Mem. S.A.It. Vol. 85, 795

Memorie della

Gaia colors of brown dwarfs

Y. Wang[1], R. L. Smart[2], H.R.A. Jones[3], and Z. Shao[4]

[1] National Astronomy Observatory of China – 20A Datun Road, Chaoyang district, Beijing China, 100012, e-mail: `yfwang@bao.ac.cn`
[2] Istituto Nazionale di Astrofisica – Osservatorio Astrofisico di Torino, Via Osservatorio 20, I-10023 Torino, Italy
[3] Centre for Astrophysics Research, Science and Technology Research Institute, University of Hertfordshire, Hatfield AL10 9AB, UK
[4] Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China;

Abstract. The Gaia mission will allow us to study several hundred L and T dwarfs. An understanding and calibration of a well defined bright L dwarf sample from the Gaia mission will impact many areas of astronomy from the history of our Galaxy to understanding hot exoplanet atmospheres. We collect SDSS and 2MASS photometry for 580 L and 131 T dwarfs. We examine the SDSS/2MASS average colors for M0 to T6 and estimate Gaia colors for the same samples. From the spectral type vs SDSS/2MASS colors we find for stars there is a monotonic increase while the brown dwarfs vary in their colors due to their complex atmospheres. We find the predictions for Gaia colors from empirical and theoretical approaches are not consistent.

Key words. Stars: abundances – Stars: atmospheres – Stars: brown dwarfs, L dwarfs

1. Introduction

Brown dwarfs are sub-stellar objects that have mass between the most massive planets and the least massive stars, with spectral type spread across late M, L, T and Y dwarfs. In the year 1995, the first two brown dwarfs were discovered: one was a late M (Rebolo et al. 1995) and another was a T dwarf (Nakajima et al. 1995). Brown dwarfs have colors that overlap with those of M dwarf stars and also of the new exoplanets. The majority of known brown dwarfs are L dwarfs because of their brightness. The Gaia mission will directly observe $\sim$ 500 L0 to L5 dwarfs and a few late L and early T dwarfs (Smart 2014). This Gaia sample will enable a fine calibration of the change in physical characteristics as a function of absolute luminosity, color and spectral features. The long lifetimes, unchanged chemical composition, age dependant spectral type and brightness relative to other brown dwarfs will make L dwarfs prime candidates for studying the history of Galaxy. To understand what the photometry of Gaia will provide for L dwarfs we look at the SDSS/2MASS and predicted Gaia colors for M0 to T6.

2. Brown dwarf optical and near-infrared colors

We collected the 2MASS Point source All Sky Catalogue and SDSS DR10 photometry for all

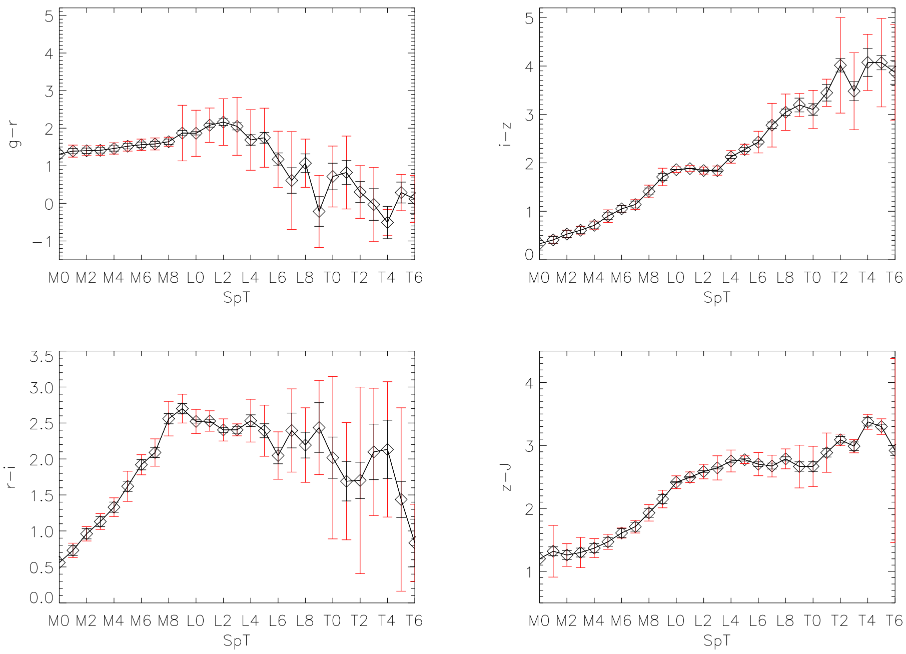

Fig. 1. Color-SpT diagrams for M0 to T6 dwarfs. The red error bars are the standard deviation of the colors for each spectral bin and the black error bars are average errors in each spectral bin. For the M dwarfs, we set the black error bars to be 0.07 as discussed in the text.

