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# DISCOVERY OF AN M8.5 DWARF WITH PROPER MOTION $\mu = 2\farcs38$ PER YEAR

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## ABSTRACT

We report the discovery of LSR 1826+3014, a very faint ($V = 19.36$) star with a very large proper motion ($\mu = 2\farcs38$ yr$^{-1}$). A low-resolution red spectrum reveals that LSR 1826+3014 is an ultracool red dwarf with spectral type M8.5 V and with a radial velocity $v_{\rm rad} = +77 \pm 10$ km s$^{-1}$. LSR 1826+3014 is thus the faintest red dwarf ever discovered with a proper motion larger than $2''$ yr$^{-1}$. Optical and infrared photometry suggest that the star is at a distance $d = 13.9 \pm 3.5$ pc from the Sun, which implies that it is moving relative to the local standard of rest with a total velocity of $175 \pm 25$ km s$^{-1}$. The numerical integration of its orbit suggests that LSR 1826+3014 is on a halo-like Galactic orbit.

*Subject headings:* Galaxy: halo — solar neighborhood — stars: kinematics — stars: low-mass, brown dwarfs

## 1. INTRODUCTION

Very few stars are known to have proper motions $\mu > 2''$ yr$^{-1}$. The Luyten half-second (LHS) catalog (Luyten 1979) lists only 60 systems (which include nine resolved doubles and two resolved triples) with proper motions in that range, and few systems have been added since. The discovery of a faint $\mu = 2\farcs13$ yr$^{-1}$ white dwarf (ER 8 = GJ 3770) was reported by Ruiz et al. (1986). More recently, the candidate halo white dwarf F351-50 was discovered by Ibata et al. (2000); its proper motion is $\mu = 2\farcs33$ yr$^{-1}$.

Most of these extremely rare objects are very nearby stars, within 10 pc of the Sun. Proxima, our closest neighbor, has a proper motion $\mu = 3\farcs853$ yr$^{-1}$ (ESA 1997). However, a few of the very high proper-motion stars lie beyond 10 pc, which means that they have velocities relative to the Sun that are larger than 100 km s$^{-1}$ and that they are likely to be local members of the Galactic thick disk or halo. One example is the nearby subdwarf LHS 42 ($\mu = 3\farcs21$ yr$^{-1}$, spectral type sdK4), which is a very likely member of the Galactic halo (Fuchs & Jahreiss 1998). The star with the largest known proper motion is the star discovered by Barnard (1916), which bears his name and is moving at $\mu = 10\farcs3$ yr$^{-1}$; Barnard's star, with spectral type M4.0 V (Kirkpatrick, Henry, & McCarthy 1991), is believed to be a member of the thick disk (Allen & Martos 1987).

Apart from the two faint white dwarfs mentioned above, all the known stars with $\mu > 2''$ yr$^{-1}$ are relatively bright; none of them are fainter than $R = 15$. This may be an observational bias since faint stars with very large proper motions are notoriously difficult to find. On the other hand, it is the faintest components of the halo that are expected to be detected as faint high proper-motion stars. The fact that few faint stars with large proper motions are known may simply reflect the very low local density of low-luminosity halo stars. Clearly, the discovery of faint ($R > 15$) stars with proper motions $\mu > 2''$ yr$^{-1}$ can have profound implications for our understanding of the density, composition, and kinematics of the halo.

In this Letter, we report the discovery of LSR 1826+3014, a very faint ($R > 17$) star with a proper motion of $\mu = 2\farcs38$ yr$^{-1}$. Our spectroscopy shows the star to be an M8.5 dwarf at a distance of about 13.9 pc, moving relative to the local standard of rest with a velocity of about 175 km s$^{-1}$. This low-mass star appears to have an orbit that is most consistent with membership in the Galactic halo.

