LSR1610-0040: the first early-type L subdwarf

Sébastien Lépine\textsuperscript{1,2,3}, R. Michael Rich\textsuperscript{4}, and Michael M. Shara\textsuperscript{1}

ABSTRACT

We report the discovery of LSR1610-0040, a previously unreported $r = 17.5$ star with a very high proper motion $\mu = 1.46'' \text{yr}^{-1}$. This very cool star ($b-i=6.3$) is found to have a peculiar spectrum that does not fit into the standard sequence of late-M dwarfs and L dwarfs. Rather, the spectrum is more typical of an ultra-cool subdwarf, with weak bands of TiO and no detectable VO. But because LSR1610-0040 is so much redder than any other sdM known, and because it does not appear to fit well into the sdM sequence, we propose that LSR1610-0040 be assigned a spectral type sdL, making it the first early-type L subdwarf known. Evidence suggests that LSR1610-0040 is an old, metal-poor star whose mass is just above the limit of hydrogen burning ($M \approx 0.08M_\odot$).

Subject headings: Stars: late-type — stars: low-mass, brown dwarfs — subdwarfs — stars: fundamental parameters — Galaxy: stellar content

1. Introduction

Recent years have seen the discovery, through the use of large infrared surveys, of numerous objects extending the main sequence down to, and beyond the limit of hydrogen burning (Kirkpatrick \textit{et al.} 1999), and well into the substellar regime (Burgasser \textit{et al.} 2002). This sequence of objects, which go from spectral type M, to spectral type L, to spectral

\textsuperscript{1}Department of Astrophysics, Division of Physical Sciences, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024, USA, lepine@amnh.org, shara@amnh.org

\textsuperscript{2}Kalbfleisch research fellow

\textsuperscript{3}Visiting Astronomer, MDM observatory

\textsuperscript{4}Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095, USA, rmr@astro.ucla.edu
type T, consists almost exclusively of relatively metal-rich, red dwarfs and brown dwarfs. To this date, however, no equivalent spectroscopic sequence exists for subdwarfs. Cool, red, M subdwarfs (sdM) are the metal-poor equivalent of the red dwarfs, and they are the low-mass representatives of Population II stars. The current spectroscopic sequence of M subdwarfs does not extend beyond spectral subtype sdM8.0 (Lépine, Shara, & Rich 2003), and very few “ultra-cool subdwarfs” (spectral subtype sdM6.0 and later) are known. As a result, the physical properties of old, very low mass stars in the Galaxy are poorly constrained.

Nevertheless, extremely cool subdwarf stars of spectral type later than sdM8 are likely to exist in small but significant numbers. Deep photometry of the globular cluster Messier 4 strongly suggest that its main sequence extends beyond spectral type sdM8 (Richer et al. 2002). If very cool, hydrogen burning “L subdwarfs” (sdL) do exist in globular clusters, then they are most likely to exist in the thick disk or halo as well and should be detected in the field. They should however be relatively rare, as they correspond to a thin slice of the mass range just above the H-burning limit. Estimates place them at less than 1 in 30,000 stars in the solar neighborhood. But their probability of detection should be significantly increased in samples of high proper motion stars, which are strongly biased towards high-velocity (halo) objects. Nearby L subdwarfs are thus most likely to be identified among large samples of faint, high proper motion stars.

Recently, Burgasser et al. (2003) have identified what is most likely the first metal-poor L subdwarf. This candidate sdL, known as 2MASS 0532+8246, is a faint object with a large proper motion (μ ≃ 2.6″ yr⁻¹) identified in the 2MASS survey from its large optical to infrared color (it has no detectable counterpart in the in the blue and red Palomar Sky Survey plates). While its spectral energy distribution is analogous to an L7 dwarf, 2MASS 0532+8246 shows unusually strong lines of TiO and metal hydrides in the optical, as well as an unusually strong collision-induced H₂ absorption in the infrared. Evidence suggests it is substellar. This discovery opens the prospect for obtaining a classification sequence for metal-poor objects down to the hydrogen-burning limit and beyond. At this point, there remains a wide gap to be filled between the known ultra-cool sdM and 2MASS 0532+8246, before a consistent sequence can be established.

