1993AJ....105..614R

NEWLY IDENTIFIED COLD SUBDWARFS: LHS 375, LHS 407, LHS 3181, AND LHS 3555

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Received 7 July 1992; revised 17 September 1992

ABSTRACT

Four new cold subdwarfs have been identified from Luyten's *LHS Catalogue* (1976), LHS 375, LHS 407, LHS 3181, and LHS 3555. CCD *B*, *V*, *R*, and *I* photometry; infrared *J*, *H*, and *K* photometry and spectra of the stars have been obtained. We discuss their location in different color–color diagrams. They suggest a subdwarf class, and are consistent with the strengths of their CaH bands with respect to TiO bands. We also obtained CCD trigonometric parallaxes indicating absolute visual magnitudes for them from 1.5 to 2 mag below the dwarf main sequence.

1. INTRODUCTION

The presence of underluminous cold subdwarfs (CSDs) in the solar neighborhood has been recognized since the works of Cayrel (1968) and Eggen (1973).

They were found to define a sequence about 0.7 mag below the solar-abundance main sequence in the $H-R$ diagram. These stars are quite rare and very faint, so that it has been hard to find them in sufficient numbers to study them as a class (Greenstein 1989b). However, the high velocity of these CSDs betray their presence in proper-motion surveys like Luytens' *LHS Catalogue* (Luyten 1976).

Individual CSDs have been identified and studied by Veeder (1974), Upgren & Weis (1975), Hartwick *et al.* (1976, 1984), Dahn & Harrington (1978), and Ake & Greenstein (1980). They found that CSDs have halo kinematics, they separate from the main sequence defined by disk dwarfs in different color–color diagrams. It was also found that their spectra show strong bands of hydrides like MgH, CaH, FeH, and weak TiO bands compared to disk dwarfs, indicating low abundance of metals consistent with their halo kinematics.

The U.S. Naval Observatory CCD trigonometric parallax program (Monet *et al.* 1992), has provided accurate distances for a large sample of faint stars, including 72 LHS stars with *V* and *I* CCD photometry. They identified 17 stars in the sample as CSDs which lie below the Main Sequence in the M_v vs $V-I$ diagram. The small errors involved in the M_v determination of the USNO stars establishes beyond doubt the presence of a subdwarf sequence with a magnitude cutoff near $M_v=14.5$. Confirmation of this minimum luminosity would be an important constraint to models of stellar interiors and evolution relevant to the metal-poor population of the Galaxy (Van den Bergh *et al.* 1983; D'Antona 1987; D'Antona & Mazzitelli 1985).

In this paper we present evidence confirming the CSD nature of four LHS stars (Luyten 1976), LHS 375, LHS 407, LHS 3181, and LHS 3555, for which we obtained CCD trigonometric parallaxes, *B*, *V*, *R*, *I* CCD photometry, *J*, *H*, *K* IR photometry and spectroscopy.

[1]Visiting Observer at Cerro Tololo Inter-American Observatory (NOAO), operated by AURA under contract with the NSF.

2. OBSERVATIONS

2.1 CCD Trigonometric Parallaxes

The observations were performed at the CTIO 1.5 m telescope with the $f/13.5$ secondary. As detectors we used two different RCA (320×512) CCDs (the scale was 0.3″/pix), after normalization of the frames taken with both CCDs, no noticeable differences were found in the coordinates of the Star Reference Frame. In Table 1 we present a summary of the observations and the resulting relative parallaxes.

Star centroids (x,y) were determined using DAOPHOT. All the frames were taken within ±1 h of hour angle from the meridian and corrected for differential color refraction.

With the exception of LHS 375, the fields have Star Reference Frames with poor geometric configurations, not surrounding the program star so that the extrapolation of the plate constant which is needed, decreases the precision of the parallax star coordinates. In addition, for LHS 3555 the low precision is also due to its faint apparent magnitude.

2.2 Spectroscopy

Spectra were obtained in February 1991 with the CTIO 4 m telescope equipped with an R–C spectrograph and a CCD detector. The slit was 2″ wide and the spectral resolution approximately 20 Å.

TABLE 1. CCD trigonometric parallaxes.

Star	Epoch range	Number of frames	Number of nights	Number of ref. stars	Relative Parallax m.a.s.
LHS375	1986.4–1990.2	31	11	6	39 ± 1
LHS407	1986.4–1990.2	34	12	6	31 ± 2
LHS3181	1986.4–1990.6	34	12	6	26 ± 3
LHS3555	1986.5–1990.6	38	13	5	12 ± 6

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TABLE 2. Photometry and absolute visual magnitudes.