## 2. PROPER-MOTION DISCOVERY

The very high proper-motion star LSR 1826+3014 was discovered through our automated search for stars with large proper motion using the Digitized Sky Survey (Lépine, Shara, & Rich 2002), undertaken as part of the NStars Program. The star was found in a relatively crowded Milky Way field at Galactic latitude $b = +18\fdg31$. The very large proper motion of the star is above the detection threshold of our SUPERBLINK software, and it was not initially flagged as a high proper-motion star. However, SUPERBLINK also identifies candidate variable objects as it compares the Digitized Sky Survey POSS-I (xx103aE+plexi) and POSS-II (IIIaF+RG610) scanned red plates. LSR 1826+3014 was first noticed as a pair of candidate variable stars lying within about $2'$ of each other, one star showing up in the POSS-I plate only, the other one in the POSS-II plate only. Suspecting this could be a star with an extremely large proper motion, we searched for archival images of this field at different epochs. The Digitized Sky Survey includes three more images of the field around LSR 1826+3014. The Quick-V northern plate (IIaD+W12) does not go deep enough to detect the star; the POSS-II blue plate (IIIaJ+GG385) shows a very faint star, near the detection limit, at the location expected for a high proper-motion star. The POSS-II near-IR (IVN+RG9) plate shows a relatively bright star again at the location expected for a star with a very large proper motion. To provide definitive evidence that the star is a high proper-motion object, we obtained an *R*-band image of the same field at the Calypso telescope (Kitt Peak) in 2002 April. Again, we found the star at the exact location expected for a very high proper-motion object.

The three epochs of red-band images are displayed in Figure 1. Shown are $4' \times 4'$ sections of the POSS-I red, POSS-II red, and Calypso *R*-band image. The high proper-motion star is indicated by a circle. The three images span over 50 years,

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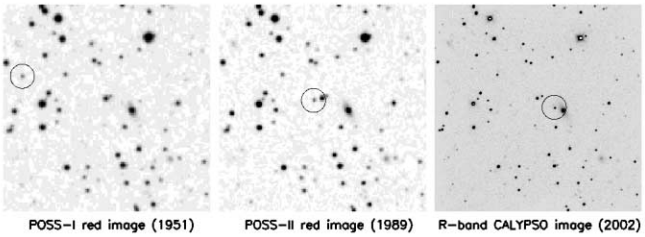


FIG. 1.—New high proper-motion star LSR 1826+3014. *Left*: Red plate of the first epoch Palomar Sky Survey, obtained in 1951. *Middle*: Red plate of the second epoch Palomar Sky Survey, obtained in 1989. *Right*: *R*-band Calypso image, obtained in 2002. All the fields are 4′.0 on the side, with north up and east left. The circles are drawn centered on the location of LSR 1826+3014 at each epoch. LSR 1826+3014 appears to be headed toward the core of a background galaxy.

during which time LSR 1826+3014 has moved by a little more than 2′.

We reprocessed the POSS-I and POSS-II plates for this region of the sky with SUPERBLINK, this time allowing for the detection of stars with proper motions up to 3″ yr$^{-1}$. This time the software easily identified LSR 1826+3014 and calculated a proper motion $\mu = 2\farcs38$ yr$^{-1}$. The proper motion measured by SUPERBLINK is the proper motion of the star calculated relative to the mean position of all objects within 4′ of the candidate high proper-motion star (image superposition); the astrometric solutions from the first Digitized Sky Survey are used to obtain the local scale of the scanned plate.

With a proper motion $\mu = 2\farcs38$ yr$^{-1}$, LSR 1826+3014 ranks as the stellar system with the 42d largest proper motion on the sky, and one of the faintest stars known with a proper motion larger than 2″ yr$^{-1}$. LSR 1826+3014 appears to be headed toward the bulge of a background galaxy (see Fig. 1). By extrapolating the motion of the star, we estimate that it will move within 0″.4 of the centroid of the core of that galaxy around the 2006.5 epoch.