In this paper, we report the discovery of LSR1610-0040, a very red star with a large proper motion μ = 1.46″ yr⁻¹. Our spectroscopy reveals that the star shows features associated with ultra-cool M subdwarfs, although it appears to be significantly cooler than the coolest sdM known to date, the sdM8.0 star LSR1425+7102. As it appears to be intermediate between ultra-cool sdM stars and the candidate sdL object 2MASS 0532+8246, we propose that LSR1610-0040 is the first known example of an “early-type” L subdwarf.
2. Proper Motion Discovery and Photometry

The high proper motion star LSR1610-0040 was discovered as part of our new search for high proper motion stars in the northern sky using the Digitized Sky Survey (Lépine, Shara, & Rich 2002), performed as a part of the NStars initiative. The Digitized Sky Survey discovery fields are presented in Figure 1. The left panel shows the 1953 POSS-I red (xx103aE + plexi) image of a $4.25' \times 4.25'$ field centered on the position of the star at epoch 2000.0. The right hand side shows the 1992 POSS-II red (IIIaf + RG 610) image of the same field. The large temporal baseline makes the motion of LSR1610-0040 very obvious; the star is moving at a rate $\mu_{RA} = -0.77'' \text{yr}^{-1}$, $\mu_{DEC} = -1.23'' \text{yr}^{-1}$.

The star is not recorded in the LHS catalog (Luyten 1979) and a search on Simbad (http://simbad.u-strasbg.fr/Simbad) around that location on the sky yielded no results, confirming that this high proper motion star is being reported here for the first time. We have found counterparts of the star in the USNO-B1.0 catalog (Monet et al. 2003). The object is identified from the blue, red and infrared POSS-II plates and the calculated USNO-B1.0 photographic magnitudes are $b = 21.1$, $r = 17.5$, and $i = 14.8$. The USNO-B1.0 lists this star as having a proper motion $[\mu_{RA}, \mu_{DE}] = [+162,-370] \text{mas yr}^{-1}$, which suggests an incorrect pairing to a first epoch object on the POSS-I plates. Indeed, the USNO-B1.0 gives for that star a first epoch POSS-I blue magnitude $b_1 = 21.2$ but no first epoch POSS-I red magnitude ($r_1 = 0.0$). As it turns out, visual examination of scanned survey images reveal that the star does not show up on the POSS-I blue (103aO) plate at the position extrapolated from the proper motion, although it shows up very clearly on the POSS-I red (103aE) plate. But the reality of this high proper motion star cannot be cast into doubt, as the star clearly shows up on 10 other optical survey plates: as a faint star on 2 different SERC-EJ (IIIaJ) plates, as a much brighter star on 2 other SERC-ER (IIIaF), and also on 2 each of POSS-II blue (IIIaJ), red (IIIaF), and infrared (IVN) plates. In each case the position accurately matches the extrapolated proper motion of the star at the epoch of the plate.

The high proper motion star also shows up as a bright star in the 2MASS survey, and we find it to be a perfect match to the a bright object in the 2MASS All-Sky Point Source Catalog. Identified as 2MASS J16102900-0040530, it has infrared magnitudes $J = 12.91$, $H = 12.32$, and $K_s = 12.02$.

3. Spectroscopy

The star LSR1610-0040 was observed on the night of 19 February 2003, at the 2.4m Hiltner telescope of the MDM Observatory. A spectrum of the star was obtained with the
MkIII spectrograph equipped with 2048×2048 front-side illuminated, thick LORAL CCD (“Wilbur”). We used a 300 l/mm grating blazed at 7500Å, with a red order blocking filter. The star was imaged through a 0.8″ slit, yielding a nominal spectral resolution of 7Å. Standard spectral reduction was performed with IRAF using the CCDPROC and SPECRED packages, including removal of telluric features. Calibration was derived from observations of the standards Feige 66 and Feige 67 (Massey & Gronwall 1990). Both the target and the standard were observed at the smallest possible airmass (< 1.3) and with the slit at the parallactic angle to minimize slit loss due to atmospheric diffraction, providing excellent spectrophotometric calibration.

