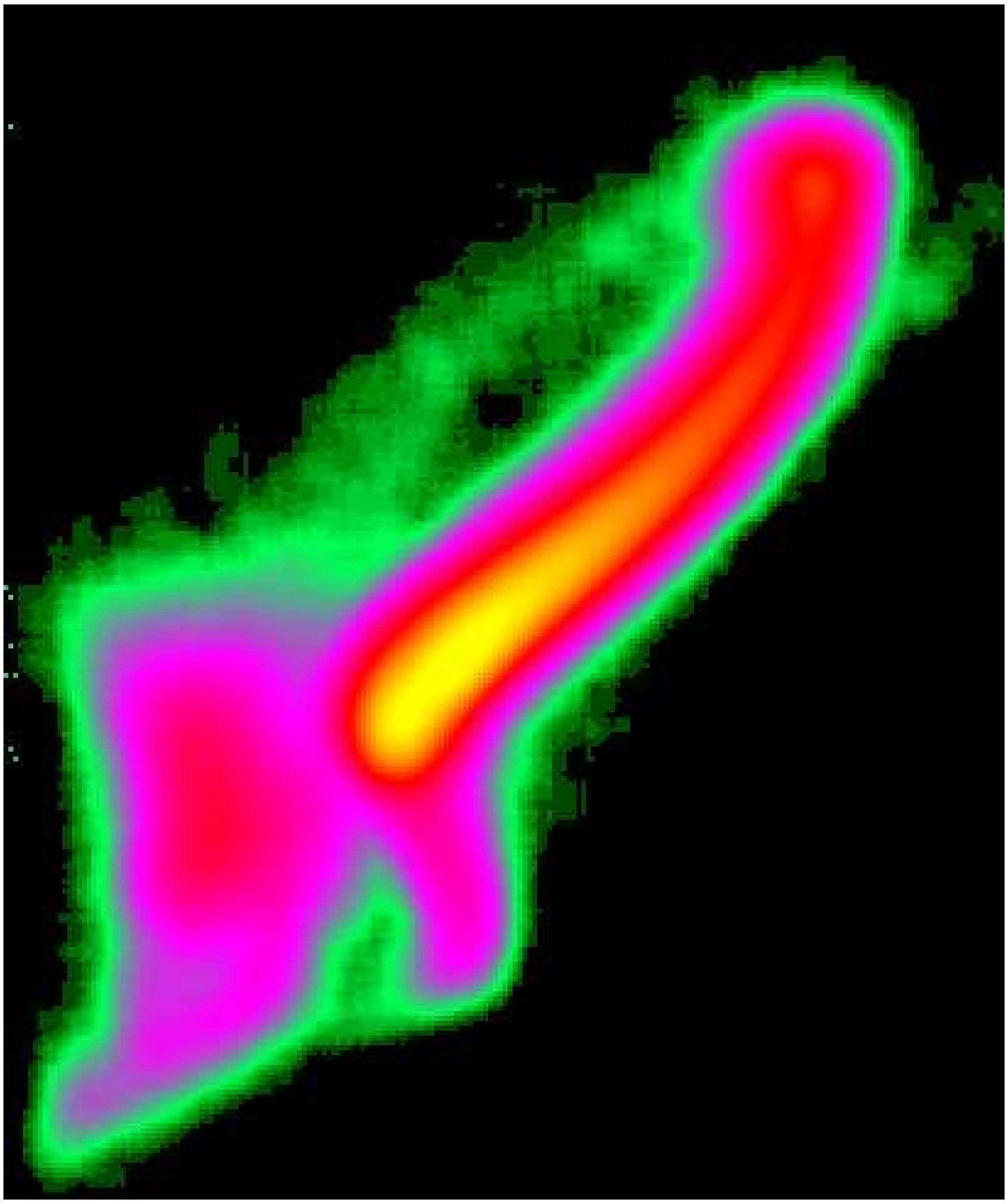

Fig. 2.— The number density, displayed on a logarithmic scale, of $\sim$1.9 million stars with $u < 20.5$ from SDSS Data Release 1 in the $g-r$ vs. $u-g$ color-color diagram (increasing from green to red to yellow; the color ranges are -1 to 3, and -1 to 2, for $u-g$ and $g-r$, respectively). The most prominent features are the main stellar locus (yellow and red towards upper right) and the clump of low-redshift quasars (red and purple towards the left edge). The fainter feature, colored green, above and to the left from the main locus is the locus of $\sim$1,000 binary stars. The properties of this locus are consistent with a distribution of M dwarf – white dwarf pairs with varying luminosity ratio. The root-mean-scatter of stars perpendicular to this locus is only $\sim$0.1 mag.

