ENERGY DISTRIBUTION OF LOW-LUMINOSITY STARS

Maria Teresa Ruiz,[a),b)] Claudio Anguita,[b)] and Jose Maza

Departamento de Astronomia, Universidad de Chile, Casilla 36-D, Santiago, Chile

Miguel Roth

Las Campanas Observatory, Carnegie, Casilla 601, La Serena, Chile

ABSTRACT

Trigonometric parallaxes, CCD and IR photometry, and low-resolution spectroscopy of three cold white dwarfs (ER8, LHS 483, and LHS 378) and a dM8 red dwarf (LHS 3003) are presented and used to calculate their distances, luminosities, and bolometric corrections. Results clearly indicate a nonblack body shape of the energy distribution for the cold white dwarfs, this is very clear in the case of LHS 378 which shows a strong IR defficiency similar to LHS 1126.

I. INTRODUCTION

Given the difficulties involved in obtaining observational data on faint stars, the faint ends of the luminosity functions of degenerate stars (Liebert, Dahn, and Monet 1988) and that of the main-sequence stars (Wielen, Jahreiss, and Kruger 1983) are very poorly defined.

The question of a possible increase in the number of stars with ever decreasing mass up to substellar values (brown dwarfs) is an open problem (D'Antona and Mazzitelli 1986) which is far from settled, the statistical significance of the number of these low-mass stars in the available catalogs is negligible.

In the case of the cold degenerates the question of their number density at the faintest luminosities $\log L/L_\odot \approx -4.5$, is crucial for understanding the evolution of WDs, their cooling mechanism, and the potential use of the drop at the faint end of the luminosity function to measure the age of the galactic disk (Winget *et al.* 1987; Iben and Laughlin 1989; Wood 1990).

Knowledge of the luminosity of these faint stars involves determination of their distances, which is now possible thanks to the use of CCD detectors in trigonometric parallax measurements (Monet and Dahn 1983; Anguita and Ruiz 1988) and also their spectral energy distribution for which IR (J, H, K) photometry has been proven to be crucial (Leggett 1989).

In this paper we present CCD trigonometric parallaxes, CCD B, V, R, I, and IR J, H, K photometry and spectroscopy of three cold white dwarfs (ER8, LHS 483, and LHS 378) and for the extreme red dwarf (dM8) LHS 3003.

II. OBSERVATIONS

a) CCD Parallaxes

They were obtained using the CTIO 1.5 m telescope with the $f/13.5$ secondary and an RCA CCD detector. The scale is 0.3″/pix. Starting May 1986, frames were obtained every 3 months, during the period when the stars were available in the sky. For ER8 and LHS 378 observations covered a period of 1 yr, while for the other stars a period of 3 yr was considered for the parallax calculations. A detailed description of the observing procedure and method used in calculating the parallaxes is given by Anguita and Ruiz (1990). Table I presents the resulting parallaxes.

b) CCD, BVRI Photometry

With the CTIO 1.5 m telescope and a RCA CCD detector during the night of 31 March 1989 we obtained photometry of the program stars. The filters were Johnson's B, V, R, and I of Kron–Cousins. We observed Graham's E fields standards for calibration (Graham 1982). The photometry was reduced using DAOPHOT on a Microvax II at the University of Chile, Astronomy Department Image Processing Facility. Colors thus obtained have an average precision of 7%.

c) IR Photometry

Near-infrared (J, H and K) magnitudes were obtained with the Dupont 2.5 m telescope at Las Campanas Observatory in May 1989, using an InSb detector cooled to solid nitrogen. An apperture of 10″ was used and the telescope was displaced some 25″ for sky subtraction after a careful examination of the field on the guiding camera in order to avoid contamination by other faint stars. Integrations were typically of the order of 200 s and the instrumental magnitudes were calibrated using the CTIO set of faint IR standards (Elias *et al.* 1982). A summary of the visual and IR magnitudes is given in Table II.

d) Spectroscopy

In April 1988 and 1989, spectra of these stars were obtained with the 3.6 m telescope at La Silla (ESO), equipped with EFOSC, the detector was a blue coated RCA CCD, and the spectral resolution 20 Å. A He-Ar lamp was used for wavelength calibration, and three standard stars were observed each night for flux calibration. The spectra were reduced using IRAF in a SUN workstation at CTIO.

III. RESULTS AND DISCUSSION

Figures 1–3 show the spectra of the observed degenerates ER8, LHS 483, and LHS 378, the absence of spectral fea-

TABLE I. Parallaxes.

