FINDING EXTREME SUBDWARFS

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Received 2007 September 28; accepted 2007 December 7; published 2008 February 12

ABSTRACT

I develop a new technique to identify M-type extreme subdwarfs (esdMs) and demonstrate that it is substantially more efficient than previous methods. I begin by obtaining spectroscopy and improved photometry of a sample of 54 late-type halo candidates using the rNLTT reduced proper-motion (RPM) diagram. From spectroscopy, I find that four of these are esdMs, three of which were previously unknown. From the improved photometry, I show that all four lie in a narrow RPM corridor that contains only four non-esdMs. Hence, with good photometry (i.e., without spectroscopy), it appears possible to select esdM candidates with a 50% esdM yield. This is more than an order of magnitude more efficient than previous methods.

Key words: stars: late-type – stars: low mass, brown dwarfs

Online-only material: color figures

1. INTRODUCTION

Extreme subdwarfs are very metal-poor red dwarf stars that are among the oldest stars in the galaxy. These objects are generally members of the Galactic halo and hence comprise the majority of nearby very metal-poor halo stars. While extremely metal-poor subdwarfs may be found at a range of spectral types, the term "extreme subdwarf" generally refers to a late-type (K or M) very metal-poor ([Fe/H] ~ −2) star.

Extreme subdwarfs are a largely untapped resource in Galactic studies, but might prove to be an interesting new population with which to conduct detailed studies of the local Galactic halo. In particular, they may be an interesting population in which to search for the most metal-poor stars. Due to their low luminosity, few extreme subdwarfs are currently known; as such, these stars are rarely the focus of Galactic studies. Nonetheless, with large photometric surveys from which to select candidates imminent and with large telescopes available for spectroscopic follow-up, studies of these nearby but faint halo stars will be feasible.

Relatively few extreme subdwarfs are currently known, the majority having been found in studies targeting nearby stars (e.g. Gliese & Jahreiss 1991; Reid et al. 1995; Hawley et al. 1996; Gizis 1997). The definition of the M, sdM, and M-type extreme subdwarf (esdM) spectral classes by Gizis (1997) includes only 17 esdM stars out of 79 K- and M-dwarfs in the sample. Reid & Gizis (2005) state that only 13% of their 367 proper motion-selected late-type dwarfs are extreme subdwarfs. More work has been done recently on targeted searches for ultracool extreme sub dwarfs, i.e., stars with [Fe/H] ~ −2 and spectral types later than esdM7. These stars are even more elusive, with only a handful currently known. A recent census of ultracool subdwarfs is given by Lépine et al. (2007).

This paper describes a promising technique to find efficiently a significant number of bright, nearby extreme subdwarfs. I select 54 metal-poor subdwarf candidates from a reduced proper-motion (RPM) diagram and obtain spectroscopy and improved photometry from this sample. I use spectral line indices to classify the stars into dwarf, subdwarf, and extreme subdwarf luminosity classes and then show that the improved photometry allows definition of a narrow region on the RPM diagram in which 50% of the sample are confirmed esdMs.

2. SAMPLE SELECTION

The stars studied in this paper have been selected from the revised NLTT (rNLTT) catalog of Gould & Salim (2003) and Salim & Gould (2003). The rNLTT matches Luyten’s original NLTT high-proper motion catalog with the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997) second data release. The revised catalog contains 35,725 NLTT stars and is relatively complete (∼97%) for stars brighter than V < 18 mag with δ > −33°, over a region corresponding to the second incremental 2MASS data release (∼44% of the sky). Because the rNLTT gives proper motions as well as optical and infrared colors, it is an ideal resource from which to select a sample of nearby halo, and hence metal-poor, stars (Salim & Gould 2002).

Subdwarfs were selected using an RPM diagram, which plots the RPM, H_M = m + 5 log µ + 5, versus a color index and is used to separate stars into distinct luminosity classes. This work follows Salim & Gould (2002, 2003) and employs a wide wavelength baseline (V − J) to sort high-proper-motion stars in the rNLTT cleanly into main-sequence star, subdwarf, and white dwarf classes.