The spectrum of the star is displayed in Figure 2. The main spectral features of the very red object are identified. The most prominent features are the molecular bands of CaH, TiO, FeH, CrH, and H$_2$O, and atomic lines of K I, Rb I, and Na I. We measured the radial velocity of the star from the centroids of the K I $\lambda\lambda$7665,7699 and Rb I $\lambda\lambda$7800,7947 atomic absorption lines. After correction for the earth’s motion in space, and accounting for uncertainties, we find that the star has a large heliocentric radial velocity $V_{hel} = -130 \pm 15$ km s$^{-1}$.

4. Spectral classification

A comparison with the standard sequence of M dwarfs (Kirkpatrick, Henry, & McCarthy 1991) and L dwarfs (Kirkpatrick et al. 1999), shows no clear similarity between LSR1610-0040 and any single one of the subtypes of the metal-rich sequence. Rather, our star shows a variety of features which are reminiscent of both late-type M dwarfs and early to mid-type L dwarfs. While the spectral energy distribution of LSR1610-0040 is comparable to that of a late-type M dwarf, the molecular bands of TiO beyond 7500Å are unusually weak. The VO bands, which are strong in all late-type M dwarfs and early-type L dwarfs, are completely absent (or extremely weak) in LSR1610-0040. The spectral features most at odds with an M dwarf classification are the two prominent atomic lines of Rb I, which are normally seen only in L dwarfs. The detection of the FeH and CrH bands redwards of 8000Å especially the relatively strong FeH bandhead at $\lambda$9896 are also reminiscent of early-L to mid-L spectra, although the bands do appear to be relatively weaker. On the other hand, the strong CaH and TiO bands around 7000Å are completely at odds with the standard L dwarf sequence.

On the other hand, the spectrum of LSR1610-0040 bears a significant resemblance to the spectrum of the ultra-cool sdM8.0 star LSR1425+7102 (Lépine, Shara, & Rich 2003). In particular, both stars have strong CaH $\lambda6750$ and TiO $\lambda7053$ bands, but very weak TiO $\lambda7589$ and $\lambda8432$ as well as weak CrH and FeH. The main differences are the RbI lines,
absent in LSR1425+7102, and the significantly redder color of LSR1610-0040. Overall, it looks like the spectrum of LSR1610-0040 is consistent with the star being a new type of extremely cool subdwarf. Thus, the many peculiarities in the spectrum of LSR1610-0040, when it is compared to the M-L dwarf sequence, could be explained simply in terms of a low metal abundance.

But LSR1610-0040 does not fit well into the standard sdM sequence. Spectral subtypes for sdM stars are based on the strengths of the CaH and TiO molecular bands around 7000Å (Reid, Hawley, & Gizis 1995), as measured by the CaH2, CaH3, and TiO5 indices. For LSR1610-0040 we measure CaH2=0.257, CaH3=0.478, and TiO5=0.295. Applying these values to the standard quantitative classification scheme of M subdwarfs, developed by Gizis (1997) and expanded by Lépine, Shara, & Rich (2003), nominally yields a spectral type sdM6.0. However, this spectral assignment is completely inconsistent with the spectral energy distribution of LSR1610-0040. To quantify this, we use the Color-M index, which measures the slope of the spectrum in the 6500Å-8000Å range (Lépine, Rich, & Shara 2003). The value we find for LSR1610-0040 (Color-M=4.7) is significantly larger than the typical value for sdM6.0 stars (Color-M≃2.2), even larger than the value we measured in the only known sdM8.0 star LSR1425+7102 (Color-M=2.4). The extreme color of LSR1610-0040 is also confirmed by the optical photometry: with a \( b-i = 6.3 \), the star is significantly redder than LSR1425+7102 (\( b-i = 4.6 \)). The same holds true for the infrared to optical color: LSR1610-0040 has \( r-K_s = 5.5 \), while the sdM8.0 has \( r-K_s = 4.3 \).

