UPDATED COLORS FOR COOL STARS IN THE SDSS

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ABSTRACT

We present updated colors for M and L dwarfs based on photometry from the third data release of the Sloan Digital Sky Survey (SDSS). These data are improved in quality and number from earlier results. We also provide updated equations for determining photometric parallaxes from SDSS colors of late-type stars. Walkowicz, Hawley & West (2004) have recently presented new techniques for studying the magnetic activity of low-mass stars and their method relies on an accurate determination of SDSS color. We derive new relationships between SDSS colors and other common passbands and present updated formulas from Walkowicz et al. (2004) for determining the level of magnetic activity in M and L dwarfs.

Subject headings: stars: late-type — stars: low-mass, brown dwarfs — stars: activity — stars: distances — astronomical data bases: surveys

1. INTRODUCTION

The Sloan Digital Sky Survey (SDSS; York et al. 2000; Gunn et al. 1998; Fukugita et al. 1996; Hogg et al. 2001; Smith et al. 2002; Pier et al. 2003), as of its third data release (DR3; Abazajian et al. 2005), has spectroscopically observed approximately 20,000 M and L dwarfs. These data have been used to examine magnetic activity (West et al. 2004; hereafter W04), search for low mass subdwarfs (W04), and study the properties of white dwarf- M dwarf binary systems (Raymond et al. 2003) with an unprecedented quantity of data. Hawley et al. (2002; hereafter H02) first characterized a sample of the M, L and T dwarfs from the early data release (EDR; Stoughton et al. 2002) of SDSS. As a part of their study, they provided average colors for each spectral type and calculated both spectroscopic and photometric parallaxes as a function of spectral type and color respectively. Many current studies are using low mass stars to probe the structure and composition of the Galaxy (West et al. 2005, in preparation; Juric et al. 2005, in preparation; Covey et al. 2005, in preparation; Bochanski et al. 2005, in preparation) and rely on the colors and photometric parallaxes provided by H02. However, these colors, and therefore the photometric parallaxes, were based on the EDR version of the SDSS photometric pipeline. Subsequent SDSS data releases have utilized updated photometric software, resulting in RMS changes of several hundredths of a magnitude compared to the EDR photometry. The photometric pipelines for both Data Release 1 (DR1; Abazajian et al. 2003) and Data Release 2 (DR2; Abazajian et al. 2004) contain improved software that more rigorously calibrates the data and more accurately accounts for sky subtraction in the psf photometry. The SDSS photometric pipeline was frozen after DR2 ensuring that the DR3 photometry presented in this paper will not change due to SDSS processing alterations.

The latest SDSS data releases have also dramatically increased the number of spectroscopically observed stars, allowing us to select a large sample of high signal-to-noise stars, a luxury not possible with the smaller EDR dataset. Our signal-to-noise cuts provide more accurate spectral types and photometry. This ability to make quality cuts on the data and still retain a large sample has substantially altered some of the colors reported in H02. In this paper, we report an updated set of low mass star colors from a high signal-to-noise subset of the W04 sample, and derive new photometric parallax relations using the updated photometry of the H02 sample.

In order to aid in the analysis of magnetic activity in W04, a new technique was designed by Walkowicz, Hawley & West (2004; hereafter WHW) for calculating the ratio of the luminosity in Hα (L_{Hα}) to the bolometric luminosity (L_{bol}). WHW determined a χ factor, that when multiplied by the Hα equivalent width (EW), gives the value of L_{Hα}/L_{bol}. The χ factor varies with spectral type and WHW used the low mass star colors reported in H02 to derive χ as a function of color. Here we present new equations for determining χ, based on our updated photometry.

2. DATA

All of the SDSS photometry reported in this study has been reduced using the DR3 version of the SDSS photometric pipeline (Photo 5,4,25). Our main sample of low mass stars comes from the W04 spectroscopic sample. The stars were selected from the SDSS database based on their r − i and i − z colors (see W04 for a detailed description), and have been spectral-typed using...
and i relations can vary by as much as 0.4 magnitudes, most bars are the spreads given by H02. Although the mean differences in the four colors presented in Table 1 (Figure 1). The error bars for those presented by H02, we plot the difference in color as function of spectral type. The uncertainties in the absolute magnitude for the four colors reported in Table 1. Error bars are the spreads reported in H02. Discrepancies in the r − i and i − z colors are likely due to our large sample size and high signal-to-noise quality cut. Because the z − J and i − J colors are from the same stars as used by H02, the color differences in these bands reflect changes in the SDSS photometric pipeline.