Subdwarfs are selected from the RPM diagram as in Marshall (2007) using discriminator lines as defined by Salim & Gould (2003). Unlike that of Marshall (2007), however, this sample was selected from the entire rNLTT, i.e., the stars were not required to be equatorial. The stars studied here are required to have (V − J) > 3.5 mag. It should be noted that this criterion yields a sample of very late-type metal-poor (halo) stars, though they may not necessarily be extreme subdwarfs. This color cut was employed simply because the rNLTT photometry is not accurate enough to select reliably only the bluer stars in this region, where the more metal-poor extreme subdwarfs are expected to lie. This is discussed in more detail in Section 5.

The above criteria yield 54 subdwarfs. These stars are marked on the RPM diagram of the entire rNLTT in Figure 1.

3. OBSERVATIONS AND DATA REDUCTION

Photometric and spectrophotometric observations were obtained during 2003–2004 at the MDM Observatory on Kitt Peak, Arizona, and at the Cerro Tololo Inter-American Observatory (CTIO) in Chile.
Spectrophotometric observations were obtained with the CTIO 1.5 m telescope and with the MDM Observatory 2.4 m telescope. Observations generally covered the wavelength range 6500–8100 Å. All observations were obtained using a north–south oriented slit, and observations were made as the targets transited the meridian (±1 h of transit) in order to minimize slit losses.

The CCDS Spectrograph\(^1\) was used for all observations obtained at the MDM 2.4 m telescope. The 350 l mm grating and a 1′0 (87 μm) slit was used for all observations, producing a spectral resolution of 3.4 Å per resolution element.

\(^1\) See http://www-astronomy.mps.ohio-state.edu/MDM/CCDS/.

4. RESULTS

4.1. BVRI Photometry

Table 1 presents new photometry for the 54 selected stars, along with existing 2MASS photometry. Column 1 of Table 1 gives the NLTT identifier of each target; Columns 2–3 give the position of the star. Columns 4–7 present the \(B\), \(V\), \(R\), \(I\), and \(V - I\) photometry measured in this work. The \(V - J\), \(V - H\), and \(V - K\) color indices in Columns 8–10 are formed by simply taking the difference between the \(V\)-band color measured here and the infrared 2MASS photometry. Column 11 indicates how many photometric measurements were averaged together to form the final photometry. In general, multiple photometric measurements were obtained of each star; 128 measurements of 54 stars were obtained, and 43 stars have more than one measurement.

Figure 2 shows a RPM diagram constructed with the new photometry presented here, along with improved photometry of 564 candidate subdwarfs from Marshall (2007). Note that two of the stars in this sample have scattered to lower RPMs; this is most likely due to a misidentification, either in this work or in the NLTT (or the original Luyten catalog).

4.1.1. Photometric Errors

The photometric errors were determined by comparing the photometry of each of the 43 stars with multiple measurements (see Figure 3). The error estimates (0.03, 0.07, 0.04, 0.07) mag in \((V, B - V, V - R, V - I)\) were derived from the average of the standard deviations of these multiple measurements. (See Marshall 2007 for a more thorough discussion)

4.1.2. Comparison with NLTT Photometry

The NLTT photometry (derived from USNO-A; Monet 1996, 1998) is quite inaccurate at magnitudes as faint as those studied here. Figure 4 compares the photometry measured in this work with that given by NLTT. Overplotted in the figure is the relation found by Marshall (2007) describing the comparison between modern, more accurate photometry, and the NLTT values. If six outliers are removed, the scatter is about of 0.25 mag, in good agreement with the estimate by Salim & Gould (2003). These may be due to a misidentification or perhaps simply to poor photometry in the NLTT.

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\(^2\) See http://www.ctio.noao.edu/spectrographs/60spec/60spec.html.

