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THE esdM6.5 STAR LSR J0822+1700: A NEW ULTRACOOL EXTREME SUBDWARF[1]

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ABSTRACT

Spectroscopic observations reveal that the recently discovered high proper motion star LSR J0822+1700 is an ultracool extreme subdwarf, with spectral type esdM6.5. This is only the second known extreme subdwarf with a spectral type later than esdM6.0, the other one being the star APMPM J0559−2903 (esdM7.0). Our new spectra of LSR J0822+1700, of APMPM J0559−2903, and also of the very metal-poor esdM6.0 star LHS 1826 all show the defining signature of cool esdM objects: very deep absorption bands due to molecular CaH flanked by very weak absorption due to TiO. Our new spectrum reveals than the molecular bands in LHS 1826 are a little weaker than previously reported, and we reclassify the star as esdM5.5. We show that all three stars have low metallicities ($[m/\mathrm{H}] \leq -1.5$) and kinematics consistent with halo membership. These objects represent the low-mass end of Population II stars in the vicinity of the Sun. The new ultracool extreme subdwarf LSR J0822+1700 appears to be significantly more metal-poor than APMPM J0559−2903, as evidenced by its much weaker TiO absorption. An interesting feature in the spectrum of LSR J0822+1700 is the existence of detectable absorption lines of Rb I and Cs I, usually associated with much cooler subtypes in dwarf stars (L dwarfs). We suggest that Rb I and Cs I are relatively strong in LSR J0822+1700 because of a critical combination of very low temperature and very low metallicity.

Subject headings: Galaxy: halo — Galaxy: stellar content — stars: late-type — stars: low-mass, brown dwarfs — stars: Population II — subdwarfs

1. INTRODUCTION

The current classification system (Gizis 1997) for M dwarfs and subdwarfs separates the stars into three broad classes. The M dwarfs (M or dM) consist of stars with solar or near solar abundances ($[m/\mathrm{H}] \sim 0.0$), the M subdwarfs (sdM) are stars with clearly subsolar abundances ($[m/\mathrm{H}] \sim -1.2$), while the extreme subdwarfs (esdM) are the stars with the lowest observed metallicities ($[m/\mathrm{H}] \sim -2.0$; see Gizis & Reid 1997). The classification system is based on the relative strength of the TiO and CaH absorption bands, whose ratio is believed to be dependent on the star's metallicity, a trend that is confirmed by atmospheric models of low-mass stars (Hauschildt, Allard, & Baron 1999).

Today, the complete spectroscopic sequence for M dwarfs is well established and extends well beyond the latest subtypes (M7–M9) and into the cooler L dwarf and T dwarf sequences (the realm of substellar objects). Large numbers of late-type M dwarfs (often dubbed *very low mass stars* as they are the coolest hydrogen-burning objects) have been identified and studied. In contrast, very few M subdwarfs and extreme M subdwarfs with cool atmospheres have been spectrographically confirmed. While the spectroscopic sequence for sdM stars has recently been extended down to spectral subtype sdM8.0 (Lépine, Rich, & Shara 2003b), and beyond into the new sdL subclass (Lépine, Shara, & Rich 2003d; Burgasser et al. 2003), the situation with cool esdM stars is more sketchy. Only two objects with spectral type esdM6.0 and later are currently known. The first one is the star LHS 1826, classified by Gizis (1997) as an esdM6.0. This star is suspected to be an extremely metal-poor object, as evidenced by the nondetection of the TiO band near 7500 Å. The second object is the star APMPM J0559−2903, discovered by Schweitzer et al. (1999) with an assigned spectral type of esdM7.0, although it lies very close to the range of sdM stars.

In this Letter, we present spectroscopic observations revealing the recently discovered high proper motion star LSR J0822+1700 to be the third known ultracool esdM. With a spectral subtype esdM6.5, the star is significantly more metal-poor than APMPM J0559−2903 and thus lies well within the realm of esdM stars. Because it is both cooler than LHS 1826 and more metal-poor than APMPM J0559−2903, LSR J0822+1700 is a new benchmark object among the extreme subdwarfs.