	V	B−V	V−R	R−I	J	J−H	H−K	d pc	v_t km s^{-1}	M_V
LHS375	15.68	1.87	1.08	1.12	11.84	0.45	0.18	25.6	169	13.64
LHS407	16.57	1.93	1.06	1.33	12.93	0.49	0.33	32.4	211	14.02
LHS3181	17.18	1.69	1.02	1.19	13.89	0.45	0.34	37.9	100	14.29
LHS3555	17.93	1.94	1.10	0.97	14.72	0.19	0.08	82.0	217	13.36

Flux standards and a He–Ne–Ar lamp were observed during the night to calibrate the data. At CTIO, IRAF packages were used for data reduction (the resulting spectra are displayed in Figs. 4, 5, 6, and 7).

2.3 CCD Photometry

B, V, R, I CCD photometry was obtained in August 1991 and April 1992 at the CTIO 1.5 m telescope with the *f*/13.5 secondary and a Tek (1024×1024) CCD chip. The filters were Johnson's *B,V* and *R,I* of Kron–Cousins. Graham's *E* field standards were observed each night for calibration (Graham 1982). Magnitudes thus obtained have accuracies of about 3% (Table 2).

2.4 IR Photometry

J,H,K photometry was obtained in April and August 1991, at the CTIO 4 m telescope with an InSb (58×62) array. Four exposures for each object at four different positions in the array were taken. Elias' standards were observed for calibration (Elias *et al.* 1982). IR photometry is summarized in Table 2. Magnitudes have been transformed to CIT system following Leggett (1992). The accuracy is about 5% to 8%.

3. RESULTS AND DISCUSSION

The subdwarf nature of the stars discussed in this work became apparent after a spectroscopic follow-up of proper motion stars included in our CCD parallax program. Their spectra show the characteristic enhancement of hydride bands like MgH and CaH with respect to TiO bands, typical of low metallicity late K and M subdwarfs (Greenstein 1989a; Hartwick *et al.* 1976; Monet *et al.* 1992). In atmospheres with low metal content, species formed by two "metals" like TiO, CaOH, and VO, are reduced compared to those requiring only one metal, like MgH and CaH (Greenstein 1965). This effect is qualitatively confirmed by the results of the models by Allard (1990) applied to the extreme subdwarf LHS 169, and by Mould's (1976a) models used by Greenstein (1989a) to estimate metallicity of the subdwarf LHS 522.

It is well-known that the molecular bands of TiO and CaH in the spectra of late-type stars are gravity and temperature sensitive; this behavior has been explored by Mould (1976b) using model atmospheres. The temperature dependence of molecular band strengths in late-type dwarfs has been established and calibrated by various authors (e.g., Spinrad 1973; Wing *et al.* 1976; Boeshaar 1976; Wing & Dean 1983). Therefore, to use the ratio of band strengths like CaH/TiO, as a diagnostic of metallicity it is crucial to confront the results with those obtained from a sample of "normal" metallicity stars with the same temperatures.

To confront colors, magnitudes, and spectral features of our CSDs we use as control samples the common proper motion stars (cpm) published by Ruiz & Maza (1990), and the single proper motion stars from Takamiya (1991). The advantage of selecting these objects for comparison is mainly based on the fact that their photometry and spectroscopy were done with the same instrumentation used for the CSDs, thus making the process more reliable. The stars in the control sample are mainly old disk stars with tangential velocities between 50 to 180 km/s for the cpm systems (Ruiz & Maza 1990). It is interesting to note that weakness of TiO bands with respect to hydrides and the

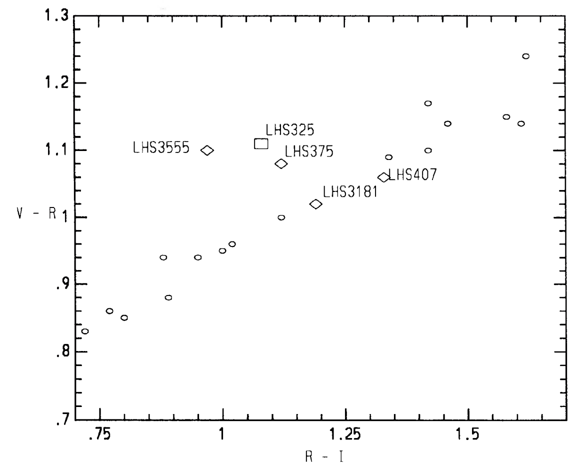

FIG. 1. $V-R$ vs $R-I$ diagram. Single disk type stars from Takamiya (1991) drawn with circles. Only LHS 325 and LHS 3555 show peculiar colors compared to disk stars.