This raises the possibility that LSR1610-0040 should be considered an “L subdwarf” (sdL), by extension of the M-L dwarf sequence to an equivalent sdM-sdL sequence. Such a sequence is, however, not yet defined beyond spectral type sdM8.0, and the only other known candidate sdL to this date is the extremely cool metal-poor object 2MASS 0532+8246 (Burgasser et al. 2003). Spectroscopic features in 2MASS 0532+8246 which make it stand apart from the L dwarf sequence could help explain some of the “anomalies” observed in LSR1610-0040. In particular, TiO bands are unusually strong in 2MASS 0532+8246. If this is true of the whole sdL sequence, then the strong TiO λ7053 band observed in LSR1610-0040 might not be so unusual for an early-type sdL. But overall, the fact that 2MASS 0532+8246 is evidently so much cooler than LSR1610-0040 makes any comparison between the two stars difficult.

In order to shed further light on the status of LSR1610-0040, we compare its spectral energy distribution to the theoretical models of low mass, metal-poor stars computed by Baraffe et al. (1997). Assuming that LSR1610-0040 is related to M subdwarfs, which have a metallicity around \([m/H] \sim -1.2 \) (Gizis 1997), we compare it to models with \([m/H] = -1.0, -1.3, \) and \(-1.5 \). We conclude that LSR1610-0040 is most consistent with a hydrogen
burning object with a mass no larger than $0.085\,M_\odot$, and with an effective temperature in the range 2100K-2500K. Exact values for the mass and effective temperatures are dependent on the metallicity of the object; a detailed spectroscopic modeling will thus be required to pinpoint the fundamental parameters of the star. In any case, the estimated range in effective temperature (2100K-2500K) is consistent with the effective temperatures generally assigned to metal-rich early-type L dwarfs (Dahn et al. 2002).

Hence we have a cool star whose spectrum clearly suggests a metal-poor composition, whose color is much redder than any other known sdM stars, and for which the standard spectral classification scheme of Gizis (1997) for sdM stars is invalid. Furthermore, its colors are consistent with a hydrogen burning star just above the hydrogen burning limit and with an effective temperature in the range normally assigned to early-type L dwarfs. We therefore propose that LSR1610-0040 should be considered the first prototype of an early-type L subdwarf, in contrast with the much cooler sdL object 2MASS 0532+8246 found by Burgasser et al. (2003), which may now be considered a late-type L subdwarf.

5. Distance and kinematics

The general spectral energy distribution of LSR1610-0040 is similar to that of a late-type M dwarf. The optical to infrared color $r - K_s \approx 5.5$ is actually similar to that of an M6 dwarf (Kirkpatrick et al. 1999); the infrared colors $J - H = 0.59$ and $H - K_s = 0.30$ are also typical of a late-type M dwarf. The absolute $J$ magnitude of an M6 dwarf is $M_J \approx 10.5$ (Dahn et al. 2002). With an $M_J = 10.5$, LSR1610-0040 would be at a distance of 30pc. This is clearly an absolute, upper limit, because subdwarfs are all underluminous relative to dwarfs of the same color. If we instead use the observation that subdwarfs of a given spectral subtype tend to have a similar absolute magnitude in the infrared as dwarfs of the same spectral subtype (Lépine, Rich, & Shara 2003), than we may assume that LSR1610-0040 has the luminosity of an early-type L dwarf, with $M_J \approx 12$ (Dahn et al. 2002). Under this assumption, LSR1610-0040 would have a distance modulus of about 1.0, placing it at about 15 parsecs from the Sun. Using the absolute magnitude calibrations of metal-rich stars for LSR1610-0040 is, however, a risky proposition at this point.

