

SPECTROSCOPY OF AN UNUSUAL EMISSION LINE M STAR

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ABSTRACT

We report moderate resolution spectroscopy of an unusual late-type, faint ($I \approx 20^m$), emission-line star, PC 0025 + 0447. This object was discovered as part of a grism survey for high redshift quasars; the very strong ($> 250 \text{ \AA}$ equivalent width) $H\alpha$ emission line was detected by our automated line search algorithm. The spectrum has two unresolved emission lines ($H\alpha$ and $H\beta$) near zero velocity, superposed on the absorption spectrum of a very red M dwarf which has strong K I, the strongest VO bands known, and relatively weak bands of TiO. The weakness of subordinate lines of Na I ($\lambda 8192$) and other spectral features suggest that it is definitely a cooler, and probably fainter, analog of LHS 2924. The strength of the emission lines indicates that PC 0025 + 0447 is very young; it may be a fading, predecessor brown dwarf at an estimated M_{bol} approaching 14^m at a distance of $\approx 60 \text{ pc}$.

1. INTRODUCTION

For the past several years we have been performing CCD grism surveys designed to detect high redshift ($z > 3$) quasars. Slit spectroscopy of one of the more promising quasar candidates revealed (to our initial dismay) it to be a faint late-type star with extraordinarily strong Balmer emission lines. In Sec. 2 we describe the observations of this unusual object; possible interpretations and estimates of the distance and luminosity are in Sec. 3. A first description of the spectrum, with critical new phenomena, is given in Sec. 4. Our grism surveys to date have covered over 60 sq. deg and consist of spectra of over half a million objects; this is the first emission line star we have discovered. (It should be noted that our survey will not find emission lines with equivalent widths less than $50 \text{ \AA}$.) The absorption spectrum accompanying the strong emission is unusual. So little is known about the faintest end of the main sequence that our somewhat speculative analysis may be justified.

2. OBSERVATIONS

Details of the Palomar CCD grism survey can be found in Schmidt *et al.* (1986, 1987). The survey employs the 4-shooter CCD camera/spectrograph (Gunn *et al.* 1987) mounted at the cassegrain focus of the Hale telescope. This project uses the telescope as a transit instrument; the four imaging 800×800 Texas Instruments CCDs are read out at the sidereal rate to produce a long, narrow tapestry (typically $75^\circ \times 8.5'$) of sky. The grisms produce slitless spectra with a dispersion of $77 \text{ \AA arcsec}^{-1}$ and a wavelength coverage of $\approx 4500\text{--}7400 \text{ \AA}$. The blue cutoff is a result of the falling sensitivity of the CCDs; the red limit is set by a filter that

blocks the strong near-infrared sky signal. This configuration was designed to detect quasars at $3 < z < 4.5$ down to $r \approx 21$. [See Schneider *et al.* (1989) for examples of grism spectra.]

In 1988 the survey technique was slightly modified; instead of using the telescope as a transit instrument, rates are placed in the tracking so that the telescope scans great circles (in our case along lines of constant right ascension). The integration time is set by adjusting the scanning (and, of course, the CCD readout) speed. We selected a rate that produces an exposure time of 300 s per CCD. The actual effective integration time per CCD is 292.5 s, as not all of the detector is illuminated. Eight survey strips, all $1.1^\circ \times 8.5'$ in size, were scanned in the summer of 1988. The positions of these areas coincide with the survey fields of Gunn *et al.* (1986). Each strip yielded several thousand spectra; all were extracted from the data and wavelength and flux calibrated. Our automated emission line search algorithm noted that the spectrum of one of the objects, PC 0025 + 0447, (hereafter abbreviated as PC 0025) possessed all the features of a quasar with a redshift of 4.4. (At the time of submission of this paper, slit spectroscopy of approximately half of the emission line candidates has been completed.)

A finding chart of the source is given in Fig. 1; the coordinates are listed in Table 1. The grism spectrum, acquired on 15 September 1988, is displayed in Fig. 2. A comparison of this spectrum with grism data of high redshift quasars (see Schneider *et al.* 1989) shows remarkable similarities: very little flux in the blue, a strong emission line with a sharp drop on the blue side, and a flat continuum to the red of the emission line. The wavelength of the feature coincided with that of $H\alpha$ at rest, but this zero redshift possibility was dismissed as unlikely based on the appearance of the grism spectrum.

A moderate resolution spectrum of the object was obtained with the 4-shooter spectrograph on 22 August 1990. The entrance aperture to the spectrograph is a $1.5''$ slit; during the exposure the slit was oriented perpendicular to the horizon to minimize losses caused by differential dispersion.