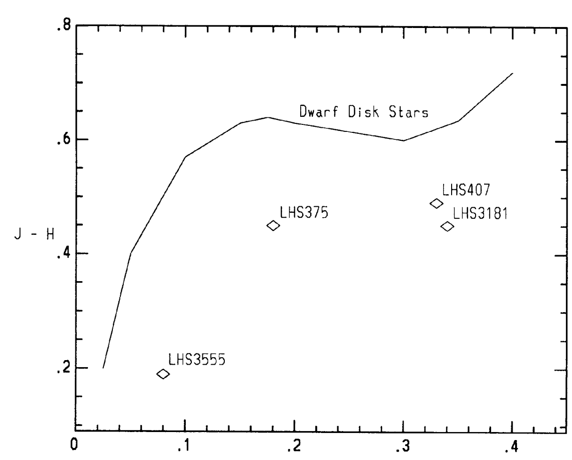

FIG. 2. *J–H* vs *H–K* diagram. The solid line represents the disk dwarfs sequence, which has a spread in *J–H* of about ±0.2 mag. The cold subdwarfs show their characteristic blue ($J-H$) atributed to an increase in the *H* and *K* opacities compared to *J*.

TABLE 3. Absorption band strengths.

Stars[(1)]	CaH/TiO	R-I
LHS375	0.74	1.12
LHS407	1.14	1.33
LHS3181	1.20	1.19
LHS3555	0.55	0.97
LHS325	0.5:	1.08
Comon proper motion binaries		
ES0439-9A	1.82	1.44
ES0439-9B	2.15	1.64
ES0439-96A	1.48	1.25
ES0439-96B	1.70	1.44
ES0439-181	1.95	1.55
ES0439-182	1.38	1.25
ES0439-136	1.65	1.11
ES0439-137	1.46	1.11
ES0440-152	1.58	1.28
ES0440-153	1.43	1.14
ES0440-132	1.88	1.43
ES0440-133	2.23	1.55
ES0440-29	1.59	1.20
ES0440-30	1.16	0.89
ES0440-386	1.26	1.03
Single proper motion stars		
ES0207-15	1.26	0.95
ES0207-37	0.97	1.02
ES0207-43	1.78	1.34
ES0207-80	1.04	0.88
ES0207-87	1.05	0.77
ES0207-125	2.25	1.42
ES0207-126	2.12	1.46
ES0207-138	1.32	1.00
ES0439-03	1.10	0.80
ES0440-31	1.11	0.89
ES0440-127	1.42	1.12
ES0440-155	2.39	1.62
ES0440-186	2.33	1.58

[(1)]Data for LHS325 from Hartwick et al. 1984. Data for cpm binaries from Ruiz and Maza, 1990. Data for single proper motion stars from Takamiya, 1991.

abnormal colors seems to be observed only in the more extreme subdwarfs (Eggen & Greenstein 1965; Hartwick *et al.* 1984; Monet *et al.* 1992; Leggett 1992), so old disk stars, like the stars in our control sample, behave in the different color–color diagrams and metallicity indices like solar-abundance disk population.

Figure 1 shows $V-R$ vs $R-I$, for the single proper motion stars (Takamiya 1991) and our CSDs. We also included LHS 325 identified as an extreme subdwarf by Hartwick *et al.* (1984). Considering the scatter, only LHS 3555 and LHS 325 show some deviation from the sequence defined by the old disk stars.[2] This was also pointed out by

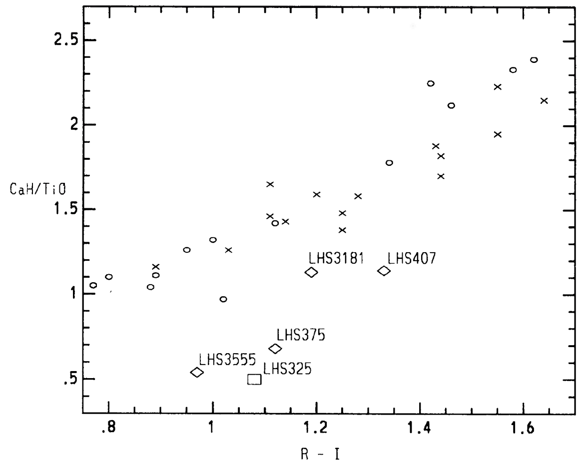

FIG. 3. The metallicity index defined as the ratio of the CaH band at ~6390 Å to the TiO band at ~6260 Å, vs $R-I$. Circles represent stars from Takamiya (1991), crosses are cpm stars from Ruiz & Maza (1990). Compared to disk stars, subdwarfs show stronger CaH and weaker TiO bands.