2. PROPER-MOTION DISCOVERY AND PHOTOMETRY

The high proper motion star LSR J0822+1700 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 star is presented in a recent paper, which updates the survey by including analysis of high-declination fields (Lépine, Shara, & Rich 2003c). The star LSR J0822+1700 is a faint object moving at a rate $\mu_{\mathrm{R.A.}} = 0\farcs36\ \mathrm{yr}^{-1}$, $\mu_{\mathrm{decl.}} = -0\farcs49\ \mathrm{yr}^{-1}$.

Photometric information was obtained from the USNO-B1.0 catalog (Monet et al. 2003) and from the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003). A search for a counterpart in the USNO-B1.0 catalog provided a clear match, yielding photographic r and i magnitudes measured from the Second Palomar Sky Survey (POSS-II) plates. This star is too faint on the POSS-II blue plates to have a recorded b magnitude. A search for a counterpart in the 2MASS All-Sky Catalog also yielded a match, providing 2MASS J, H, and K_s infrared CCD magnitudes. In Table 1, we present our compiled astrometric and photometric information on LSR J0822+1700. The position of the star is given for epoch 2000.0 in the 2000.0 equinox coordinate system (J2000.0). We also include for com-

[1] Based on observations made at the MDM Observatory, maintained and operated by the University of Michigan, Dartmouth College, the Ohio State University, and Columbia University.

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TABLE 1
The Three Coolest Extreme Subdwarfs: Astrometry and Photometry

Star	R.A. (J2000.0)[a]	Decl. (J2000.0)[a]	μ (arcsec yr^{-1})	PMA[b] (deg)	b[c]	r[c]	i[c]	J[d]	H[d]	K_s[d]
APMPM J0559−2903	05 58 58.64	−29 03 27.2	0.375	81	21.0	18.1	16.3	14.89	14.45	14.46
LHS 1826	06 09 57.86	+69 54 46.0	0.498	159	21.0	18.4	16.8	15.83	15.54	15.36
LSR J0822+1700	08 22 33.75	+17 00 18.9	0.605	143	...	18.7	17.3	15.72	15.52	15.62

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] Coordinates of the star at epoch J2000.0.
[b] Proper-motion angle.
[c] Photographic r and i magnitudes from the USNO B-1.0 catalog.
[d] Infrared magnitudes from the Two Micron All-Sky Survey.

parison the equivalent data compiled from the same sources for APMPM J0559−2903 and LHS 1826, the other two known very cool esdM stars.

3. SPECTROSCOPY

Spectroscopy was performed on the night of 2003 January 25 with the 2.4 m Hiltner telescope at MDM Observatory. A spectrum of LSR J0822+1700 was obtained with the Mk III spectrograph equipped with a 2048 × 2048 front-side–illuminated, thick LORAL CCD ("Wilbur"). We used a 300 l mm^{-1} grating blazed at 7500 Å, with a red order blocking filter. The star was imaged through a 0″.8 slit, yielding a nominal spectral resolution of 7 Å. 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 standards were observed at the smallest possible air mass (<1.3) and with the slit at the parallactic angle to minimize slit loss due to atmospheric diffraction, providing excellent spectrophotometric calibration.