the L and T dwarfs in DwarfArchives[1]. This resulted in 580 L and 131 T dwarfs with both 2MASS and SDSS photometry. For each subtype we calculate the average color excluding statistical outliers. In Table 1 we report the mean color by spectral type, the sample size for each point, the dispersion of that mean color and also an average error based on the propagation of the errors of the individual magnitudes. The SDSS/2MASS color trends for M0 to T6 is shown in figure 1 where the colors for M0 to M9 objects comes from table 2 of West et al. (2011). In West et al. they do not quote errors for their colors, however, as they limited their sample to objects with magnitude errors less than 0.05 we adopt an average error in the color of 0.07. In the calculation of our SDSS/2MASS colors no objects with errors greater than 1.0 magnitudes were used and we carry out one iteration of 3 sigma clipping in each bin.

It is known that colors with a long wavelength baseline for cool stars provide reasonably monotonic changes in color, e.g., an optical minus and infrared magnitude. Thus they can give strong diagnostic information for M to T dwarfs. This can be understood as resulting from the optical magnitude sampling the steeply rising energy distribution shortward of its peak and the infrared magnitude sampling the peak of the energy distribution.

It can be seen in the left panel of Fig. 1 that this idea breaks down for the $g - r$ and $r - i$ colors by L dwarf spectral types. We conjecture that by L dwarf spectral types although the g, r and i bands all lie in the steeply rising part of the spectral energy distribution they have become strongly dominated by Na and K resonance features which can be seen in their optical spectra (Burrows & Volobuyev 2003; Kirkpatrick et al. 2008). In this work we wish

[1] http://DwarfArchives.org

Table 1. Mean SDSS/2MASS colors by spectral type.

SpT	$g-r$ $\sigma:\bar{\epsilon}$	N	$r-i$ $\sigma:\bar{\epsilon}$	N	$i-z$ $\sigma:\bar{\epsilon}$	N	$z-J$ $\sigma:\bar{\epsilon}$	N
L0	1.86 0.61:0.05	137	2.52 0.17:0.02	111	1.86 0.06:0.00	120	2.42 0.10:0.01	105
L1	2.08 0.46:0.05	100	2.53 0.14:0.02	89	1.88 0.06:0.00	94	2.50 0.09:0.01	79
L2	2.16 0.62:0.09	43	2.40 0.15:0.03	42	1.84 0.07:0.02	44	2.59 0.12:0.01	41
L3	2.05 0.77:0.09	39	2.41 0.08:0.05	23	1.84 0.09:0.01	33	2.64 0.19:0.02	37
L4	1.69 0.81:0.14	22	2.53 0.30:0.08	19	2.12 0.13:0.03	21	2.81 0.12:0.03	18
L5	1.75 0.79:0.14	21	2.39 0.36:0.10	20	2.28 0.11:0.04	18	2.77 0.06:0.02	16
L6	1.17 0.75:0.17	20	2.05 0.33:0.11	18	2.43 0.22:0.04	19	2.68 0.16:0.04	19
L7	0.61 1.30:0.34	5	2.40 0.58:0.24	6	2.78 0.45:0.07	6	2.67 0.17:0.05	6
L8	1.07 0.64:0.25	11	2.19 0.52:0.18	11	3.05 0.38:0.06	11	2.79 0.16:0.03	11
L9	-.22 0.96:0.40	6	2.44 0.65:0.35	6	3.19 0.24:0.14	6	2.67 0.34:0.07	6
T0	0.71 0.81:0.35	5	2.02 1.13:0.29	5	3.10 0.39:0.12	5	2.67 0.32:0.08	5
T1	0.82 0.97:0.32	6	1.64 0.76:0.27	7	3.45 0.28:0.17	7	2.89 0.31:0.07	6
T2	0.30 0.70:0.28	9	1.70 1.30:0.25	9	4.01 0.99:0.14	9	3.09 0.09:0.05	8
T3	0.03 0.99:0.42	4	2.10 0.88:0.39	4	3.48 0.79:0.20	4	2.99 0.10:0.07	4
T4	0.51 0.35:0.43	3	2.13 0.94:0.41	3	4.07 0.58:0.29	3	3.38 0.12:0.07	3
T5	0.29 0.48:0.28	7	1.44 1.27:0.25	7	4.07 0.91:0.15	7	3.30 0.12:0.04	7
T6	0.12 0.63:0.38	4	0.83 0.54:0.33	5	3.87 0.98:0.24	5	2.92 1.46:0.08	5

Note: The magnitudes listed are SDSS g,r,i,z and 2MASS J. For each color and spectral bin we list the mean, standard deviation of the mean, the average error in each bin and the number of objects in each bin.