Leggett (1992): only a few halo stars in her sample showed the same marginal tendency in the $V-R$ vs $R-I$ diagram. In contrast, the infrared $J-H$ vs $H-K$ diagram is a very useful tool to separate stars belonging to different metallicity populations (Mould 1976; Hartwick *et al.* 1984; Leggett 1992). For a given $H-K$ color the low metallicity dwarfs are bluer (smaller $J-H$), due to an increase on the opacity affecting H and K relative to J (H^-, and water vapor).

The $J-H$ vs $H-K$ diagram of Fig. 2 shows the position of the CSDs with respect to disk dwarfs, represented by the solid line (Probst 1983; Leggett 1992). One has to keep in mind that the disk dwarfs sequence has a spread in $J-H$ of at least 0.2 mag; therefore, considering the errors in the CSDs' IR photometry (from 5% to 8%), the blue $J-H$

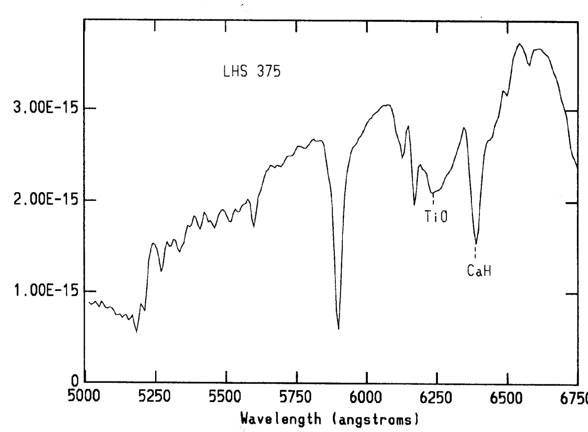

FIG. 4. Spectrum of LHS 375 obtained at CTIO with the 4 m telescope equipped with an R–C spectrograph and a CCD detector. The resolution is about 20 Å. Flux is in F_λ.

[2]In Fig. 1 we did not plot the cpm systems from Ruiz & Maza (1990). It has been found that their $V-R$ colors are in error for stars with $V-R > 0.9$. They can be corrected using the following transformation: $(V-R)_{corr} = 5.18 \times (V-R)_{old} - 3.87$.

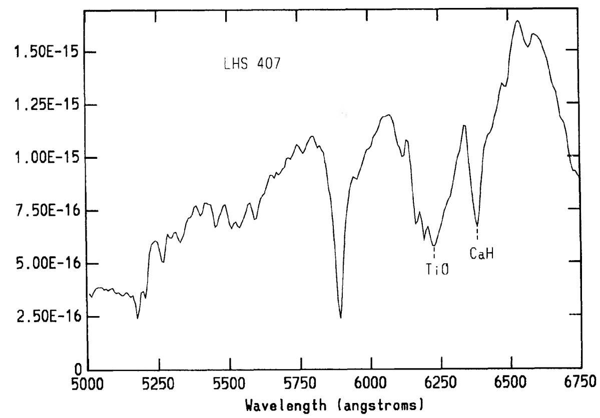

FIG. 5. Same as Fig. 4, for LHS 407.

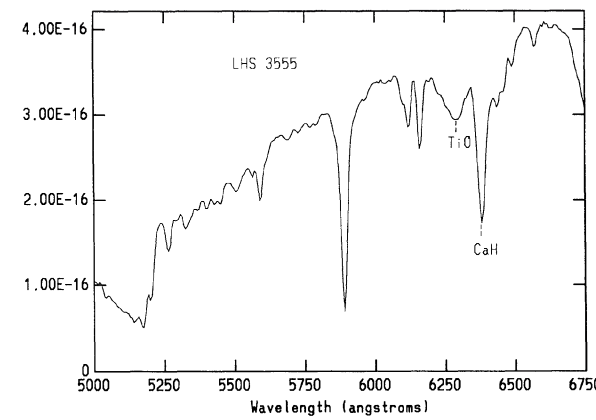

FIG. 7. Same as Fig. 4, for LHS 3555.

colors of the CSDs have only marginal individual weight. Their systematic behavior, however, is probably meaningful and consistent with a subdwarf classification for these stars.