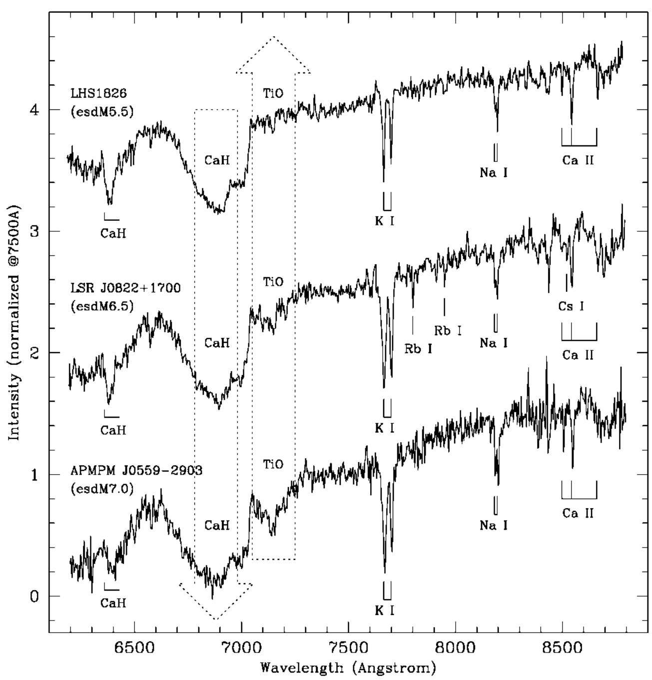

Fig. 1.—Optical spectrum of the esdM6.5 high proper motion star LSR J0822+1700 obtained with the Mk III spectrograph on the 2.4 m Hiltner at MDM. The very deep CaH band, indicative of a very late spectral type, is flanked by a very weak TiO band indicator of a low metallicity. MDM spectra of the other two known ultracool esdM stars (LHS 1826 and APMPM J0559−2903) are shown for comparison. Note the trends in the depth of the CaH and TiO molecular bands (*large arrow s*), which indicate that LSR J0822+1700 is intermediate in both $T_{\rm eff}$ and m/H between the other two stars.

For comparison, we have also obtained new spectra of LHS 1826 and APMPM J0559−2903 on the same night with the same setup. The motivation to reobserve those stars was twofold. First, we wanted to compare the three stars objectively by using spectra obtained with the same instrument and setup. Second, the existing spectra of LHS 1826 and APMPM J0559−2903 both covered only a limited spectral range (6200–7500 Å), and the spectrum of LHS 1826 was also very noisy. By obtaining new spectra of these two esdM stars, we wished to obtain more reliable information on a broader range of spectral features, especially the K i and Na i doublets beyond 7500 Å.

The resulting spectra are plotted in Figure 1. One observes in all three stars a spectral energy distribution typical of late esdM stars: strong CaH absorption bands flanked by relatively weaker TiO bands, around 7000 Å. Our spectra also reveal a prominent K i doublet in all three stars as well as a strong Na i doublet. Lines of the Ca ii triplet are also detected. Weak but significant absorption lines are detected in LSR J0822+1700 between the K i and Na i doublets, which we identify as lines of Rb i λλ7800, 7948, with equivalent widths 1.3 ± 0.5 Å and 0.8 ± 0.5 Å. Close examination in the area of the Ca ii triplet also reveals the presence of a weak absorption feature consistent with Cs i λ8521 with an equivalent width of ≈0.7 ± 0.4 Å.

Radial velocities were measured from the centroids of the K i λλ7665, 7699 doublet, Rb i λλ7800, 7947 lines (LSR J0822+1700 only), and Ca ii λλ8548, 8542, 8662 atomic line triplet. Heliocentric radial velocities are listed in Table 2. We find a substantial radial velocity $V_{\rm hel} = 70 \pm 20$ km s^{-1} for LSR J0822+1700, consistent with a thick disk or halo membership. The value we find for APMPM J0559−2903 ($V_{\rm hel} = 180 \pm 20$ km s^{-1}) matches the value of $V_{\rm hel} = 200$ km s^{-1} measured by Schweitzer et al. (1999).

We quantify the behavior of the CaH and TiO bands by calculating values for the CaH1, CaH2, CaH3, and TiO5 indices defined in Reid, Hawley, & Gizis (1995), and which serve as the main classification criteria for subdwarfs (Gizis 1997). Band strengths were calculated after shifting the spectra by their individual $V_{\rm hel}$ so that they were calculated in their respective rest frame. Band strengths and resulting spectral types are listed in Table 2. We also give the equivalent width of the K i and Na i doublets (i.e., the combined equivalent width of the two absorption lines in each doublet).