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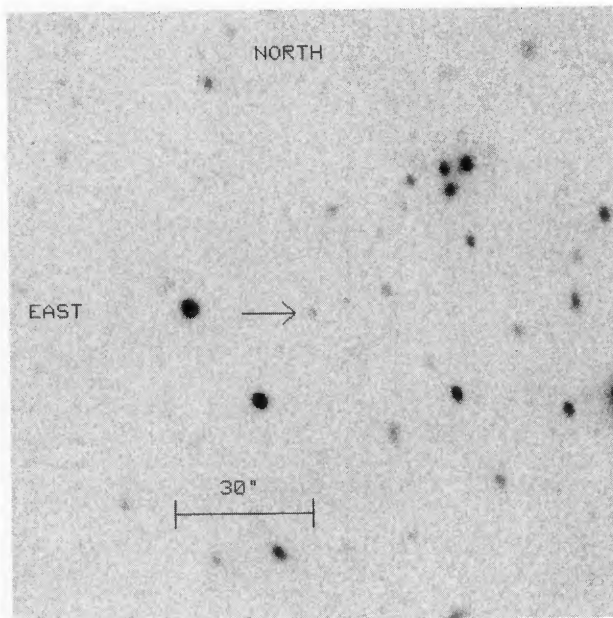


FIG. 1. Finding chart for PC 0025 + 0447. North is up, east to the left, and the field is $134''$ on a side. The image is a 300 s exposure taken through the F555W ("wide V" of the *Hubble Space Telescope's* Wide Field Planetary Camera; see Griffiths 1989) with the 4-shooter CCD camera.

The 200 line mm^{-1} grating produces spectra from 4300–9700 Å at a resolution of 25 Å. The detector is an 800×800 Texas Instruments CCD. The wavelength calibration is determined with an Ar-He-Ne arc; the rms error of the cubic fit to the lines was 0.6 Å. The F subdwarf standards of Oke & Gunn (1983) were used as flux calibrators. This slit spectrum of PC 0025 (exposure time of 3600 s), binned at 8 Å pixel^{-1} , is shown in Fig. 3; note that the atmospheric O_2 absorption bands have been removed by the extinction program, and as best possible, the atmospheric H_2O . Figure 4 displays the same spectrum, but here the ordinate is *AB* magnitude, not flux. The 8 Å pixel^{-1} binning is not adequate for the magnitude plot, as the star is so faint at short wavelengths that some pixels have negative fluxes. In consequence, 56 Å averages were taken at $\lambda < 5440$, (except in $\text{H}\beta$); 24 Å averages were taken $5440 \leq \lambda \leq 6088$; the balance of the data, although noisy, is shown at 8 Å . The existence of a strong emission line at $\approx 6550 \text{ Å}$ was confirmed. It is clearly $\text{H}\alpha$ at rest and not $\text{Ly } \alpha$ at a redshift of 4.4 since a sharp

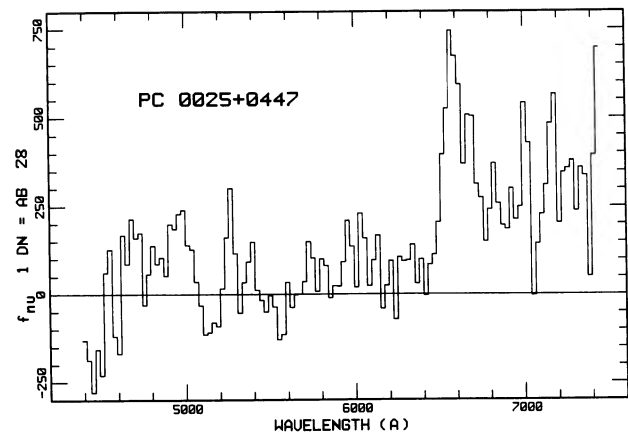


FIG. 2. The first 4-shooter grism spectrum (exposure time 585 s) of PC 0025 + 0447 obtained on 15 September 1988. Each pixel represents 25.5 Å . The spectral resolution (FWHM) is $\approx 110 \text{ Å}$. The unit of flux along the vertical axis is $2.29 \times 10^{-31} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$ ($= AB$ magnitude 28). The $\text{H}\alpha$ emission line is clearly visible, and there is a suggestion of $\text{H}\beta$ emission.

$\text{H}\beta$ emission line is also present (whose existence can be seen, if not totally believed, in the grism spectrum of Fig. 2). The balance is the complex line and band spectrum of a late dMe dwarf. The emission line strength and continuum level are similar on the 1988 and 1990 exposures; unless we have been spectacularly fortunate in our selection of dates of observation, this is not a case of dramatic flares on a normally quiescent star.

Before proceeding we should make some cautionary remarks. The seeing disk was considerably smaller than the width of the slit (the emission lines have FWHMs of only $\approx 20 \text{ Å}$); this may lead to errors in the measured radial velocities. A more serious defect with the data involves the flux calibration. Since more than an octave of wavelength is covered, there will be some second-order interference at wavelengths redward of 8000 Å. The F subdwarf flux calibration standards, however, are not nearly so red; the overlapping order produces an overestimate of the quantum efficiency of the spectrograph and a smooth depression of the calculated red flux in the object. The actual spectrum of PC 0025 is even redder than shown. This interference may also cause some systematic effects on the removal of the atmospheric absorption bands, as the blue light of the standard stars will artificially dilute the depths of the absorption; this produces an insufficient correction in the data of objects with redder colors than the standard star. This dilution, however, will be modest, and cannot introduce features of the observed size (at 8500 and 9500 Å) in PC 0025; the calibrated spectra of other "red" objects taken on the same night do not show any significant features that could be attributed to this effect. One should also remember that the spectrum in Fig. 3 was taken through a slit; the errors in the absolute flux calibration may be several tenths of a magnitude.