\(^3\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
4.2. Spectroscopic Classification

The stars are classified following Gizis (1997). This technique defines a set of spectral line indices to be applied to moderate-resolution ($R \approx 3000$) spectra to determine whether a given star is a dwarf ([$m/H] \approx -0.0$), subdwarf ([$m/H] \approx -1.2$), or extreme subdwarf ([$m/H] \approx -2.0$). The line indices are centered on the CaH and TiO molecular features that are prevalent and easily measurable in moderate-resolution spectra of late-type stars and whose strength is dependent on the star’s metallicity. The CaH indices are compared to the TiO index and discriminator lines are drawn to separate the three classes of stars.

4.2.1. Measurement of Line Indices

The line indices described by Gizis (1997) are measured by integrating over a spectral region containing the absorption feature of interest, then comparing the result to a nearby
Figure 2. Reduced proper-motion diagram constructed using the improved photometry. The small points in this figure show the photometry of the earlier-type (F, G, K) subdwarfs studied by Marshall (2007). The crosses represent the new photometry of the 54 late-type subdwarfs studied here. (A color version of this figure is available in the online journal)

Figure 3. Standard deviation of multiple photometric measurements of a given star as a function of magnitude. The mean photometric error in these measurements is 0.03 mag in $V$, 0.07 mag in $B - V$, 0.04 mag in $V - R$, and 0.07 mag in $V - I$. All of this error is likely to be due to measurement error, as the stars are not expected to be variable.

4.2.2. Determination of Spectroscopic Classification

Spectroscopic classification is determined as described by Gizis (1997). Following the procedure described therein, the CaH$_2$ and CaH$_3$ indices are compared to the TiO5 index for each star, and discriminator lines are drawn to distinguish the luminosity classes. Figure 5 shows the classification scheme as defined by Lépine et al. (2003), based on the Gizis (1997) indices: Figure 5(a) separates dwarfs (top, open triangles) from subdwarfs (middle, filled squares) and extreme subdwarfs (lower right, open stars). The discriminator in Figure 5(b) separates dwarfs (top) from subdwarfs and extreme subdwarfs (bottom).

Once the stars have been classified according to luminosity class, the relations given in Gizis (1997) are used to determine the spectral type of each star. These relations are stated to be accurate to $\pm 0.5$ subclass.

Table 3 presents the indices measured in each spectrum: Column 1 gives the NLTT identifier and Columns 2–3 are the new $V$ and $V - I$ photometry. Columns 4–5 give the date and telescope on which the spectrum was obtained. The indices measured in each spectrum are given in Columns 6–8. Column 9 of Table 3 gives the classification of each star as determined in this work. Spectral classifications are given to 0.5 subclass for M-type dwarfs, subdwarfs, and extreme subdwarfs. For earlier K-type dwarfs, the relations are somewhat less accurate and these determinations are given to the nearest subclass, or if found to be earlier than K5, simply cited as “K.”
classifies it as M4.5; here, a spectral type of M4.0 is measured. The roughly ±0.5 subclass differences seen in these common determinations are in accord with the expected uncertainty in the technique.

5. DISCUSSION

Six extreme subdwarfs are found in this sample of 42 candidates. Four of the six are esds (NLTT09262: esdM3.5, NLTT37223: esdM3.5/6.0, and NLTT52449: esdM5.0), although the exact type of NLTT37223 remains ambiguous. The classification of NLTT05282 (esdM9.5) is less secure since it is not clear that this technique is applicable to such late spectral types. This may be an interesting target for further study. Two stars, NLTT47221 and NLTT11568, are found to be esdK stars.

Figure 9(a) shows the RPM diagram presented in Figure 2, with the three luminosity classes shown by different symbols. This figure shows the separation of the three luminosity classes quite distinctly: extreme subdwarfs (open stars) lie to the left of the diagram, as expected due to their lower metallicity which makes them bluer at a given luminosity. The subdwarfs (filled squares) are slightly redder than the extreme subdwarfs, and the near-solar-metallicity M-dwarfs (open triangles) lie to the right of the diagram. The two circled points are the esdK stars. Since the classification scheme was devised to classify early- to mid-M dwarfs and subdwarfs, it is less secure for K-type stars. It is possible that these two stars classified as esdK are in fact sdK or K-dwarfs. This may also be seen in Figure 5; the esdK stars in this figure are the outliers to the top right.