We have also downloaded the DR3 photometry for the stars from the H02 study in order to recalibrate the photometric parallax measurements in the manner of H02. The uncertainties in the absolute M_j magnitudes and the spectroscopic parallax relations from H02. The uncertainties in the absolute M_j magnitudes from that paper are ∼ 0.5 magnitudes.

We use the sample of spectrophotometric stars from WHW to derive new relations for log(χ) as a function of color. We follow the exact method of WHW, but utilizing the updated colors from this study.

3. RESULTS

3.1. Mean Colors

Using the DR3 colors for the samples discussed above, we calculate updated r − i, i − z, z − J and i − J colors for M and early L dwarfs. Table I shows these values sorted according to spectral type. The mean r − i and i − z colors come from the W04 sample and the z − J and i − J colors come from the updated H02 data. It is important to note that the parentheses in the table give the standard deviations of the mean colors and do not reflect the photometric uncertainties (which are at most ∼ 0.07 magnitudes). Instead, these values reflect the intrinsic scatter in the color distribution at a given spectral type.

To demonstrate the difference between our colors and those presented by H02, we plot the difference in color (this study − H02) as a function of spectral type for the four colors presented in Table I (Figure 1). The error bars are the spreads given by H02. Although the mean relations can vary by as much as 0.4 magnitudes, most of the discrepancies fall within the ranges reported by H02. The r − i and i − z colors that we measure for stars with spectral types M0, M6 and M7 have significant differences from those of H02. These offsets are due to our larger sample size, and our use of only high signal-to-noise SDSS data. The z − J and i − J data come from the same stars used by H02, but the EDR photometry has been replaced by that of DR3. Although some of the difference comes from our data quality cut, much of the offset can be attributed to changes in SDSS photometry.

Using the mean colors, we derive new photometric parallax relations for the i − z and i − J colors by plotting the absolute i-band magnitude as a function of color. We fit the M_i vs. i − z relation with a 3 part linear piece-wise function, which is a better description of this relation than a polynomial fit. Spectral types later than L0 are not included because of the similar i − z colors for stars cooler than L0. The M_i vs. i − J relation is best fit by a second order polynomial. Figure 2 and Figure 3 show these relations for the i − z and i − J colors respectively. In both figures, the error bars on the upper panels indicate the intrinsic spread in color at each spectral type. The fit to the color-magnitude relation is indicated on the lower panels. These fits can be expressed by:

\[
M_i(0.37 < i - z < 0.70) = 7.18 + 3.14(i - z) \pm 0.08
\]
\[
M_i(0.70 < i - z < 1.26) = 3.13 + 8.93(i - z) \pm 0.25 \quad (1)
\]
\[
M_i(1.26 < i - z < 1.84) = 11.4 + 2.39(i - z) \pm 0.31
\]
\[
M_i = -3.12 + 7.28(i - J) - 0.65(i - J)^2 \pm 0.21 \quad (2)
\]

Fig. 1.— Color difference between this study and H02 as function of spectral type for the four colors reported in Table I. Error bars are the spreads reported in H02. Discrepancies in the r − i and i − z colors are likely due to our large sample size and high signal-to-noise quality cut. Because the z − J and i − J colors are from the same stars as used by H02, the color differences in these bands indicate changes in the SDSS photometric pipeline.

Fig. 2.— Absolute i-band magnitude as a function of mean i − z color at each spectral type. The upper panel error bars show the intrinsic scatter in the colors and do not represent photometric uncertainties. The lower panel gives the same data together with the updated photometric parallax relation from Equation 1.
# Table 1