We also present 500 s 4-shooter slit spectra of two intrinsically faint stars, LHS 2924 and LHS 2930, obtained in March 1989. The instrumental configuration and reduction procedure (and the possible systematic errors in the flux calibration and atmospheric absorption correction) for these data were the same as that described above. In addition, colleagues (J. B. Oke and Don Hamilton) provided unpublished spectra of late-type stars taken with the Double

TABLE 1. Properties of PC 0025 + 0447.

Parameter	Value
Right ascension (1950.0)	$00^{\text{h}}25^{\text{m}}07.3^{\text{s}} \pm 0.3^{\text{s}}$
Declination (1950.0)	$+04^{\circ} 47' 14'' \pm 5''$
l	110.5
b	-61.2
V	24.0 ± 0.3
$V - I$	4.4 ± 0.4
$\text{H}\beta$	
Equivalent Width	$510 \pm 220 \text{ Å}$
Line Flux	$2.0 \pm 0.2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$
Velocity*	$+260 \pm 60 \text{ km s}^{-1}$
$\text{H}\alpha$	
Equivalent Width	$274 \pm 27 \text{ Å}$
Line Flux	$6.1 \pm 0.2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$
Velocity*	$+100 \pm 30 \text{ km s}^{-1}$

*The velocities may contain a large systematic error since during the observations the image size was significantly smaller than the size of the entrance aperture of the spectrograph; see Sec. 2.

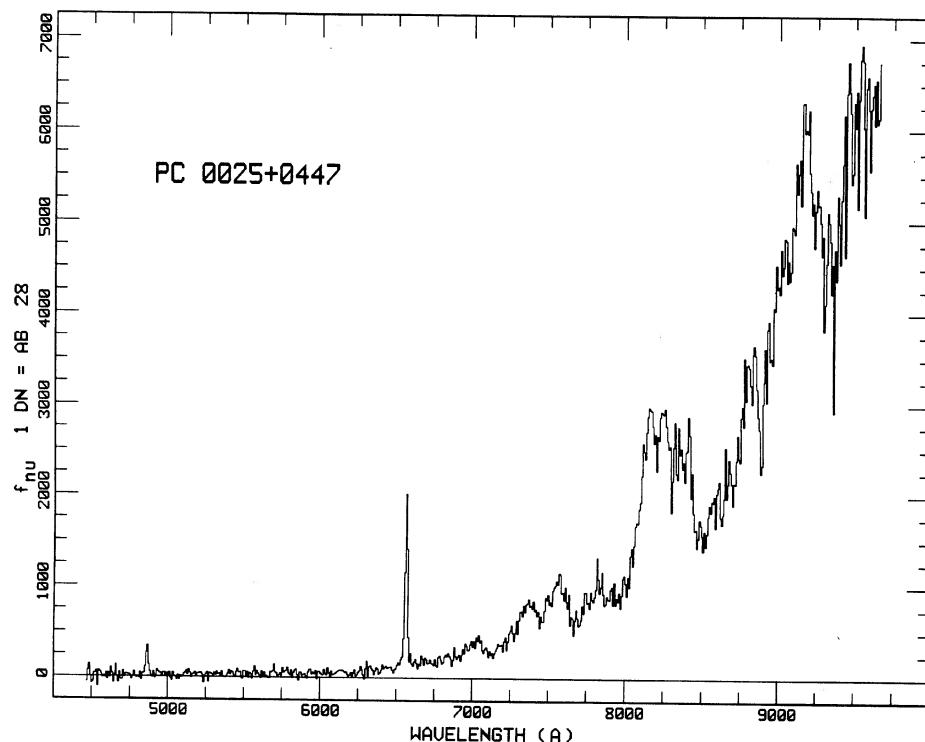


FIG. 3. The slit spectrum of PC 0025 + 0447, acquired on 22 August 1990 with the 4-shooter spectrograph. The exposure time is 3600 s, the resolution is ≈ 25 Å, and each pixel is 8 Å. The flux scale is the same as in Fig. 2.

Spectrograph (DBSP) and the 4-shooter spectrograph for this study.

3. DISCUSSION: WHAT AND WHERE IS IT?

A convincing argument that PC 0025 is not an intergalactic giant is the strength of the resonance lines of K 1, a feature

present only in dwarfs and here easily seen even at the bottom of the atmospheric O₂ band. The emission lines have unusually high contrast to the neighboring continuum; its flux provides some poor guidance on its distance. The line profiles of the two emission features were fit to Gaussians, to measure centroids, widths, and strengths; the results are given in Table 1. At our resolution both lines are unresolved