4. ANALYSIS

Our measured CaH band strengths in LHS 1826 are significantly weaker than those estimated by Gizis & Reid (1997). The CaH2, CaH3, and TiO5 indices are very sensitive to instrumental noise, especially in low- to medium-resolution spectra, because the reference region used as the pseudocontinuum

TABLE 2
THE THREE COOLEST EXTREME SUBDWARFS: SPECTROSCOPY

Star	v_{hel} (km s^{-1})	CaH1[a]	CaH2[a]	CaH3[a]	TiO5[a]	Equivalent Width[b] K I	Equivalent Width[b] Na I	Spectral Type
APMPM J0559−2903	180 ± 20	0.691	0.210	0.349	0.631	28.5 ± 1.5	5.5 ± 1.0	esdM7.0
LHS 1826	15 ± 20	0.453	0.294	0.420	0.968	14.5 ± 1.5	4.0 ± 1.0	esdM5.5
LSR J0822+1700	70 ± 20	0.365	0.227	0.346	0.891	30.0 ± 1.5	4.5 ± 1.0	esdM6.5

[a] Spectroscopic indices (see text).
[b] Total equivalent widths of the K I and Na I doublets.

is only 4 Å wide. Hence, it is very possible that the CaH2 and CaH3 indices, calculated by Gizis & Reid (1997) from their noisy spectrum, overestimated the CaH band strength in LHS 1826. The values we derive are more consistent with a spectral subtype of esdM5.5, down from their spectral type esdM6.0. The relative weakness of the K I and Na I doublets in LHS 1826, as compared, e.g., to those of LSR J0822+1700 (see Table 2), also argue in favor of assigning an earlier spectral subtype. This reclassification places LHS 1826 on a par with LHS 1742a, the only other known esdM5.5.

On the other hand, our measurements of the CaH and TiO band strengths in APMPM J0559−2903 are consistent with the values calculated by Schweitzer et al. (1999), and we thus confirm that the star has a spectral subtype esdM7.0, still the latest among the known esdM objects. Overall, spectroscopy suggests that the new esdM star LSR J0822+1700 is about as metal-poor as LHS 1826 but significantly cooler. Furthermore, the new star is probably about as cool as APMPM J0559−2903 but significantly more metal-poor. LSR J0822+1700 thus represents a unique combination of low mass and low metallicity (see Fig. 2), making it a benchmark esdM object.

We have used the NextGen grid of model atmospheres by Hauschildt et al. (1999) to estimate effective temperatures ($T_{\rm eff}$) and metallicities (m/H) for the three esdM stars. For each star, we performed a χ^2 fit over the wavelength range 6250–8000 Å on a subgrid of synthetic spectra generated from models with $T_{\rm eff}$(K) = 2900, 3000, 3100, 3200, 3300, 3400 and m/H = −3.0, −2.5, −2.0, −1.5, −1.3.[5] The surface gravity was fixed at $\log g = 5.0$. For LHS 1826, we obtained the best fit with $T_{\rm eff} = 3200$ K, and $m/{\rm H} = -2.5$, while for APMPM we confirmed the values derived by Schweitzer et al. (1999), finding $T_{\rm eff} = 3100$ K and $m/{\rm H} = -1.5$. For LSR J0822+1700, not surprisingly, the best fit was obtained at an intermediate grid point with $T_{\rm eff} = 3100$ K and $m/{\rm H} = -2.0$. We note that despite their extreme properties, these stars are still clearly burning hydrogen in their cores.