Alternatively, we can estimate a distance for LSR1610-0040 based on the models of Baraffe et al. (1997). A $0.083\,M_\odot$ star with a metallicity $[M/H]=-1.0$ to -1.5 should have absolute magnitudes $M_R \approx 16.3$, $M_I \approx 13.8$, and $M_J \approx 11.8$. These values suggest a distance modulus $\approx 1.1$ for LSR1610-0040, which is consistent with the estimate given above. Given all the uncertainties, we conclude that a distance modulus in the range 0.5-1.5 is a reasonable estimate for LSR1610-0040, and we thus conservatively place the star at a distance of 12-
20pc, or d=16 ± 4pc

Based on this distance, the large proper motion yields an estimated transverse velocity $V_t = 110 \pm 30 \text{km s}^{-1}$. Combined with the radial velocity measurement, we calculate a space motion $[U, V, W] = [-117 \pm 18, -108 \pm 24, -10 \pm 19] \text{km s}^{-1}$ relative to the local standard of rest, where $U$ is towards the Galactic center, $V$ towards the direction of Galactic rotation, and $W$ towards the north Galactic pole. This places LSR1610-0040 just outside the 2σ limits of disk stars, as defined by Chiba & Beers (2000). The relatively low value of $W$ makes it most likely for LSR1610-0040 to be an Intermediate Population II star, i.e. a possible member of the old disk, although a halo membership cannot be excluded. In any case, the kinematics support the idea that LSR1610-0040 is an old star.

6. Conclusions

We have discovered a cool star with a large proper motion $\mu = 1.46'' \text{yr}^{-1}$. Spectroscopy reveals that the star doesn’t fit in the standard M dwarf and L dwarf sequence, and that it is most likely a metal-poor object. The star is shown to be much redder than any other known subdwarf, and cannot be fitted in the sequence of M subdwarfs. The star appears to be somewhat intermediate between the ultra-cool sdM8.0 star LSR1425+7102 and the recently discovered L subdwarf 2MASS 0532+8246. We suggest that LSR1610-0040 is the first example of an “early-type” L subdwarf.

This star should be considered a high priority target for astrometric parallax determination. Because it is a relatively bright object in the red (i=14.8) and infrared (J=12.9), LSR1610-0040 is an easy target for follow-up observations. Absolute magnitudes will help determine whether this star stands at the very limit of hydrogen burning for a metal poor star. Available data suggest that LSR1610-0040 is most likely a $\approx 0.08M_\odot$ subdwarf at a distance $d = 16 \pm 4\text{pc}$. Detailed spectroscopic modeling will be required to determine the abundance and surface gravity of the object.

We thank the referee, J. E. Gizis, for very useful comments on the manuscript. SL is a Kalbfleich research fellow of the American Museum of Natural History. This research program is being supported by NSF grant AST-0087313 at the American Museum of Natural History, as part of the NStars initiative.
REFERENCES

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1997, A&A, 327, 1054

Burgasser, A. J., Kirkpatrick, J. D., Brown, M. E., Reid, I. N., Burrows, A., Liebert, J., Matthews, K., Gizis, J. E., Dahn, C. C., Monet, D. G., Cutri, R. M., Skrutskie, M. F. 2002, ApJ, 564, 421

Burgasser, A. J., Kirkpatrick, J. D., Burrows, A., Liebert, J., Reid, I. N., Gizis, J. E., McGovern, M. R., Prato, L., & McLean, I. S. 2003, ApJ, in press

Chiba, M., & Beers, T. 2000, AJ, 119, 2843

Dahn, C. C., Harris, H. C., Vrba, F. J., Guetter, H. H., Canzian, B., Henden, A. A., Levine, S. E., Luginbuhl, C. B., Monet, A. K. B., Monet, D. G., Pier, J. R., Stone, R. C., Walker, R. L., Burgasser, Adam J., Gizis, J. E., Kirkpatrick, J. D., Liebert, J., & Reid, I. N. 2002, AJ, 124, 1170