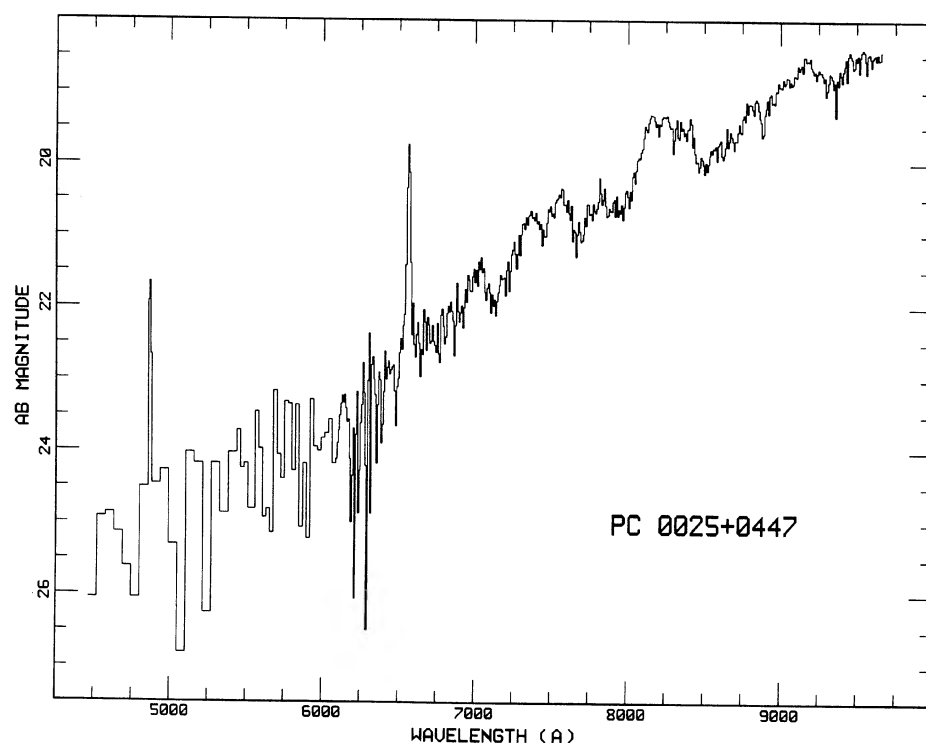


FIG. 4. The spectrum of Fig. 3 plotted as AB magnitude instead of flux. At short wavelengths the data have been binned (except for the H β emission line) to improve the signal-to-noise ratio.

(FWHM $< 20 \text{ \AA}$) and appear slightly displaced with inconsistent velocities, a discrepancy that may result from the seeing disk being significantly smaller than the slit width ($1'' = 16 \text{ \AA}$). The flux in $H\beta$ is a relatively large fraction of $H\alpha$, consistent with unsaturated emission as in a stellar chromosphere. Merrill (1940) notes that TiO bands distort the Balmer decrement in giants, especially weakening $H\alpha$, β ; the overlying TiO molecules fracture emission lines into several components, weakening them wherever TiO is strong.

In flare dMe stars, in contrast, the emission Balmer decrement is smooth and flat, as illustrated in Greenstein (1977) for a quiescent phase of Bond's flare star AF Psc and by Ruiz *et al.* (1990) for LHS 3003, a mid-M dwarf, not yet known to flare, with very strong emission and a flat Balmer decrement, i.e., a very active chromosphere. A misprint in Table III of Ruiz *et al.* (1990) results in $L(H\alpha)$ being overstated by a large factor; the correct line luminosity is $2.8 \times 10^{26} \text{ ergs s}^{-1}$. VB 10, one of the faintest known stars, has flares and quiescent $H\alpha$ emission. From an excellent spectrum of VB 10, kindly provided by Don Hamilton, on which he measured a $7 \text{ \AA}$ emission equivalent width, we derive $L(H\alpha) = 2.5 \times 10^{25} \text{ ergs s}^{-1}$. The ratio of the line flux to bolometric luminosity, $R(H\alpha) = L(H\alpha)/L_{\text{bol}}$, is 1.3×10^{-4} and 1.6×10^{-5} for LHS 3003 (corrected) and VB 10, respectively. The large range of $R(H\alpha)$ limits its usefulness as an accurate distance indicator. PC 0025 has two seriously contradictory properties: the largest $W(H\alpha)$ known in a star, and a spectrum suggesting that it has low bolometric luminosity. The luminosity carried by the rest of the hydrogen emission spectrum (Ly α and the recombination continuum) must be a large multiple of the $L(H\alpha)$. Table 2 lists the $H\alpha$ emission line properties of nine intrinsically faint stars.

It is instructive to investigate samples of less dramatic dMe's. Stauffer & Hartmann (1984) compiled statistics of $H\alpha$ emission lines in ≈ 250 dM's; their table shows only three with $W > 5 \text{ \AA}$ and ten with $2 \text{ \AA} < W < 5 \text{ \AA}$. Giampapa & Liebert (1986) studied 24 intrinsically faint dM's with an échelle spectrograph and found emission in eight, four of which have complete photometry and parallax data in Table 3 of Greenstein (1989). The latter permits the conversion, $W(H\alpha) \Rightarrow L(H\alpha)$, and therefore evaluation of $R(H\alpha)$. Giampapa and Liebert note "weak" emission in LHS 2930 and "none" in their faintest star, LHS 2924; we will assume $W = 1$ and $0.5 \text{ \AA}$, respectively, for these objects, to calculate their $R(H\alpha)$ in Table 2.