## Average Color by Spectral Type

| Spectral Type | $r-i$ | $i-z$ | $z-J$ | $i-J$ | $M_J$ |
|---------------|-------|-------|-------|-------|-------|
| M0            | 0.67 (0.14) | 0.37 (0.06) | 1.45 (—) | 1.92 (—) | 6.45 |
| M1            | 0.88 (0.15) | 0.48 (0.13) | 1.34 (0.09) | 1.89 (0.05) | 6.72 |
| M2            | 1.03 (0.18) | 0.58 (0.18) | 1.45 (0.17) | 2.10 (0.23) | 6.98 |
| M3            | 1.33 (0.30) | 0.70 (0.31) | 1.46 (0.15) | 2.14 (0.15) | 7.24 |
| M4            | 1.51 (0.22) | 0.84 (0.22) | 1.57 (0.14) | 2.47 (0.16) | 8.34 |
| M5            | 1.91 (0.14) | 1.05 (0.09) | 1.66 (0.09) | 2.75 (0.12) | 9.44 |
| M6            | 2.01 (0.14) | 1.10 (0.07) | 1.76 (0.09) | 3.02 (0.22) | 10.18 |
| M7            | 2.27 (0.20) | 1.26 (0.12) | 1.95 (0.15) | 3.46 (0.24) | 10.92 |
| M8            | 2.77 (0.16) | 1.62 (0.12) | 2.05 (0.13) | 3.71 (0.22) | 11.14 |
| M9            | 2.81 (0.28) | 1.69 (0.07) | 2.23 (0.09) | 4.05 (0.13) | 11.43 |
| L0            | 2.63 (0.27) | 1.84 (0.08) | 2.28 (0.09) | 4.24 (0.10) | 11.72 |
| L1            | 2.61 (0.27) | 1.83 (0.09) | 2.51 (—) | 4.41 (—) | 12.00 |
| L2            | 2.39 (0.18) | 1.80 (0.17) | 2.57 (0.11) | 4.43 (0.12) | 12.29 |

**Note.** The mean and ($\sigma$) of each color are given. Because these results were calculated using data with small measurement errors (see Section 2), the $\sigma$ in most cases represents the intrinsic scatter in the population. The M0 and L1 bins have only one star each with both $J$-band data and uncertainties that meet our SDSS data quality cuts; therefore neither have values for $\sigma$.

## Figures

**Fig. 3.** Absolute $i$-band magnitude as a function of mean $i-J$ color at each spectral type. The upper panel error bars indicate the intrinsic scatter in the colors of low mass stars. The lower panel shows the updated photometric parallax relation given in Equation 2.

**Fig. 4.** Data and fits between SDSS and Johnson-Cousins/2MASS colors: $r-i$ versus $V-I_C$ (upper) and $i-z$ versus $I_C-K_s$ (lower). Stars are binned and averaged according to their spectral type. For the $i-z$ vs. $I_C-K_s$ relation, stars with spectral type later than M6 have been binned every 2 spectral classes (M7-M8, M9-L0). Error bars represent the spread in color for each spectral type bin. Fits to both relations are given by Equations 3 and 4.

For the ranges $0.37 \leq i-z \leq 1.84$ and $1.92 \leq i-J \leq 4.43$ respectively. These results agree within the uncertainties with the relations derived by Williams et al. (2002).

### 3.2. Activity Relations

Using the updated colors from Table 1, we follow the method of WHW and derive new relations for $r-i$ as a function of $V-I_C$ and $i-z$ as a function of $I_C-K_s$. As described in WHW, the $V$, $I_C$ and $K_s$ data come from nearby samples of M0-L0 stars (for complete sample details see WHW). Individual stars have been binned according to their spectral types. Very few stars with spectral classes later than M6 exist in these samples. Therefore, the late type stars have been binned every 2 spectral types (M7-M8 and M9-L0). Figure 4 shows these relations together with our fits to the color-color relationships. The error bars represent the spread of the
colors in each bin. Note that the intrinsic spread of the population dominates the scatter and is non-trivial. The fits can be described by:

\[ r - i = -2.69 + 2.29(V - I_C) - 0.28(V - I_C)^2 \] (3)

\[ i - z = -20.6 + 26.0(I_C - K_s) - 11.7(I_C - K_s)^2 + 2.30(I_C - K_s)^3 - 0.17(I_C - K_s)^4 \] (4)

over the ranges 0.67 \( \leq r - i \leq 2.01 \) and 0.37 \( \leq i - z \leq 1.84 \) respectively. The \( i - z \) color derived from this relation has an uncertainty in the fit of 0.10 magnitudes while the \( r - i \) color has an uncertainty of 0.05 magnitudes. The uncertainty of 0.05 magnitudes is small enough that photometric errors most likely dominate the error budget for the \( r - i \) vs. \( V - I_C \) relation, rather than the uncertainty in the fit.

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