Ten percent (4/42) of the subdwarfs studied spectroscopically are shown to be esdMs according to this technique. This is a relatively high yield, given the difficulty in finding and observing candidate extreme subdwarfs. An even higher yield could be had if one were to select candidate extreme subdwarfs using more accurate photometry, targeting stars only from the blue region of a RPM diagram. As a demonstration of this point, Figure 9(b) shows the RPM diagram using the original rNLTT photometry but with the luminosity classes of the stars indicated as in Figure 2. In this figure there is no obvious way to distinguish the stars, and although the extreme subdwarfs lie in or near the newly defined region, it is no longer convincing that the entire region preferentially contains extreme subdwarfs. As discussed in Section 2, the stars studied here were not particularly selected to be extreme subdwarfs, simply to be very late-type subdwarfs, i.e., they were selected to lie within the restricted subdwarf discriminators of the RPM diagram as in Marshall (2007). However, with the exception of the two esdK stars, the extreme subdwarfs lie on a well-defined relation in the RPM diagram. A line is fit to these points, and a new set of extreme subdwarf discriminator lines is drawn with the equations $H_V = 3 \times (V - J) + 10.79$ and $H_V = 3 \times (V - J) + 11.79$. These lines are shown in Figure 10. Fifty percent of the objects within this region are subdwarfs. It is somewhat suggestive that all four extreme subdwarfs lie on a rather straight line; larger samples of stars with accurate photometry will be needed to refine these new discriminator lines.

It is now apparent that, although some scatter is still present, the more metal-poor extreme subdwarfs lie to the left of the RPM diagram, while the solar-metallicity dwarfs are toward the right, exactly as expected. It is somewhat surprising that the M-dwarf sequence lies so close to the subdwarf sequence; this may be due to a change in the slope of the red end of the M-dwarf main sequence. This will have to be investigated more carefully by constructing a color–magnitude diagram of

![Figure 5. Classification scheme for M-dwarfs, subdwarfs, and extreme subdwarfs as defined by Gizis (1997). Spectral line indices are measured in each spectrum and have been calibrated in order to divide the stars by luminosity class. In the figure M-stars are open triangles, subdwarfs are filled squares, and extreme subdwarfs are represented by open stars. Part (a) plots the main criterion, the CaH2/TiO5 ratio, that divides the stars into the three luminosity classes, using discriminators as defined by Lépine et al. (2003) (based on Gizis 1997, indices). Part (b) provides a secondary confirmation of the classification scheme, separating dwarfs from the subdwarfs.](image-url)
Figure 6. Spectra of the six extreme subdwarfs in the sample. Note that two spectra (with different derived spectral types) are shown for NLTT37223. The spectral regions near 6867 and 7594 Å are somewhat contaminated by atmospheric absorption.