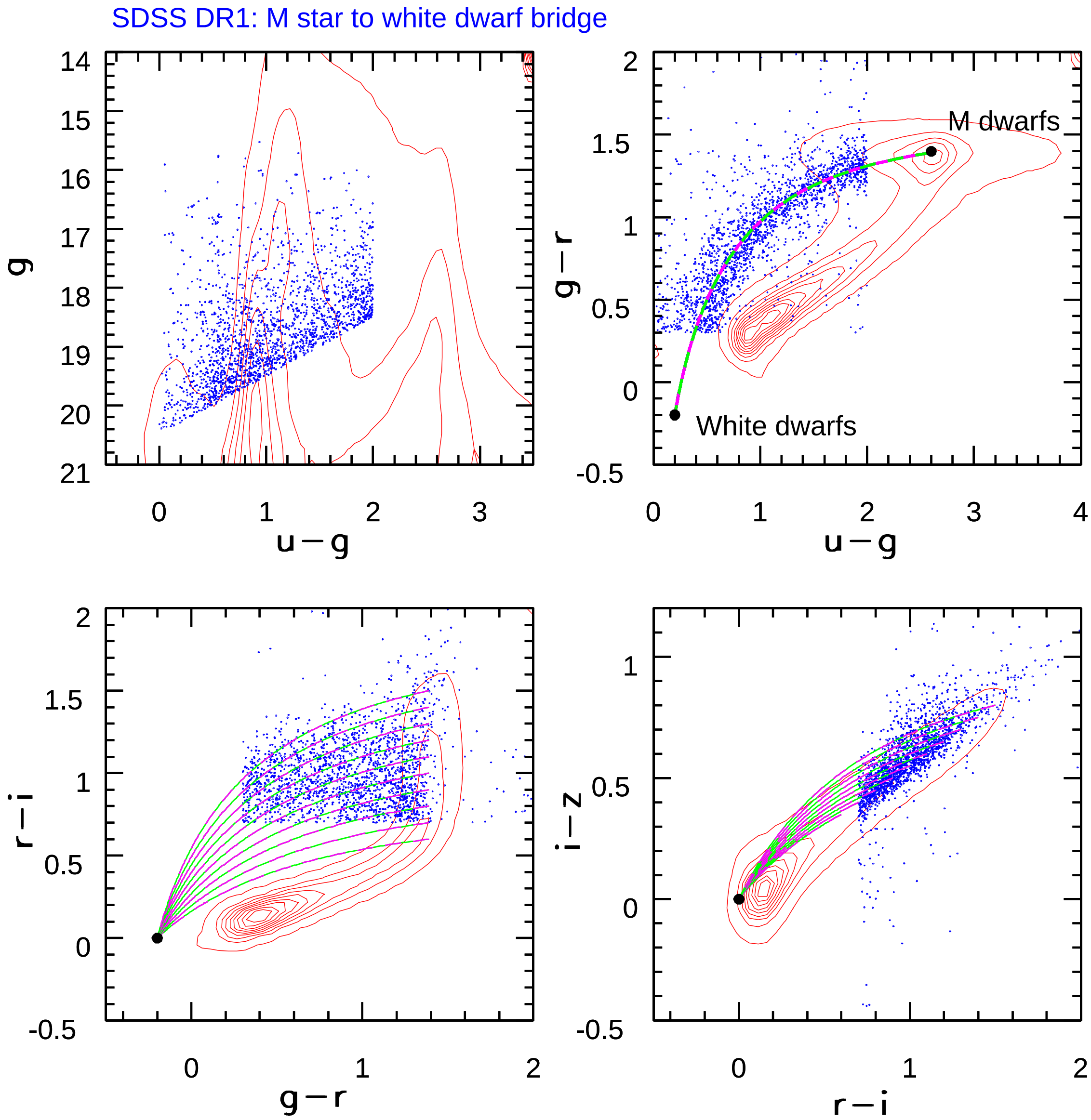

Fig. 3.— The comparison of a simple M dwarf – white dwarf pair model with the data. A representative distribution of all stars is shown by linearly spaced isopleths. 863 stars from SDSS Data Release 1 selected by requiring $u < 20.5, u - g < 2, g - r > 0.4$ and $r - i > 0.7$ are shown by dots. The model predictions are shown by lines, where each line 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 same $u - g$ and $g - r$ colors. The observed data scatter around this line is presumably due to different white dwarf colors.

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 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 please see Hawley et al. 2002, and Harris et al. 2000. The model predictions are compared to the data in Figure 3, where the dots represent 863 "DR1 bridge stars", selected by requiring $u<20.5, u-g<2, g-r>0.4$, $r-i>0.7$, and that processing flags BRIGHT, SATUR and BLENDED are not set (the flag requirement selects unique unsaturated objects).

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 $g-r$ vs. $u-g$ 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 $g-r=0.33$).

The models show that the white dwarf contribution to the i and z band fluxes is practically negligible. Hence, the absolute i band magnitude, M_i, and therefore distances, can be obtained using the M_i vs. $i-z$ color-magnitude relation from Hawley et al. (2002). We find a median of $M_i\sim 9$ for bridge stars, with a root-mean-scatter of 1 mag. The corresponding median distance is $\sim$300 pc. Given the distance to the system, the white dwarf luminosity can be easily determined. Since the sample presented here is an unbiased, flux-limited sample (with the adopted u magnitude limit, the other four SDSS magnitudes for all stars in the sample are comfortably brighter than the corresponding SDSS completeness limits), it can be used to statistically determine the cooling curve for white dwarfs (if the components are not strongly interacting). Such an analysis will be presented in a forthcoming publication (Knapp et al. 2003, hereafter Paper II).