This list of the faintest known stars is neither large or complete. These faint stars have stronger emission than

those in the Stauffer and Hartmann sample. To make a (very) rough estimate of the distance of PC 0025, we will assume that its $R(H\alpha)$ is comparable to that of known dMe's [a dubious supposition since its $W(H\alpha)$ is two orders of magnitude larger than the typical value found in such stars]. The observed $H\alpha$ line luminosity converts to an intrinsic luminosity of $L(H\alpha) = 7.3 \times 10^{22} d^2$, where d is the distance in parsecs. The distance to PC 0025 can be expressed as

$$d = 12 \left(\frac{L_{\text{bol}}}{10^{30}} \frac{R(H\alpha)}{10^{-5}} \right)^{1/2} \text{ parsecs.}$$

We believe that PC 0025 is fainter than but similar to LHS 2924; adopting that bolometric luminosity with the median $R(\alpha)$ from Table 2 ($\approx 2.5 \times 10^{-5}$) yields a distance of 19 pc. Its emission $W(H\alpha)$ of $274 \text{ \AA}$, however, is by far the largest known for late-type stars, while LHS 2924 has little or no emission. At 19 pc, the observed flux yields $L(H\alpha) = 2.6 \times 10^{25} \text{ ergs s}^{-1}$, a low value, comparable to that of VB 10, one seventh that of CN Leo (= Wolf 359). The derived distance varies as $R(H\alpha)^{0.5}$; the luminosity of LHS 2924 with the $R(H\alpha)$ from CN Leo gives $d = 33$ pc. Applying the highest known $R(H\alpha)$ (LHS 3003) results in a distance of $d = 43$ pc.

An interesting comment by an anonymous referee questioned whether further knowledge of the dependence of $L(H\alpha)$ on luminosity for dMe's might improve the distance estimated from the $H\alpha$ flux, since the relation between $L(H\alpha)$ and properties M_V and M_{bol} might be expected to offer useful guidance. Fleming *et al.* (1988) compiled such information on a sample of ≈ 30 dMe's found in the *Einstein* extended medium sensitivity survey. A linear regression to the 27 objects in their study that have both M_V and $L(H\alpha)$ measurements results in the relation

$$\log L(H\alpha) = 30.50 - 0.220 M_V.$$

The rms error in the fit is 0.34 in $\log L(H\alpha)$. One can combine this equation with the observed V magnitude and $H\alpha$ line flux of an object to derive its distance; inserting the values for PC 0025 (Table 1) yields a distance of 24 pc. This estimate is comparable to the result in the previous paragraphs, but it should be noted that at this distance PC 0025 is much fainter than any of the Fleming *et al.* (1988) stars.

Let us explore a more natural assumption leading to a luminosity and distance; assume that PC 0025 resembles but is fainter than the reddest normal dM's and dMe's with complete data given in Table 3 of Greenstein (1989). That table has systematically consistent measures of colors on the $AB_V(\lambda)$ scale and includes estimated H_2O blanketing in the derivation of M_{bol} . Assume PC 0025 lies on a logical continuation (i.e., linear extrapolation) of the color-luminosity diagrams for the faintest stars. Seven stars in Greenstein (1989) have $M_{\text{bol}} \geq 12$, of which LHS 2924 will be omitted from the statistical relations to be derived. While LHS 2924 is particularly important as the faintest, it has marked interesting spectroscopic peculiarities when compared with LHS 2930 (Probst & Liebert 1983; Liebert *et al.* 1984; Giampapa & Liebert 1986). Its relative weakening of TiO apparently shifts LHS 2924 somewhat in color-color relations, and LHS 2924 may exhibit some peculiarities in common with PC 0025. LHS 2924 and LHS 2930 have known parallaxes but weak or no $H\alpha$ emission. The six stars used to calibrate the data are VB 8, VB 10, LHS 207, LHS 2930, G45-20, and G51-15. Linear relations were derived between M_{bol} and the

TABLE 2. Properties of $H\alpha$ emission in some of the faintest stars.

Star	Eq Width Angstroms	L_{bol} $10^{30} \text{ erg s}^{-1}$	$L(H\alpha)$ $10^{26} \text{ erg s}^{-1}$	$R(H\alpha)$	Notes
AF Psc	—	24	180	7.5×10^{-5}	
GL 406	6.2	3.9	19	4.9×10^{-5}	Flare star, CN Leo
G 51-15	3.7	3.0	7.6	2.6×10^{-5}	
VB 8	4.7	2.4	5.4	2.3×10^{-5}	
LHS 3003	33	2.2	28	12.7×10^{-5}	Ruiz <i>et al.</i> (1991)
LHS 2930	1.0 :	2.0	0.8	0.4×10^{-5}	Uncertain Eq Width
VB 10	7	1.5	2.5	1.6×10^{-5}	Flare star, V1298 Aql
LHS 2924	0.5 :	1.0	0.1	0.1×10^{-5}	Eq Width is upper limit
PC 0025	274	0.7	29	40.0×10^{-5}	Based on $d=63$ pc and estimated L_{bol}

AB colors ($V-k$), ($V-I$), and ($I-k$). The infrared k magnitude is on the absolute $AB_v(\lambda)$ scale; $k = K + 1.87$. The linear relations are good fits to the observations; from χ^2 , spreads in M_{bol} are ± 0.06 , ± 0.10 , and ± 0.17 for ($V-k$), ($V-I$), and ($I-k$), respectively. LHS 2924, however, lies 0.6 mag below the new M_{bol} , ($V-I$) relation and 0.2 mag below the M_{bol} , ($V-k$) relation; we conjecture that PC 0025 shows similar, but possibly larger, deviations.