Table 3
Measured Line Indices and Spectral Classifications

| NLTT  | V   | V − J | Date         | Telescope | CaH2 | CaH3 | TiO5 | Class |
|-------|-----|-------|--------------|-----------|------|------|------|-------|
| 1352  | 19  | 0.053 | 2003 Oct 4   | CTIO      | 0.296| 0.450| 0.354| sdM6.0|
| 4308  | 19  | 1.164 | 2003 Oct 28  | MDM       | 0.344| 0.622| 0.366| M4.5  |
| 4697  | 19  | 2.973 | 2003 Nov 9   | CTIO      | 0.397| 0.608| 0.246| M5.0  |
| 5282  | 19  | 1.136 | 2003 Jul 27  | CTIO      | 0.128| 0.049| 0.740| esdM9.5|
| 5399  | 19  | 0.004 | 2003 Oct 3   | CTIO      | 0.014| 0.737| 0.130| sdM6.0|
| 6590  | 18  | 2.873 | 2003 Oct 28  | MDM       | 0.308| 0.474| 0.577| sdM5.5|
| 9260  | 18  | 2.929 | 2003 Oct 3   | CTIO      | 0.420| 0.610| 0.798| esdM3.5|
| 11568 | 19  | 2.858 | 2003 Oct 7   | MDM       | 0.934| 0.886| 1.112| esdK7  |
| 12010 | 19  | 2.046 | 2003 Oct 4   | CTIO      | 0.453| 0.619| 0.650| sdM3.5|
| 12291 | 18  | 2.661 | 2003 Oct 8   | MDM       | 0.510| 0.610| 0.775| sdM3.0|
| 12790 | 19  | 1.592 | 2003 Nov 9   | MDM       | 0.308| 0.474| 0.577| sdM5.5|
| 16693 | 18  | 2.728 | 2003 Oct 3   | CTIO      | 0.420| 0.610| 0.798| esdM3.5|
| 17301 | 17  | 2.796 | 2003 Oct 28  | MDM       | 0.421| 0.668| 0.441| sdM6.5|
| 19204 | 18  | 2.413 | 2004 Apr 15  | MDM       | 0.403| 0.648| 0.508| sdM3.5|
| 21356 | 19  | 3.584 | 2004 Nov 4   | MDM       | 0.435| 0.689| 0.491| M3.0   |
| 35216 | 19  | 3.205 | 2003 Jun 15  | MDM       | 1.132| 1.064| 1.002| K      |
| 36953 | 18  | 2.472 | 2004 Jun 10  | CTIO      | 0.442| 0.701| 0.652| sdM3.0|
| 37223 | 18  | 2.332 | 2003 Jul 28  | CTIO      | 0.225| 0.456| 0.606| esdM6.0|
| 38350 | 18  | 2.505 | 2004 Jun 10  | CTIO      | 0.319| 0.668| 0.810| esdM3.5|
| 38947 | 18  | 2.958 | 2004 Jun 11  | CTIO      | 0.457| 0.759| 0.801| sdM2.5|
| 42233 | 19  | 1.123 | 2004 Apr 14  | MDM       | 0.378| 0.579| 0.468| sdM4.0|
| 42815 | 19  | 1.350 | 2004 Apr 11  | MDM       | 0.492| 0.693| 0.751| sdM2.5|
| 45501 | 17  | 1.502 | 2003 Oct 28  | MDM       | 0.215| 0.488| 0.441| sdM6.5|
| 45952 | 18  | 1.562 | 2003 Jun 9   | MDM       | 1.132| 1.064| 1.002| K      |
| 47221 | 19  | 1.341 | 2003 Jul 26  | CTIO      | 0.210| 0.502| 0.368| sdM6.0|
| 50476 | 17  | 2.440 | 2003 Jul 27  | CTIO      | 0.346| 0.599| 0.387| sdM4.5|
| 50931 | 18  | 2.379 | 2003 Jul 28  | CTIO      | 0.379| 0.625| 0.402| M4.0   |
| 51256 | 19  | 1.794 | 2003 Oct 3   | CTIO      | 0.356| 0.596| 0.393| sdM4.5|
| 51509 | 19  | 4.374 | 2003 Oct 28  | MDM       | 0.388| 0.644| 0.388| M4.0   |
| 52449 | 17  | 2.735 | 2003 Oct 26  | CTIO      | 0.322| 0.456| 0.691| esdM5.0|
| 54542 | 18  | 3.682 | 2003 Oct 28  | MDM       | 0.404| 0.629| 0.611| sdM3.5|
| 54950 | 18  | 3.958 | 2003 Nov 9   | MDM       | 1.045| 0.980| 0.977| K5     |
| 55103 | 18  | 4.093 | 2003 Jul 26  | CTIO      | 0.306| 0.537| 0.297| sdM5.0|
| 55262 | 19  | 3.628 | 2004 Oct 7   | MDM       | 1.003| 0.957| 0.929| K5     |
Figure 7. Spectra of the 21 subdwarfs in the sample. The spectral regions near 6867 and 7594 Å are somewhat contaminated by atmospheric absorption.