## 3. PHOTOMETRY

We observed LSR 1826+3014 on 2002 April 12 under photometric conditions using the Calypso Observatory (Neill et al. 2002) Wide Field Camera in the Johnson *BV* and Cousins *RI* filters. Standard stars from the Landolt (1992) catalog were observed and used for the absolute calibration of the object. The Landolt magnitudes of the standard stars were converted to the Johnson-Cousins system. All frames were debiased and flat-fielded using IRAF (Tody 1986). The object and standard stars were measured in each of the multiple frames using the APPHOT package in IRAF, and the results were averaged. We used apertures with FWHM comparable to the seeing (4.5 pixels = 0″.675), and we used bright stars to derive a correction to 100% light. Using the multiple frames, we derived an external error for the measurements of 0.03 mag in the *B*-filter and 0.01 mag or better in the other filters. The final *B*, *V*, *R*, and *I* magnitudes for the star are listed in Table 1.

The star LSR 1826+3014 was also identified in the Two Micron All Sky Survey (2MASS) second incremental release as the bright point source 2MASS 1826113+301420. The corresponding 2MASS source was found within 0″.33 of the predicted location of LSR 1826+3014 at the epoch of the 2MASS images. The 2MASS *J*, *H*, and $K_s$ magnitudes are listed in Table 1.

TABLE 1

BASIC DATA FOR LSR 1826+3014

| Datum | Value |
|---|---|
| R.A. (2000.0) | 18 26 11.03 |
| Decl. (2000.0) | +30 14 19.1 |
| $\mu$ (arcsec yr$^{-1}$) | 2.38 |
| Proper-motion angle (deg) | 253.3 |
| $v_{rad}$ (km s$^{-1}$) | 77 ± 10 |
| *B* (mag) | 21.46 ± 0.03 |
| *V* (mag) | 19.36 ± 0.01 |
| *R* (mag) | 17.40 ± 0.01 |
| *I* (mag) | 14.35 ± 0.01 |
| *J* (mag) | 11.66 ± 0.03 |
| *H* (mag) | 11.16 ± 0.03 |
| $K_s$ (mag) | 10.80 ± 0.04 |
| Spectral type | M8.5 V |
| Distance (pc) | 13.9 ± 3.5 |
| *U* (km s$^{-1}$) | +92 ± 22 |
| *V* (km s$^{-1}$) | −26 ± 17 |
| *W* (km s$^{-1}$) | +134 ± 30 |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

## 4. SPECTROSCOPY

The star was observed at Lick observatory on 2002 July 6 using the Kast spectrograph installed at the Cassegrain focus of the 3 m Shane telescope. We used the 600 line mm$^{-1}$ grating blazed at 7500 Å to obtain a spectrum covering the range of 6300–9100 Å with a resolution of 2.33 Å pixel$^{-1}$. The star was imaged through a 2″.3 wide slit and with the slit oriented vertically to avoid slit loss due to differential atmospheric refraction. Standard spectral reduction was performed with the SPECRED package in IRAF, including normalization using a spectrophotometric standard and removal of telluric lines. The resulting spectrum is displayed in Figure 2.

Spectral classification was performed by visual comparison with the standard sequence found in Kirkpatrick et al. (1991). We found our spectrum of LSR 1826+3014 to be most similar to an M8.5 V dwarf. We also used the values of the standard M dwarf spectral indices defined in Lépine, Rich, & Shara (2003). The combined values of the VO1, TiO6, VO2, and TiO7 indices are consistent with a spectral type M8.5 V.