Of these three colors, only ($V-I$) could be measured with the 4-shooter slit spectrum; the estimated error is ± 0.4 . John R. Graham kindly made available to us his preliminary K measurement made with the Palomar 1.5 m reflector. Graham finds that $K = 14.95 \pm 0.10$; his improved results will soon be available. From the above linear extrapolations of the six faint dM's, $M_{\text{bol}} = 13.4 \pm 0.2$, 12.8 ± 0.4 , and 13.8 ± 0.1 . Adding LHS 2924's deviations from the linear relations revises the estimates to 13.6 ± 0.3 , 13.4 ± 0.64 , and 13.8 ± 0.2 . These values place PC 0025 close to LHS 2924; the spectra differ enough to suggest that the best mean should be written as $M_{\text{bol}} > 13.7$.

The only substantially fainter star known is the very red, resolved companion to a white dwarf, the suspected brown dwarf GD 165B which has $M_{\text{bol}} = 14.99$. Zuckerman & Becklin (1987, 1991) and Becklin & Zuckerman (1989) suspect this to be a genuine brown dwarf with an effective temperature ≈ 2100 K; PC 0025 is probably warmer. GD 165B has $K = 14.09$, nearly 1 mag brighter than PC 0025, but there is no report as yet of its detection below $1 \mu\text{m}$. GD 165B consequently lacks the other colors used above; its ($I-k$) would be particularly helpful in narrowing the range of possible bolometric corrections. But GD 165B and LHS 2924 together are useful in setting definite limits for PC 0025, i.e., $15 > M_{\text{bol}} > 13.7$. We need to estimate BC_I , the I bolometric corrections for PC 0025 (I being its most precise photometric datum). A quadratic fit to the bolometric corrections for the seven reddest stars predicts $BC_I = 1.51 \pm 0.22$. The limits for PC 0025 then become $16.5 > M_I > 15.2$, equivalent to distances 42 and 76 pc. We adopt $d = 63$ pc for the computations in Table 2, assuming that PC 0025 is closer to the luminosity of LHS 2924 than to that of GD 165B. At this modulus of 4.0, $M_{8190} = 15.6$, $M_{6944} = 17.9$, and $M_{5400} \approx 20.0$. These AB s are near the centers of the I , R , and V bands. This distance is grossly at odds with that from $H\alpha$ flux. If the star is in a short-lived Hayashi stage of evolution, the distance and proper motion will be radically smaller. Our assumption is that the colors and spectrum of PC 0025 are to be interpreted simply as those of a dM on the main sequence, i.e., implying a temperature. We cannot numerically estimate this temperature; the temperature scale of the lower main sequence is quite uncertain. We believe that Sec. 4 establishes that PC 0025 is cooler than LHS 2924. Even were both brown dwarfs, their temperatures, which would be a function of mass and age, are useful parameters; see Sec. 5.

The last line of Table 2 gives a hypothetical set of parameters for PC 0025 emission strength assuming $d = 63$ pc. At this distance its $R(H\alpha)$ and $L(H\alpha)$ are unsurpassed among stars in this luminosity range. We believe that the discrepancy in the distances derived from chromospheric and photospheric properties singles PC 0025 out as the site of abnormal chromospheric activity; the large equivalent width of the emission line is not caused solely by a low continuum level. This star has an intrinsically high $L(H\alpha)$, unless the distance is grossly overestimated.

4. THE SPECTRUM OF PC 0025 + 0447

A detailed study of the spectrum will be worthwhile, but the star is faint except redward of the I band. The temperature is below any calibrated by Berriman & Reid (1987); a crucial question is whether it is cool enough that completely new discriminants might appear. The strength of H_2O bands in the J , H , and K infrared bands would be most significant, and weaker terrestrial H_2O bands occur in the near infrared. At the temperature of a dM, the increased populations of higher vibrational and rotational states could bring the steam bands to below $1 \mu\text{m}$. In other very cool stars, the most reliable discriminant has been the increased strength of VO bands, as compared with the fading TiO. Such fading could be intrinsic, if polyatomic molecules or solid grains reduce the Ti available. The solids would also produce a veiling by their overlying continuum emission. An indirect effect is saturation of strong TiO bands below $8000 \text{ \AA}$, reducing the temperature contrast in that region. Wing (1973) notes that TiO indices, based on bands at $\lambda \leq 8000 \text{ \AA}$, which rapidly and continuously increase in giants, level off abruptly in his few dwarfs cooler than Wolf 359. In the coolest dM's, the weaker singlet bands of TiO do appear at $7600 \leq \lambda \leq 10\,000 \text{ \AA}$. The enhancement of VO bands at $\lambda\lambda 7400, 7900 \text{ \AA}$ is illustrated in Figs. 3 and 6. The Atlas by Turnshek *et al.* (1985) illustrates this effect in hotter dM's; G51-15 shows the VO heads at $7400, 7900 \text{ \AA}$ only as inflection points on the long wavelength wings of bands of TiO, at $7100, 7600 \text{ \AA}$. But in PC 0025, $7400 \text{ \AA}$ is clearly isolated, and $7900 \text{ \AA}$ produces a neat double band with $7600 \text{ \AA}$ of TiO, which appears to be greatly weakened. One important feature of our spectrum of PC 0025 is that the atmospheric extinction program has largely removed the strong atmospheric O_2 dip, seen in most published spectra. Within that band appear the usually concealed resonance lines of K I, $\lambda\lambda 7665, 7699$; in the PC 0025 spectrum they dominate what in other dM's is mainly TiO. The resonance lines of sodium, which are normally blended with TiO, are hard to see, only in part because of low flux; the subordinate lines of Na I at $\lambda 8192$ are present in PC 0025, but weaker than normal.

What can we predict about $\lambda 8192$ which has excitation potential $EP = 2.1 \text{ eV}$? Since the star has little radiative flux at 2.1 eV , excitation is by collision, its weakness suggests low excitation temperature. Assume that the T_{eff} and electron pressures in these cool stars are such that elements with low ionization potential are becoming neutral, towards lower T_{eff} , and that the opacity varies smoothly. Then the resonance lines of K I ($IP = 4.32 \text{ eV}$) should increase monotonically, at a T_{eff} such that Li I, ($IP = 5.37 \text{ eV}$), Na I ($IP = 5.12 \text{ eV}$) have become nearly completely neutral. Only $\lambda 8192$ decreases, relative to these resonance lines, through its Boltzmann factor $10^{-EP/kT}$. We therefore expect $W(8192)$ to increase with decreasing T_{eff} up to a maximum, and then drop rapidly, as $10^{-10584/T_{\text{exc}}}$. Excitation temperatures are usually less than T_{eff} ; near 2000 K this exponential is steep. The correlations of measured $W(8192)$ with color or bolometric luminosity are found to be good. Surface gravity increases along the lower main sequence but the expected gravity in the Burrows *et al.* (1989) for hydrogen-degenerate brown dwarfs is not much lower, ≈ 5.5 . A spectroscopic discriminant for brown dwarfs in the optical region would be invaluable. Otherwise we must rely on infrared ($J-H$), ($H-K$) photometry or even better, the infrared H_2O bands.

Fortunately the 4-shooter spectra are well corrected for the λ 7600 atmospheric O_2 band extinction. Attempts to measure $W(K\ I)$ were disappointing, however, because a residue of a strong TiO band affects LHS 2930 and LHS 2924 in differing amounts. However, K I is strong in PC 0025; its appearance in Fig. 6 suggests that it is appreciably stronger than in LHS 2924.

The measured $W(8192)$ for eleven M dwarfs are listed in Table 3. The feature lies on a flat-topped peak in the flux. The continuum was set at $\lambda\lambda$ 8140, 8260; the equivalent width was measured by simple integration $\lambda\lambda$ 8170 – 8240. The measurement process is reproducible, two measures in PC 0025 differing by only 0.4 Å. PC 0025 lacks both infrared colors and luminosity, available for the other stars; we use its $(V-I)$ although the V flux is low, and uncertain. Figure 5(a) displays the relation between the equivalent width of the Na I feature as a function of $(V-I)$ for the 11 stars in Table 3; six measurements come from excellent double spectrograph slit exposures kindly supplied by J. B. Oke; we supplement our 4-shooter data with a suspected brown dwarf in the Pleiades, supplied by D. Hamilton, which differs in having strong λ 8192. Note how clearly LHS 2924 and PC 0025 are separated from other low mass stars; the quadratic curve fitted by least squares gives them zero weight. Liebert *et al.* (1984) noted the weakness of all features in LHS 2924, and discussed it as a possible brown dwarf. The weak λ 8192 found in PC 0025 suggests that its T_{exc} is the lowest.

PC 0025 and LHS 2924 have sufficiently peculiar spectra to suggest intrinsic differences from other faint stars like VB 10 and LHS 2930 arising from substantially lower temperature, indicated by the weak λ 8192, the strengthened VO bands, and the probably weakened TiO bands. Other correlations may therefore break down at lower temperatures, e.g., the color-color relations which are dominated by TiO, which till this point showed TiO increasing monotonically with decreasing T_{eff} . In Fig. 5(b) the best fit in the M_{bol} , $W(8192)$ plane is linear; here we plot a reasonable guess that PC 0025 has $M_{\text{bol}} = 14^m$. However, a change of $\pm 1^m$ would not affect the conclusion that the Na I absorption is anomalously weak.

A brief sketch of published and current results on spectral features at $\lambda < 10\,000$ Å which are sensitive to temperature in dM's may be worthwhile.