The identification of alkali absorption lines in LSR J0822+1700 is rather intriguing. Atomic Rb and Cs atoms are ionized at temperatures exceeding 3000 K, and absorption lines of Rb I and Cs I are usually prominent only in much cooler objects, such as L dwarfs (Basri et al. 2000). Lines of Rb I and Cs I of the strengths observed in LSR J0822+1700 would be consistent, in solar metallicity objects, with effective temperatures in the range 2500 K < $T_{\rm eff}$ < 2800 K. But lower metallicities tend to bring up the alkali lines: the NextGen model grid shows that Rb I and Cs I are weak but detectable at $T_{\rm eff} = 3100$ K and $-3.0 < m/{\rm H} < -1.0$. However, at $T_{\rm eff} =$ 3100 K, the Rb I and Cs I lines are much weaker in the NextGen model spectra than in our observed spectrum of LSR J0822+1700. Dropping the effective temperature to under $T_{\rm eff} = 3000$ K in the NextGen grid brings up the Rb I lines nicely to match those of LSR J0822+1700, but it sends the TiO and CaH band strengths into serious disagreement. Perhaps the most intriguing fact is the nondetection of Rb I and Cs I in APMPM J0559−2903. This seems to indicate that LSR J0822+1700 should be the cooler of the two stars, despite being classified as 0.5 spectral type earlier. The lower metallicity of LSR J0822+1700 is not an obvious explanation: in the NextGen model grid, the strengths of the Rb I and Cs I lines do not increase systematically as the metallicity decreases but rather reach a maximum around $m/{\rm H} = -1.5$ only to decrease at smaller metallicities. It is thus difficult to explain why Rb I and Cs I should be so obvious in LSR J0822+1700 while they are not apparent at all in APMPM J0559−2903. A spurious detection in LSR J0822+1700 cannot be entirely ruled out. We note the presence of an apparent absorption line just blueward of Rb I λ7948 (see Fig. 1); this feature could not be identified with any known transition and is assumed to result from instrumental noise. While it is possible that any one of the Rb I lines are also noise spikes, the probability that two random spikes would occur within a fraction of a pixel of the expected positions of both Rb I lines is quite small. On the

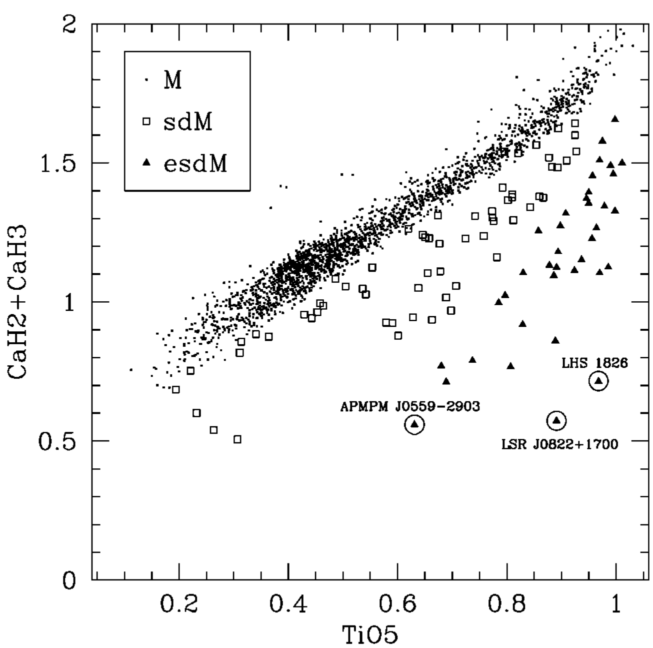

FIG. 2.—Relative strengths of the CaH and TiO molecular bands for spectroscopically identified M dwarfs, subdwarfs (sdM), and extreme subdwarf (esdM) in the vicinity of the Sun. While CaH band strengths correlate with effective temperature, TiO/CaH ratios correlate with metallicity. The three objects discussed in this Letter fall on the bottom right of the diagram and are thus the coolest of the most metal-poor objects. The newly discovered esdM star LSR J0822+1700 represents an extreme case, combining both very low $T_{\rm eff}$ and very low metallicity.

[5] The model spectra can be found at http://www.uni-hamburg.de/~stcd101/mdwarfs.html.