The radial velocity was estimated by comparing the spectrum of LSR 1826+3014 with the spectrum of the radial velocity standard HR 7002, an M6 giant, which we had observed immediately after LSR 1826+3014 on the night of July 6. We estimated the difference in radial velocity between the two stars by shifting the spectrum of HR 7002 to match the TiO band

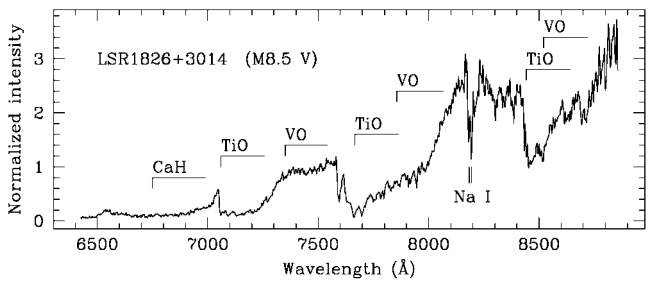


FIG. 2.—Optical spectrum of the high proper-motion star LSR 1826+3014 obtained with the Kast spectrograph on the 3 m Shane Telescope at Lick Observatory. The most prominent spectral features are identified. The spectrum is most consistent with a spectral type M8.5 V.

head at 7050 Å (the two stars had virtually the same heliocentric correction at the time of observation). The best fit was obtained with a +6 km s$^{-1}$ shift of the HR 7002 template, with a possible error of ±10 km s$^{-1}$. The star HR 7002 has a measured radial velocity $v_{\rm rad} = +70.8$ km s$^{-1}$ (Fluks et al. 1994) that yields a radial velocity $v_{\rm rad} = +77 \pm 10$ km s$^{-1}$ for LSR 1826+3014.

## 5. DISTANCE AND KINEMATICS

We use the newly calibrated ($M_V$, $V-K$) and ($M_I$, $J-K$) relationships of Reid & Cruz (2002) to obtain a photometric parallax for LSR 1826+3014. The $V-K = 8.56$ color implies an absolute magnitude $M_V = 18.72$ and suggests a distance of $d = 13.5$ pc. The $I-J = 2.69$ color implies an absolute magnitude $M_I = 13.47$, which in turn suggests a distance of $d = 15.0$ pc. We also use the absolute magnitude/spectral type relationship calibrated by Lépine et al. (2003) to obtain a spectroscopic parallax for the star; a spectral type of M8.5 V is consistent with an absolute magnitude $M_{K_s} = 10.18$, which suggests a distance of $d = 13.2$ pc. Note that the spectroscopic distance is consistent with the photometric distance.

The mean value of the three distance estimates is $d = 13.9$ pc. Each of the color/magnitude and spectral type/magnitude relationships has a scatter of about ±0.5 mag, which corresponds to a distance error of ±25% or ±3.5 pc. We therefore adopt for LSR 1826+3014 an estimated distance of $d = 13.9 \pm 3.5$ pc. These results can be compared with the recent compilation by Dahn et al. (2002) of late-type M dwarfs and L dwarfs with geometric parallaxes. One finds that the $I$, $J$, and $K_s$ magnitudes of LSR 1826+3014 are all consistent with an M8.5 dwarf at a distance of 13–15 pc.

Using the proper motion, distance estimate, and measured radial velocity for LSR 1826+3014, we calculate the motion of the star relative to the local standard of rest in ($U$, $V$, $W$)-space, where $U$ is the velocity toward the Galactic center, $V$ is the velocity toward the direction of Galactic rotation, and $W$ is the velocity toward the north Galactic pole. We use as the motion of the Sun relative to the local standard of rest the values estimated by Dehnen & Binney (1998): ($U$, $V$, $W$) = (+10, + 5, + 7) km s$^{-1}$. We find the velocity components of LSR 1826+3014 to be $U = +92 \pm 22$ km s$^{-1}$, $V = -26 \pm 17$ km s$^{-1}$, and $W = +134 \pm 30$ km s$^{-1}$ relative to the local standard of rest.