Taking advantage of the fact that we had spectra for the CSDs and for the control samples, we attempted a calibration of some spectral features with colors. We estimated the relative strength of hydrides and oxides as a function of a temperature sensitive color, that may be used to evaluate the underabundance of metals. For such purpose we selected the TiO band near 6260 Å and the CaH band near 6390 Å (flux at the deepest point in the band with respect to 0), and as a temperature indicator the color $R-I$. The metallicity index CaH/TiO and color $R-I$ for the CSDs and the control samples are given in Table 3 and presented in Fig. 3. Again the CSDs show a systematic behavior, with stronger CaH with respect to TiO than old disk stars. Figures 4, 5, 6, and 7 are spectra of the CSDs with the CaH and TiO bands (used in Fig. 3 and Table 3) indicated.

Up to this point all the evidence we have presented for classifying LHS 375, LHS 407, LHS 3181, and LHS 3555 as subdwarfs is based on systematic trends with respect to disk stars, in the different diagrams discussed. It would be hard to assign a definite extreme subdwarf type to them if it was not for the fact that we also have CCD trigonometric parallaxes for them (summarized in Table 1).

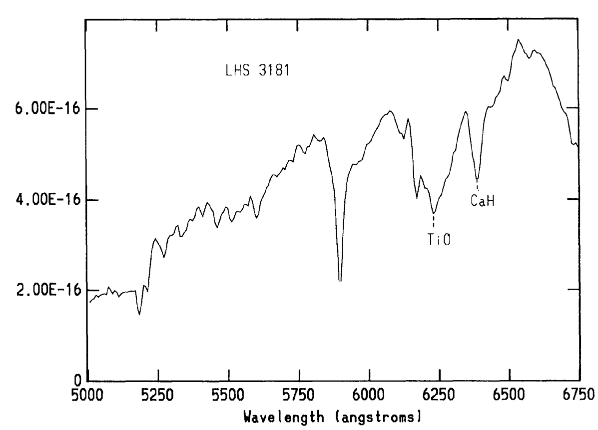

FIG. 6. Same as Fig. 4, for LHS 3181.

With the absolute visual magnitudes and colors in Table 2 we can plot our stars in the M_v vs $V-I$ diagram of stars with accurate trigonometric parallaxes from Monet *et al.* (1992). In this diagram the authors have established the presence of a subdwarf sequence, formed by 17 stars, about 1.5 mag below the disk main sequence. In Fig. 8 we have schematically reproduced the M_v vs $V-I$ diagram from Monet *et al.* (1992). We have also drawn the cpm stars from Ruiz & Maza (1990), which have photometric parallaxes. These stars lie in the disk main-sequence area while the CSDs lie on top of the extreme subdwarf sequence, and discriminate from disk stars beyond observational uncertainties.

CCD parallaxes have proven to be crucial in the effort of recognizing cold subdwarfs: these stars are faint and

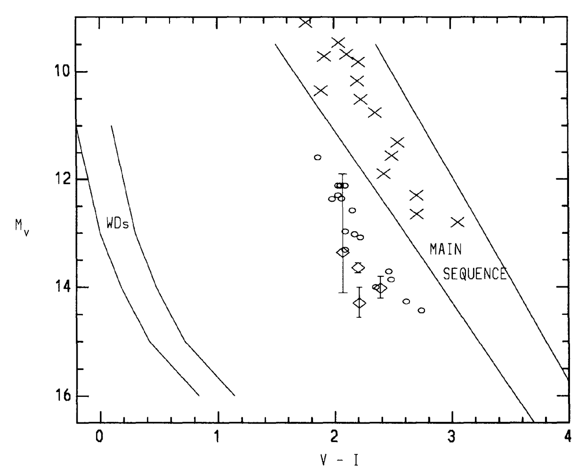

FIG. 8. A schematic representation of the M_v vs $V-I$ diagram from Monet *et al.* (1992). The position of the disk main sequence and white dwarfs are indicated. Crosses represent stars (cpm) from Ruiz & Maza (1990), and the extreme subdwarfs from Monet *et al.* are drawn as circles. Our CSDs (diamonds) lie on top of the subdwarf sequence.

very accurate distances are required in order to overcome the natural scatter of disk stars in the Main Sequence. We can expect that soon more of these CSDs will be identified in the USNO CCD parallax program as well as in our Southern CCD parallax program (Anguita & Ruiz 1988). This will be important for the determination of the luminosity function of metal-poor stars and to find their critical mass for hydrogen burning. Both questions need to beaddressed in order to have a better understanding of the early history of our Galaxy.

We would like to thank M. Hamuy, S. Leggett, and J. García for help with data reductions. This project received partial support from Grant No. 995-89 from FONDECYT.

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