Gizis, J. E. 1997, AJ, 113, 806 (G97)

Kirkpatrick, J. D., Henry, T. J., & McCarthy, D. W. 1991, ApJS, 77, 417

Kirkpatrick, J. D., Reid, I. N., Liebert, J., Cutri, R. M., Nelson, B., Beichman, C. A., Dahn, C. C., Monet, D. G., Gizis, J. E., & Skrutskie, M. F. 1999, ApJ, 519, 802

Leggett, S. K., Allard, F., & Hauschildt, P. H. 1998, ApJ, 509, 836

Lépine, S., Shara, M. M., & Rich, R. M. 2002, AJ, 124, 1190

Lépine, S., Shara, M. M., & Rich, R. M. 2003, ApJ, 585, L69

Lépine, S., Rich, R. M., & Shara, M. M. 2003, AJ, 125, 1598

Luyten W. J. 1979, LHS Catalogue: a catalogue of stars with proper motions exceeding 0.5" annually, University of Minnesota, Minneapolis (CDS-Vizier catalog number I/87B)

Massey, P., & Gronwall, C. 1990, ApJ, 358, 344

Monet, D. G., et al. 2003, AJ, 125, 984

Mould, J. R., & McElroy, D. B. 1978, ApJ, 220, 935

Reid, I. N., Hawley, S. L., & Gizis, J. E. 1995, AJ, 110, 1838
Richer, H. B., Brewer, J., Fahlman, G. G., Gibson, B. K., Hansen, B. M., Ibata, R., Kalirai, J. S., Limongi, M., Rich, R. M., Saviane, I., Shara, M. M., & Stetson, P. B. 2002, ApJ, 574, L151
Table 1. Basic Data for LSR0822+1700

| Datum        | Value | Units         |
|--------------|-------|---------------|
| RA (2000.0)  | 16:10:28.85 | h:m:s        |
| DEC (2000.0) | -00:40:53.0 | d:m:s        |
| μ            | 1.46   | " yr⁻¹       |
| pm           | 253.2  | °             |
| \(v_{hel}\) | -130   | km s⁻¹        |
| b¹           | 21.1±0.3 | mag           |
| r            | 17.5±0.3 | mag           |
| i            | 14.8±0.3 | mag           |
| J²           | 12.91±0.02 | mag         |
| H            | 12.32±0.02 | mag         |
| Kₜ           | 12.02±0.03 | mag         |
| Spectral Type| sdL    |               |
| Distance     | 12±3   | pc            |
| U            | -111±18 | km s⁻¹        |
| V            | -85±29  | km s⁻¹        |
| W            | -24±21  | km s⁻¹        |

¹Photographic B, R, and I magnitudes from USNO B-1.0 catalog.

²Infrared J, H, and Kₜ magnitudes from 2MASS All-Sky Point Source Catalog.
Fig. 1.— The new high proper motion star LSR1610-0040. Left: red plate of the first epoch Palomar Sky Survey, obtained in 1953. Right: red plate of the second epoch Palomar Sky Survey, obtained in 1992. Both fields are 4.25′ on the side, with north up and east left. Circles are drawn centered on the location of LSR1610-0040 at each epoch. The star is moving with a proper motion $\mu = 1.46''$yr$^{-1}$. 
Fig. 2.— Optical spectrum of the high proper motion star LSR1610-0040. Note the extreme slope of the pseudo-continuum, indicative of a low temperature. Also note the weakness of the TiO bands and the complete absence of the VO bands, usually prominent in late-type M dwarfs. The strong Rb I lines are reminiscent of L dwarfs, although the hydride bands are unusually weak. We interpret this spectrum as a clear indication that the star is both very cool and metal-poor, and assign a spectral type “sdL:”.

LSR1610–0040, sdL: