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The Classification of L Dwarfs: Is It Based on Clouds or Temperature?

Denise C. Stephens

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

Abstract. A continuous L dwarf classification sequence requires the combined use of far optical (visible) and near infrared spectral indices. However, the visible and near infrared indices currently in use assign subtypes that differ by up to three subclasses due to differences in cloud opacity for objects with the same effective temperature. Therefore, it may be impossible to combine visible and near infrared spectral indices to create one L dwarf classification system, and two classification variables may be necessary.

1. Introduction

To create a continuous L dwarf spectral classification sequence that smoothly transitions from the latest M dwarfs to the earliest T dwarfs, it is necessary to assign spectral class using both far optical (here after referred to as visible) and near infrared spectral indices. However, the nearly one magnitude range in 2MASS $(J - K_s)$ colors observed for L dwarfs with the same visible spectral type suggests that although these objects have similar visible characteristics, their near infrared spectral features vary greatly (Figure 1a). If we assume that the visible spectral indices used for classification are primarily a function of effective temperature $T_{\rm eff}$, then the scatter in near infrared color suggests that the spectral energy distribution of L dwarfs in the near infrared is sensitive to a different physical parameter, such as the opacity of clouds or gravity. It should therefore not be possible to correlate spectral classifications in the visible with spectral classifications in the near infrared since the two systems are dependent on spectral indices controlled by different physical parameters.

2. Comparison of Visible and Near Infrared Spectral Classifications

To determine the possibility of correlating near infrared and visible spectral indices, we examined the near infrared colors and classifications of 22 L dwarfs. These objects were selected because they had both a near infrared classification assigned by Geballe et al. (2002), and a visible classification assigned by either Kirkpatrick et al. (1999, 2000), Fan et al. (2000), Schneider et al. (2002), or Hawley et al. (2002). We plotted each of these L dwarfs twice in Figure 1b using a triangle to indicate the visible classification, a circle to indicate the near infrared classification, and an arrow to connect the two.

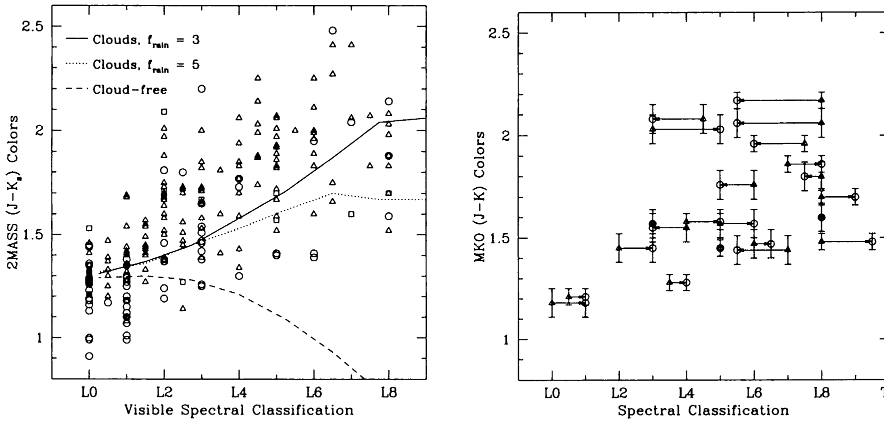

Figure 1. Figure 1a presents 2MASS $(J - K_s)$ colors (Kirkpatrick 2002) for all of the L dwarfs that have visible spectral classifications. The triangles, circles and squares represent objects discovered by the 2MASS, SDSS, and other sky surveys respectively. Figure 1b presents MKO (*J*-*K*) colors (Leggett et al. 2002) for 22 L dwarfs that have both visible (triangle) and near infrared (circle) spectral classifications.

We found that although two-thirds of the 22 L dwarfs had spectral classifications in the visible that agreed to within one spectral type with the near infrared, there were seven L dwarfs whose classification differed by more than one spectral type. The majority of these objects were also found to have very red MKO (*J*-*K*) colors. An interesting trend in classification was then found for the L dwarfs classified as very late objects in the visible. If these objects had very red colors, they were usually classified as much earlier L dwarfs in the near infrared. Whereas if their colors were blue, they were usually assigned to a later L type. This correlation between near infrared colors and classification suggested to us that a second parameter, such as clouds or gravity, might be influencing the measured flux ratio of the near infrared spectral indices.

3. The Influence of Cloud Opacity on Near Infrared Index Values

Theoretical modeling has shown that the very red colors of L dwarfs in the near infrared can be attributed to the condensation of dust and the formation of clouds (Tsuji et al. 2002, Marley et al. 2002). It has also been shown that as the cloud opacity increases, the near infrared colors become redder. In figure 1a we present 2MASS $(J - K_s)$ colors that were determined from high resolution spectra of theoretical atmosphere models (Marley et al. 2002). These solar metallicity models have g = 1000 m s^{-2} and T_{eff} values ranging from 2000 K to 1300 K. They also include an adjustable f_{rain} parameter to account for the unknown micro-physical and dynamical properties of clouds (Ackerman & Marley 2001).

The f_{rain} parameter is the ratio of the sedimentation velocity to the convective velocity. Therefore, if the value of f_{rain} is small this corresponds to very

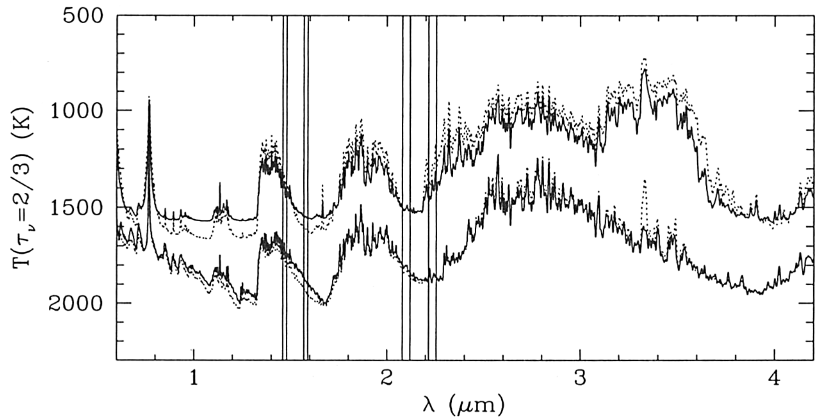

Figure 2. The effect of variable cloud opacities on the depth of the photosphere as a function of effective wavelength is shown.

little precipitation, and dense clouds with large vertical extent. For models with a larger value of f_{rain}, sedimentation is more efficient, resulting in thinner clouds with lower opacity values. It's clear in Figure 1a that as the f_{rain} value decreases and the cloud opacity increases, the near infrared colors also increase, becoming redder. Therefore L dwarfs with the reddest near infrared colors, most likely have very large cloud opacities.

Using high resolution spectra computed from these models (Saumon et al. 2000), we were able to explore how slight changes in cloud opacity could alter the value of the near infrared 1.5 μm H_2O and 2.2 μm CH_4 indices used by Geballe et al. (2002) to assign spectral type in the near infrared. Figure 2 presents spectra for models with T_{eff} of 1300 K and 1700 K.

At each temperature, two cloud models were calculated one with an f_{rain} value of 3 (solid) and the other with an f_{rain} value of 5. On top of these models we then placed vertical lines to indicate the location and width of the 1.5 μm H_2O and 2.2 μm CH_4 spectral indices introduced by Geballe et al. (2002) for the classification of L dwarfs.

It is apparent from the models that the 1.5 μm H_2O index will be sensitive to very small differences in cloud opacity for L dwarfs with the same effective temperature. The flux at 1.6 μm decreases as the cloud opacity increases since photons generated deeper in the atmosphere are unable to penetrate through the clouds. In contrast, the slope of the water band at 1.5 μm is less affected by small changes in cloud opacity since these bands form quite high in the atmosphere where the clouds are still optically thin. The net result is that the value of the 1.5 μm H_2O index will decrease for objects with higher cloud opacities, until it eventually becomes degenerate. At that point all of the very red L dwarfs will have similar water index values.

If we look at the effect of cloud opacity on the 2.2 μm CH_4 index, we find that for the hotter L dwarfs, this index is insensitive to cloud opacity. However, for the cooler L dwarfs, the 1300 K model suggests that the appearance and strength of the methane band at 2.2 μm will be a very sensitive function of

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the cloud opacity. These models suggest that for late L dwarfs with the same effective temperature, the methane band will first appear in objects with lower cloud opacities. Therefore L dwarfs that are classified as L8 in the visible will have similar or later classifications in the near infrared due to the appearance of the methane band. Whereas the late L dwarfs with redder colors will be assigned to earlier spectral types in the near infrared because their increased cloud opacity inhibits the appearance of the methane band.

4. Conclusion

These results show that the current visible and near infrared classification of the L dwarfs is not well correlated. Objects belonging to the same visible spectral class will have different near infrared classifications due to the important role clouds play in controlling the near infrared spectral energy distribution. This will result in degenerate values for the 1.5 μm H_2O and 2.2 μm CH_4 spectral indices. This degeneracy was not found in the original Geballe et al. (2002) classification paper because the majority of L dwarfs used to define these indices have near infrared MKO (J-K) colors less than 1.8. Since these L dwarfs are bluer, the degeneracy due to cloud opacity was not apparent and went unnoticed.

Although the visible and near infrared spectral classifications for the L dwarfs will not agree, they are still both valid because they group together objects with the same spectral features. However, it appears that the features in the visible are mainly correlated with effective temperature, while the spectral features in the near infrared depend on effective temperature, cloud opacity, and possibly gravity. Therefore the final subtypes assigned by visible and near infrared classifications may never agree, and it will be necessary to create a new classification variable to characterize the near infrared flux distribution. This will result in two classification variables, an L subtype to characterize the effective temperature based on the visible classification, and an independent subtype to characterize the cloud opacity and gravity of the L dwarfs based on their near infrared spectral features.

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