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 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 Paper II. 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 3800–9200A, 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 2 are G stars; both are close to the boundary of color-selection boundary, and one is part of a complex blended source). We display a representative sample of spectra in Figure 4. 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 $\sim$1.0, see the lower left panel in Figure 3). 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).

5. Conclusions

The accurate multi-band SDSS photometry for a large number of stars allowed the detection of a new feature in the broad-band 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 than includes an M dwarf and a white dwarf, with the system's position on the bridge determined by the components' luminosity ratio.

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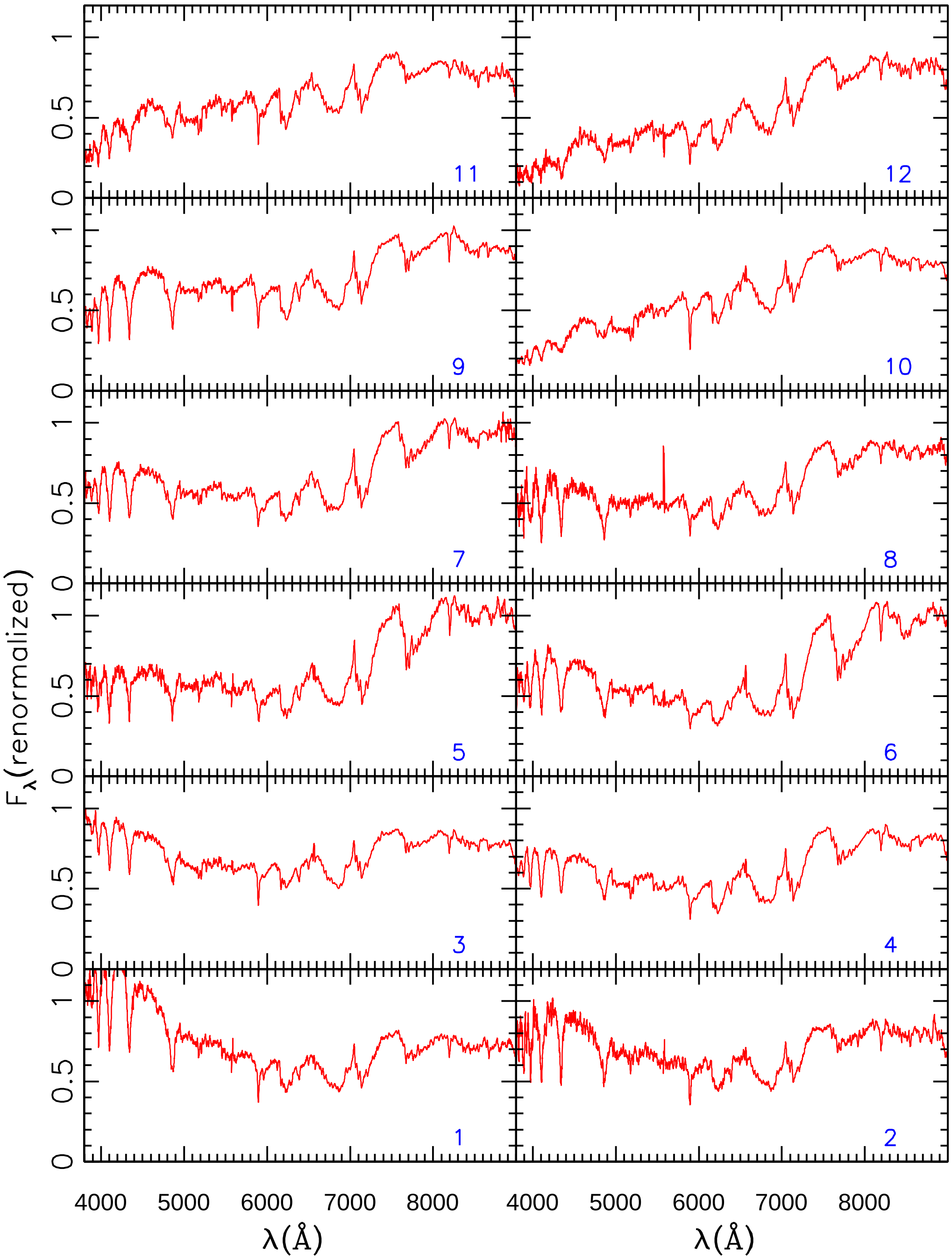

Fig. 4.— SDSS spectra for a subsample of stars whose SDSS colors are consistent with an M dwarf – white dwarf binary system. In all the shown systems the red half of the spectrum is typical of an M dwarf, while the blue half is consistent with a white dwarf spectrum. Note prominent Hα emission for stars 3 and 6. The feature at $\sim$5,577A is due to the night sky.

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