TABLE 3
The Three Coolest Extreme Subdwarfs: Estimated Distance and Kinematics

Star	d (pc)	U (km s^{-1})	V (km s^{-1})	W (km s^{-1})
APMPM J0559−2903	70 ± 18	−96 ± 11	−183 ± 20	48 ± 30
LHS 1826	117 ± 29	−161 ± 43	−213 ± 58	20 ± 08
LSR J0822+1700	106 ± 26	120 ± 44	−269 ± 61	108 ± 20

other hand, we note that our spectrum of APMPM J0559−2903 is noisier than our spectrum of LSR J0822+1700. It is thus possible that Rb I and Cs I are also present in APMPM J0559−2903 but hiding in the instrumental noise. Should that be true, then higher quality spectra of APMPM J0559−2903 (obtained from at least a 4 m class telescope) should lead to the straightforward detection of Rb I and Cs I absorption lines with equivalent widths ≈0.5 Å.

We have estimated the distances of the three stars using the spectral type/absolute magnitude calibration for esdM stars derived in Lépine, Rich, & Shara (2003a). This relationship is defined from the small sample of spectroscopically identified esdM stars for which astrometric parallaxes exist (only 19 stars). The latest esdM star for which there exists an astrometric parallax is LHS 1742a (esdM5.5); it is thus necessary to extrapolate the (linear) relationship to estimate the absolute magnitudes of LSR J0822+1700 and APMPM J0559−2903. The resulting spectroscopic distances should thus be used with caution. Results are listed in Table 3. The nearest star is APMPM J0559−2903, at a distance of about 70 pc. The other two stars are located just beyond 100 pc from the Sun. The fact that the nearest known representatives of these types of very metal-poor, low-mass stars are found at such relatively large distances emphasizes their extreme rarity in the vicinity of the Sun (note that the volume within 120 pc of the Sun is expected to contain ≈500,000 stars).

From our estimated distances and the measured radial velocities and proper motions, we have calculated the components of the velocity *UVW* in the Galactic reference frame, where *U* is the velocity toward the Galactic center, *V* the velocity in the direction of Galactic rotation, and *W* the velocity in the direction of the north Galactic pole. Values are also listed in Table 3. All three stars have large negative components of *V*, which are consistent with halo membership. Interestingly, they also appear to be on very eccentric orbits with low perihelion, bringing them at some point well inside the Galactic bulge.

The existence of only three known late-type esdM stars prevents us from drawing any significant conclusions about their actual number density. Clearly, these objects are important since they represent the low end of the subdwarf mass function. The identification of more objects of that type would be extremely helpful in determining the mass and luminosity function of the halo.

5. CONCLUSIONS

Our recently discovered high proper motion star LSR J0822+1700 is revealed to be a new extreme subdwarf (esdM) of unprecedented low temperature and metallicity. Model fits suggest an effective temperature $T_{\rm eff} = 3100$ K with a metallicity $m/{\rm H} = -2.0$. Our new esdM star is both more metal-poor than the esdM7.0 star APMPM J0559−2903 and cooler than the very metal-poor star LHS 1826, which we reclassify as esdM5.5 (from esdM6.0). We thus find that LSR J0822+1700 represents an important addition to the extreme subdwarf zoo, populating a new slot in mass/metallicity parameter space. The new object should thus be extremely helpful in refining atmospheric models of low-mass, metal-poor stars. In that context, our detection of relatively strong lines of alkali metals (Cs I, Rb I) in LSR J0822+1700 is very interesting, as we did not detect them in either LHS 1826 or APMPM J0559−2903.

Using our previous calibration of absolute magnitudes as a function of the esdM subtype, we estimate spectroscopic distances for all three stars, placing them between 70 and 120 pc from the Sun. These distances must be used with caution; the spectroscopic distance calibration is extrapolated from esdM stars with earlier spectral subtypes. It is imperative that astrometric distances be obtained for the three stars discussed in this Letter, in order to anchor the distance calibrations to the bottom of the esdM sequence.

The estimated kinematics of all three cool esdM stars is largely consistent with halo membership, as can be expected for such very metal-poor objects. Future efforts will be invested in the identification of more of these low-mass, low-metallicity stars, from follow-up spectroscopy of very faint objects drawn from our upcoming catalog of high proper motion stars. While extremely rare in the vicinity of the Sun, these stars play an important role as we move toward the determination of the luminosity and mass function of the local halo population.

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