Figure 8. Spectra of the 15 K- and M-dwarfs in the sample. The spectral regions near 6867 and 7594 Å are somewhat contaminated by atmospheric absorption.
late-type stars with known distances, but this result is opposite that found by Gould (2003). Since the extreme subdwarfs lie to the blue side of the RPM diagram, future searches for extreme subdwarfs should target only the defined region. This will be more straightforward when studying stars with accurate photometry at faint magnitudes (e.g., stars found in the Sloan Digital Sky Survey (SDSS) catalog).

6. SUMMARY AND FUTURE WORK

A new, efficient method for finding extreme subdwarfs has been described. New photometry and spectroscopic observations of 54 subdwarfs have been presented, allowing for the construction of an accurate RPM diagram of the targets. Using spectral line indices measured in the moderate-resolution spectra and a classification technique defined by Gizis (1997), 42 late-type dwarfs are classified and four esdM stars are found, three of which are previously unclassified. A new selection method is defined which uses a RPM diagram to select more efficiently a sample of extreme subdwarfs. With the new selection criteria, ~50% of candidates should be confirmed extreme subdwarfs. It should be noted that this technique has a strong kinematic bias inherent in the sample selection and should not be used to define an unbiased sample of extreme subdwarfs. Rather, this technique selects stars on the basis of their high-proper motion and is therefore only sensitive to stars with velocities perpendicular to the line of sight.

Although the entire rNLTT has now been mined for extreme subdwarfs, there are prospects for finding even more nearby extreme subdwarfs. Larger proper-motion surveys now exist (e.g., Lépine & Shara 2005). Furthermore, the SDSS SEGUE project contains proper-motion information for many more Galactic stars than was previously available. Applying the techniques developed here to these larger databases will certainly produce many more candidate extreme subdwarfs for follow-up spectroscopic study.

It should be noted that the rNLTT is not complete for magnitudes as faint as the stars studied here. Searching for these stars in a catalog with a fainter brightness limit is sure to produce more candidates, although fainter targets will be more difficult to follow-up spectroscopically. With large, efficient telescopes, however, even very faint extreme subdwarfs will be accessible for follow-up study.

The author acknowledges many useful conversations about the sample selection with A. Gould and many enjoyable observing runs with D. L. DePoy.

REFERENCES

Gizis, J. E. 1997, AJ, 113, 806
Gizis, J. E., & Reid, I. N. 1997, PASP, 109, 849
Gliese, W., & Jahreiss, H. 1991, in Preliminary Version of the Third Catalog of Nearby Stars, ed. L. E. Bratzmann, & S. E. Gesser (Greenbelt, MD: NASA)
Gould, A. 2003, ApJ, 583, 765
Gould, A., & Salim, S. 2003, ApJ, 582, 1001
Hawley, S. L., Gizis, J. E., & Reid, I. N. 1996, AJ, 112, 2799
Lépine, S., Rich, R. M., & Shara, M. M. 2003, AJ, 125, 1598
Lépine, S., Rich, R. M., & Shara, M. M. 2007, ApJ, 669, 1235
Lépine, S., & Shara, M. M. 2005, AJ, 129, 1483
Marshall, J. L. 2007, AJ, 134, 778
Monet, D. G. 1996, BAAS, 188, 5405
Monet, D. G. 1998, BAAS, 193, 112003
Reid, I. N., & Gizis, J. E. 2005, PASP, 117, 676
Reid, I. N., Hawley, S. L., & Gizis, J. E. 1995, AJ, 110, 1838
Salim, S., & Gould, A. 2002, ApJ, 575, 83
Salim, S., & Gould, A. 2003, ApJ, 582, 1011
Skrutskie, M. F., et al. 1997, in The Impact of Large-Scale Near-IR Sky Survey, ed. F. Garzon et al. (Dordrecht: Kluwer), 187