Star	μ (″yr^{-1})	π (″)	d (pc)	$v_{\rm T}$ (km s^{-1})
ER8	2.18	0.068 ± 0.003	14.7 ± 0.7	153
LHS 483	1.08	0.070 ± 0.004	14.3 ± 0.8	73
LHS 378	1.18	0.069 ± 0.004	14.5 ± 0.8	82
LHS 3003	0.96	0.161 ± 0.006	6.2 ± 0.2	28

TABLE II. Photometry.

Star	B	V	R	I	J	H	K
ER8	18.45	17.05	16.32	15.72	15.19	14.66	14.9
LHS 483	17.91	17.08	16.44	15.97	15.41	15.13	15.05
LHS 378	17.47	16.44	15.95	15.43	14.76	14.93	14.57
LHS 3003	18.39	17.05	15.58	12.78	9.88	9.32	8.95

FIG. 3. LHS 378, same as Fig. 1 but with integration time of 1200 s.
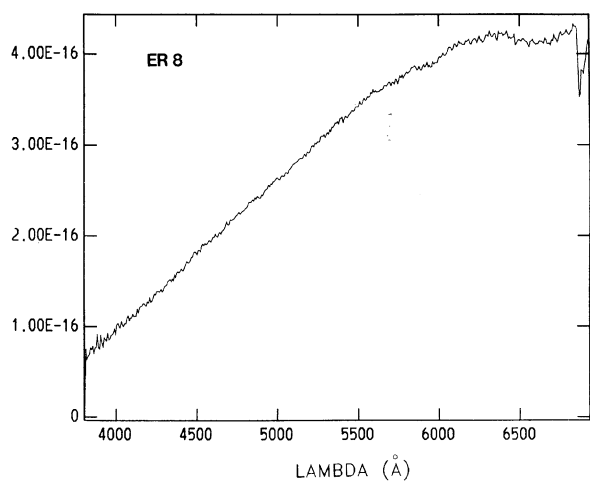
FIG. 1. ER8, the spectrum was obtained with the ESO 3.6 m telescope at La Silla, equipped with EFOSC (B300) and an RCA CCD detector. The integration time was 3600 s. Fλ in ergs cm^{-2} s^{-1} Å^{-1}.
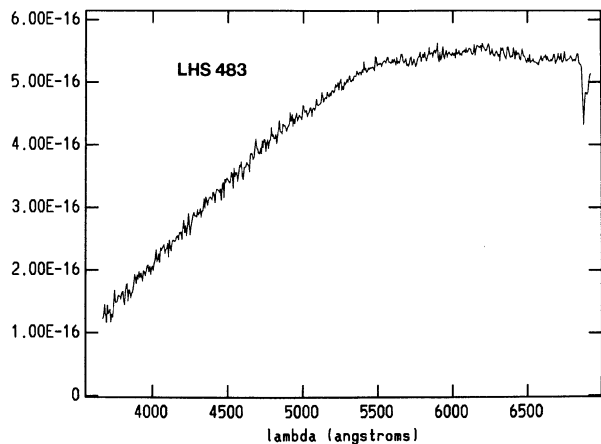

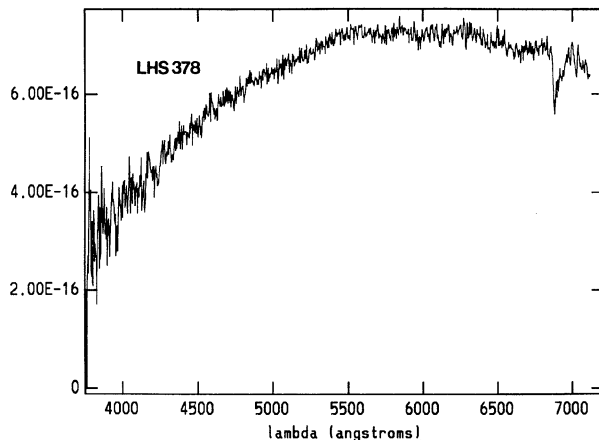FIG. 2. LHS 483, spectrum obtained with the same instrument as for that in Fig. 1. The integration time was 3000 s.

tures is typical of these cold stars. Very little information can be drawn from their optical spectra. Given that the energy distributions in Figs. 5–7 are far from that of a blackbody, in order to get a temperature for these stars one has to use a model atmosphere. If we use for comparison the emerging monochromatic fluxes for red degenerates with pure- helium or helium-rich atmospheres (Kapranidis 1985; Mould and Liebert 1978) we get a temperature of 4000 K for LHS 483, for ER8 and LHS 378 the temperatures predicted by comparing their observed colors with those predicted by the models give contradictory results possibly indicating a different source of opacity in their atmospheres.

Figure 4 shows the spectrum of the red dwarf LHS 3003. This star presents strong chromospheric activity. Table III gives the measured emission-line fluxes. According to the strength of the TiO and CaOH absorption bands LHS 3003 can be classified as an dM8 similar to vB10.

To obtain the luminosity of these stars we have plotted the fluxes in the various filters ($BVRIJHK$) against wavelength (see Figs. 5–8). No reddening correction has been applied considering that these stars are all nearby. The hand-drawn line between the points has been extrapolated for $\lambda > K$. For the degenerates most of the energy is contained between the B and K filters, therefore an error in the extrapolation of the energy distribution, in Figs. 5–7, will not make a large differ-
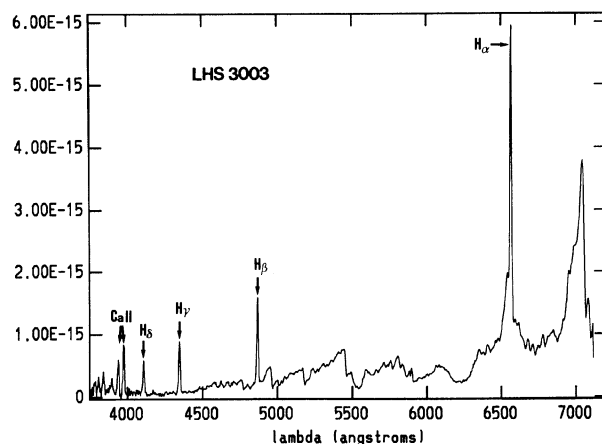

FIG. 4. LHS 3003, same as Fig. 1 but with integration time of 1200 s.

TABLE III. LHS 3003 emission-line fluxes.

Identification	λ (Å)	$F_\lambda^a \times 10^{15}$	$F\lambda$ ($H\beta = 100$)	Equivalent width (Å)
H10	3797	2.8	17	42
H9 + ?	3835	4.6	28	73
H8	3889	3.4	20	44
Ca II	3934	6.9	42	130
Ca II + Hϵ	3969	9.9	60	187
Hδ	4101	7.4	45	165
Hγ	4340	10.7	64	165
Hβ	4861	16.6	100	74
Hα	6563	55.3	333	33

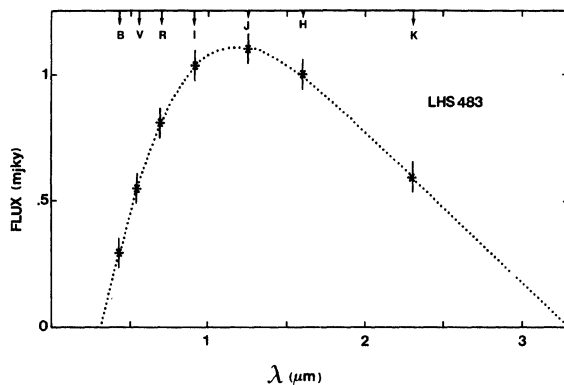^{a} In ergs cm^{-2} s^{-1} Å^{-1}.

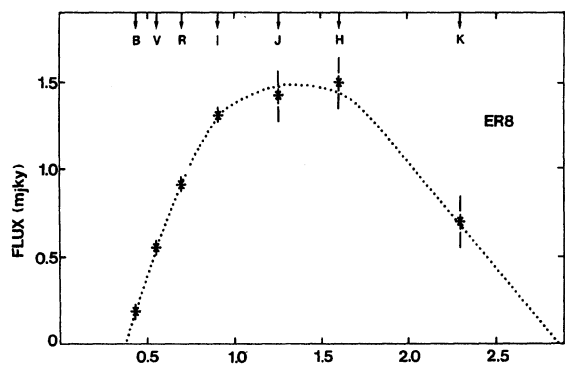FIG. 6. Same as Fig. 5 but for LHS 483.

FIG. 5. Energy distribution for ER8, error bars are indicated for the different fluxes.
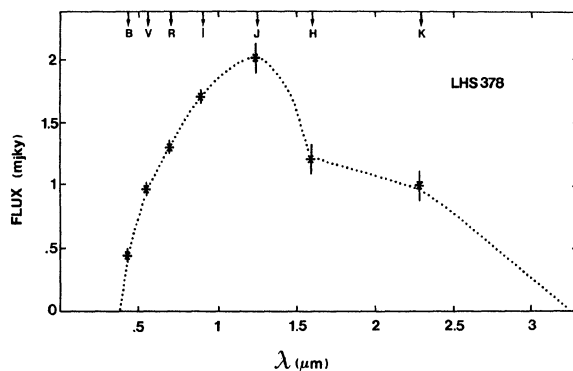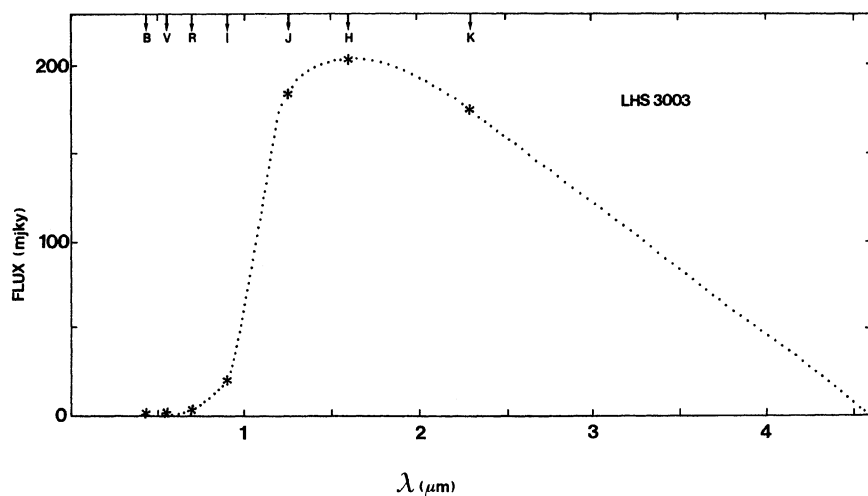

FIG. 7. Same as Fig. 5 but for LHS 378.

FIG. 8. Same as Fig. 5 but for LHS 3003.

ence in the resulting luminosities. In the case of the red dwarf LHS 3003 (Fig. 8) the extrapolated flux is more important.

Luminosities were calculated integrating the area under the curves in Figs. 5–8. The results are summarized in Table IV.

ER8. This star was discovered by Ruiz *et al.* (1986) due to its large ($2.18''$/yr) proper motion. From Fig. 5 we get a luminosity for ER8 $= 4.7 \times 10^{-5} L_\odot$ but unfortunately at the time of the IR observations there was a faint very red star close to ER8 that was included in the $10''$ aperture. Recent estimates of the IR colors of that faint star suggest that its total contribution to ER8 luminosity calculated above is about 20%, so a better value for the luminosity of ER8 is $3.7 \times 10^{-5} L_\odot$.

LHS 483. This star as well as LHS 378 and LHS 3003 are included in Luyten's *LHS Catalogue* (1979). In Liebert *et al.* (1988) a preliminary parallax of $0.058'' \pm 0.006''$ is quoted. We obtain a larger parallax, making this star one of the lowest luminosity (bolometric) degenerates known.

LHS 378. The energy distribution in Fig. 7 shows a strong IR defficiency similar to the one found by Lebofsky and Liebert (1984) in the cold white dwarf LHS 1126. In the case of LHS 1126 Lebofsky and Liebert, based on a shallow absorption present at $\lambda 4600$ Å, suggest that the IR defficiency could be due to the presence of C_2, although a detail interpretation awaits model atmospheres that can take into account the presence of C_2 molecules and its contribution to the opacity.

LHS 3003. The strong chromospheric activity present in this star is a signature of relative youth, which in this case is confirmed by its low tangential velocity, both indicating that the star is a member of the young disk population. Its low luminosity, only slightly exceeding that of vB10, one of the

TABLE IV. Luminosities.

Star	M_v	M_{Bol}	B.C.	$L/L_\odot$
ER8	16.2 ± 0.1	15.8 ± 0.1	0.4	$(3.7 \pm 0.5) \times 10^{-5}$
LHS 483	16.3 ± 0.1	15.8 ± 0.1	0.5	$(3.7 \pm 0.5) \times 10^{-5}$
LHS 378	15.6 ± 0.1	15.3 ± 0.1	0.3	$(6.3 \pm 0.5) \times 10^{-5}$
LHS 3003	18.1 ± 0.1	12.7 ± 0.1	5.4	$(6.4 \pm 0.4) \times 10^{-4}$

lowest luminosity red dwarfs known (Greenstein, Neugebauer, and Becklin 1970), leaves this star in the limit of having the minimum mass for hydrogen burning.

Tangential velocities in Table I of the three degenerates are consistent with membership to the old galactic disk.

It is worth stressing the fact that cold degenerates have energy distributions that are very different from a blackbody (unlike red dwarfs like LHS 3003) and thus it is not useful to try to characterize their spectra by a blackbody temperature which does not have a physical meaning. We conclude that it seems clear that in order to improve our understanding of these objects it is crucial at this point to have more realistic model atmospheres to compare them with, nonetheless we know this is a very difficult task.

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