to point out the differences in the two kind of error bars in Figure 1 (a) black ones: the average error of the colors from the propagation of the individual error of the magnitudes and (b) red ones: the standard deviation of the colors for each spectral type bin. An increase in the spread of the standard deviation of colours at a particular spectral type can be seen to shift to progressively later spectral types as the color becomes redder: for g-r the scatter increases at M9, $r-i$ at L4, $i-z$ at L6 and $z-J$ at L9. Although in detail each of the colors investigated behaves differently these spectral types give an empirical limit of where these colors become of little use for spectral typing purposes. Additionally, it is notable that the error bars (red and black) are typically larger for spectral types where dust is appearing (M6 to L0) and disappearing in the atmosphere (L7 to T0). It should be noted that since colors are not in general derived contemporaneously, differences may arise from intrinsic color variability or from different colors produced by different metallicity or gravity. In addition, we can see that the mean $g-r$ colors have very large scatters after the M dwarfs, which in part arises because the dwarfs cooler than M are very faint in g magnitude and hence their uncertainties are very large.

3. Brown dwarf Gaia colors

The Gaia mission samples the spectral energy distribution of each source by a dedicated spectrophotometric instrument providing low resolution spectra in the blue and red bands. The integrated flux of these spectra yield G_{BP} and G_{RP} magnitudes as two broad passbands. In Jordi (2012) they provide transformation equations to estimate the G_{BP} and G_{RP} from the SDSS $r-i$ based on stellar spectra: $G_{BP} - G_{RP} = 0.5132 + 2.5922(r-i) - 0.6063(r-i)^2 + 0.1065(r-i)^3$ Using the $r-i$ colors in Table 1 we estimate $G_{BP} - G_{RP}$ colors for our spectral range and show this in Figure 2. We note this equation is developed from stellar spectra so any use for brown dwarfs with very different spectra is an extrapolation. As a comparison we have also plotted the $G_{BP} - G_{RP}$ relation from Sarro et al. (2013) based on the DPAC

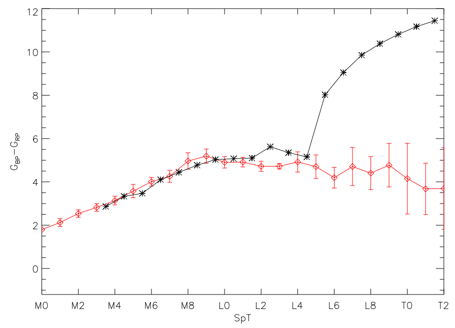

Fig. 2. Predicted $G_{BP} - G_{RP}$ vs SpT for M0 to T1 dwarfs. The curve with red diamonds indicates Gaia color from the transformations equation from Jordi (2012). The error bars are from formal error propagation of the $r - i$ scatter. The curve with black asterisks indicates Gaia model color from Sarro et al. (2013) Table 1.

Gaia filter simulator and spectra from BT-Settl model atmospheres.

The difference in colors later than L5 between the transformation and the simulations is partially due to the problems with the extrapolation to non-stellar objects but it is also probably due to shortfalls in the BT-Settl models. We note that for empirical reference King et al. (2010) give the R-z colors of Eps Indi Ba (T0.5) and Bb (T6) as 5.58 and 5.82 respectively. By the second release of Gaia we will have the blue and red colors of the L dwarfs visible to Gaia and as shown by Figure 1 and in the work of Sarro et al. (2013) the variations of similar spectral types even within these colors may provide us with clues on how to unravel the age-mass degeneracy that is limiting the full exploitation of L dwarfs for the study of our Galaxy.

Acknowledgements. This work is supported by the Marie Curie 7th European Community Framework Programme grant n.247593 Interpretation and Parameterization of Extremely Red COOL Dwarfs (IPERCOOL) International Research Staff Exchange Scheme. ZS acknowledges support from grant NSFC11390373. YW acknowledges support from grant Y41J0331v01. This research has benefitted from the M,L,T and Y dwarf compendium housed at DwarfArchives.org

References

Burrows, A., Volobuyev, M. 2003, ApJ, 583, 985

Jordi, C. 2012, Photometric relationships between Gaia photometry and existing photometric systems, `http://www.rssd.esa.int/cs/livelink/open/2760608`

King, R.R., McCaughrean, M.J., Homeier, D., et al. 2010, A&A, 510, A99

Kirkpatrick, J.D., Cruz, K.L., Barman, T.S., et al. 2008, ApJ, 689, 1295

Nakajima, T., Oppenheimer, B.R., Kulkarni, S.R., et al. 1995, Nature, 378, 463

Rebolo, R., Zapatero Osorio, M.R., Martín, E.L. 1995, Nature, 377, 129

Sarro, L.M., Berihuete, A., Carrión, C., et al. 2013, A&A, 550, A44

Smart, R.L., 2014, MSAIt, 85, 649

West, A.A., Morgan, D.P., Bochanski, J.J., et al. 2011, AJ, 141, 97