Using these values, we can calculate the probable orbit of the star. We use the Galactic mass model of Dauphole & Colin (1995), which includes separate terms for the bulge, disk, and halo. We integrate with a Runge-Kutta fourth-order integrator, in time steps of $10^3$ yr. Figure 3 shows a 950 Myr integration of the orbit of the star plotted in the ($R$, $z$)-plane, where $R$ is the Galactocentric distance in cylindrical coordinates and $z$ is the distance from the plane. The star is shown to oscillate in the range 5.5 kpc $< R <$ 14.5 kpc ($-6.0$ kpc $< z < +6.0$ kpc), which strongly suggests that LSR 1826+3014 is a member of the Galactic halo. Its spectrum, however, is not consistent with a very metal-poor object. It is thus possible that LSR 1826+3014 is a star initially born in the disk that later got ejected into the halo.

Based on its kinematics, LSR 1826+3014 is most likely to be a relatively old (≥5 Gyr) object. Comparison with the evolutionary model of Chabrier et al. (2000) shows that the $J$ and $K$ magnitudes of LSR 1826+3014 are consistent with those of a 5–10 Gyr old star with a mass 0.08 $M_\odot < M_* <$ 0.09 $M_\odot$. The star is thus relatively close to the hydrogen-burning limit.

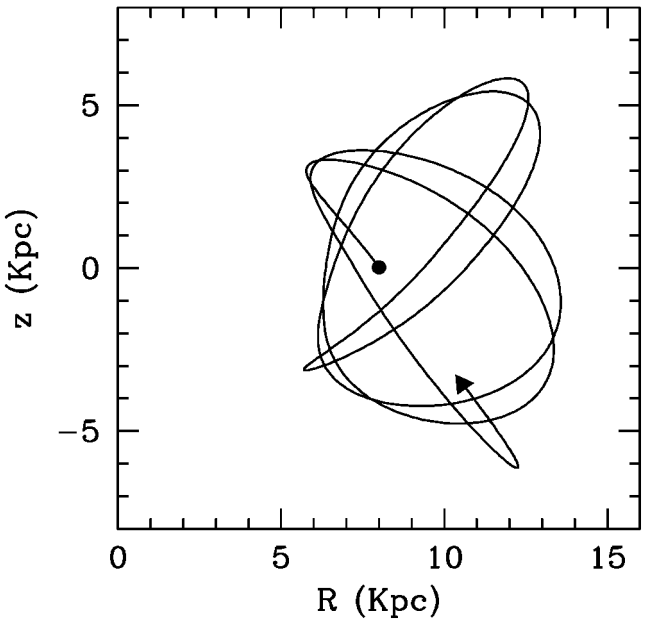


FIG. 3.—Galactic orbital motion of LSR 1826+3014 extrapolated over the next 950 Myr (*filled circle*: starting point, *arrowhead*: ending point). The star's trajectory takes it up to 6 kpc from the plane of the disk.

## 6. CONCLUSIONS

We have discovered one of the faintest stars on the sky with a proper motion greater than 2″ yr$^{-1}$. The star LSR 1826+3014 is a low-mass red dwarf of spectral type M8.5 V at a distance of 13.9 ± 3.5 pc from the Sun. It is moving on the sky with a proper motion of 2.″38 yr$^{-1}$ and has a spectroscopic radial velocity $v_{\rm rad} = +77 \pm 10$ km s$^{-1}$. The star has a very large motion relative to the local standard of rest. Its calculated Galactic orbital motion strongly suggests that it is a member of the halo, reaching heights of about 6 kpc above the plane of the Galactic disk.

A trigonometric parallax should be obtained to confirm the extreme value of its motion relative to the local standard of rest. Although the star does not appear to be significantly metal-poor, its status as a possible disk star ejected from the plane, an extreme old disk star, or a true halo star should be addressed by careful measurement of its metal abundance. That an old hydrogen-burning object should be so cool as to have the spectrum of an M8.5 dwarf indicates that it must be extremely close to the hydrogen-burning limit. That makes LSR 1826+3014 a unique object among the high-velocity stars.

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