VO: It is unfortunate that little quantitative data on VO

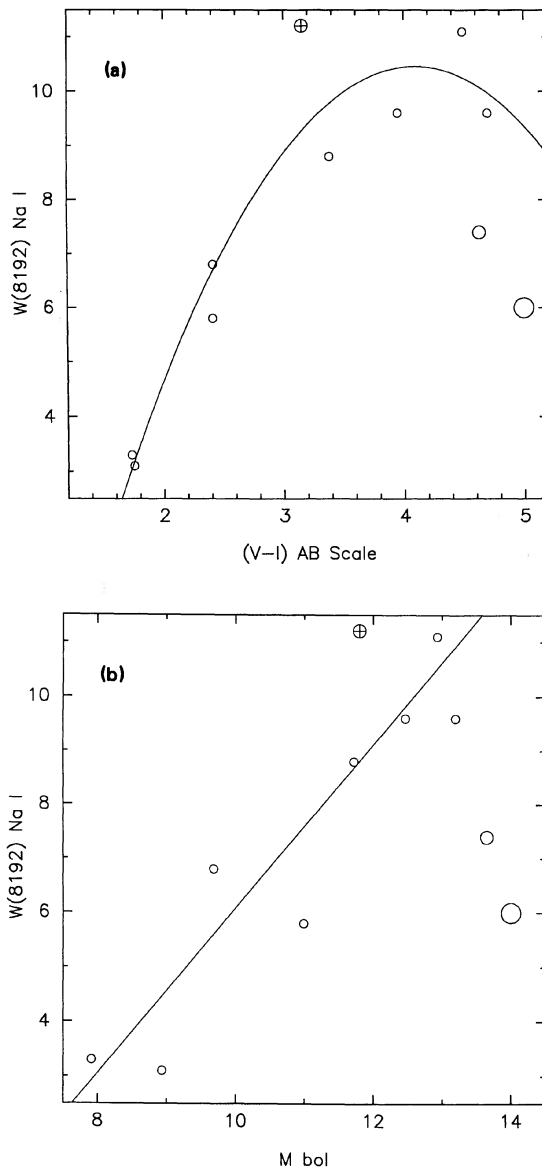


FIG. 5. (a) The equivalent widths of the subordinate line of Na I (the unresolved triplet λ 8192). The $(V-I)$ values are narrowband ($AB_{5405} - AB_{8140}$) measurements from CCD spectra. The circled cross, a suspected brown dwarf in the Pleiades, has a strong line. The quadratic least-squares fit omits LHS 2924 (larger open circle) and PC 0025 + 0447 (largest open circle), both of which have weak λ 8192. (b) Same symbols as (a), but with M_{bol} as the ordinate. The diagonal line is the best linear fit; the largest circle, PC 0025 + 0447, lacks distance and infrared data and is plotted at the estimated $M_{\text{bol}} = 14$. Both LHS 2924 and PC 0025 clearly have abnormally weak λ 8192.

TABLE 3. Equivalent widths of Na I λ 8192 in late-M dwarfs.

Star	$(I-k)^a$	$(V-k)^a$	M_{bol}^c	$W(8192)^b$	Instrument	Observer
G 191-51	0.32	2.05	7.91	3.3	DBSP	Oke
G 171-47	0.40	2.15	8.93	3.1	DBSP	Oke
G 89-19	0.50	2.91	9.68	6.8	DBSP	Oke
G 171-48	0.67	3.08	10.99	5.8	DBSP	Oke
G 109-35	1.10	4.48	11.72	8.8	DBSP	Oke
G 51-15	1.36	5.31	12.47	9.6	DBSP	Oke
PPL 1	2.67 ^c	5.82 ^c	11.80 ^c	11.2	4-Shooter	Hamilton
LHS 2930	1.79	6.28	12.93	11.1	4-Shooter	This Paper
VB 10	2.08	6.78	13.20	9.6	4-Shooter	Hamilton
LHS 2924	2.60	7.23	13.65	7.4	4-Shooter	This Paper
PC 0025	2.9 ^d	7.2 ^d	> 13.7	6.0	4-Shooter	This Paper

Notes to TABLE 3

a) Data taken from Table 3 of Greenstein (1989).

b) Equivalent widths of blend measured between 8170 Å and 8240 Å.

Continuum level set at 8140 Å and 8260 Å.

c) Colors and luminosity possibly on a different system.

d) Based on preliminary measurements by John R. Graham.

has yet been published, and the required computations of molecular equilibria are lacking. In an early survey of “infrared stars,” Wing *et al.* (1967) found what they identified as a strong VO feature at $1.05\ \mu\text{m}$ increasing in their coolest stars; this feature was later identified as FeH. Hawkins & Bessell (1988) studied 12 very late dM's found in a faint photographic survey of the south galactic pole. Their AAT spectra show that VO is quite strong in the reddest stars; to

the eye, at least, none have VO as strong as does PC 0025, nor the TiO “veiling” noted. Also visible on the AAT spectra, in a largely unexplored wavelength range, are strong bands like those seen in PC 0025 at $\lambda\lambda$ 8500, 8900, 9300 (possibly triple). After this paper had been completed, a paper on this topic by Bessell (1991) appeared; while largely photometric, this study illustrates a total of about 40 AAT spectra of dM’s with IDS and CCD spectra for some of the very red objects. A first inspection shows that of these only LHS 2065 displays substantial weakening of TiO/VO, accompanied by strong VO bands. This star has moderate H α emission, but it is not quantitatively evaluated by Bessell. In our opinion LHS 2065 should be included in the list of coolest stars. Returning to our spectra, the strong, relatively sharp feature at λ 8900 is the strongest feature of the infrared singlet system of TiO (Pearse & Gaydon 1976). But the “extreme infrared system” of VO has numerous bands from 8540 to 8670 Å, as well as the well known groups near 7400, 7900 Å; we propose that the λ 8500 feature is largely VO. Good Palomar CCD double-spectrograph data (from J. B. Oke) show increasing strength of the three far infrared bands in the faintest dM’s (G51-15, VB 8, VB 10). It is strong in our LHS 2930 4-shooter spectrum and even more so in the LHS 2924 data. The relation between the strengths of these near-infrared features and TiO strengths at $\lambda \leq 8000$ appears to be quite nonlinear. In PC 0025, the weakness of TiO at $\lambda \leq 8000$ Å could arise from saturation or other sources of veiling. If veiling exists, the strength of the two shorter wavelength bands of VO corresponds to a large concentration of that molecule. The VO spectrum has numerous bands in its “red” system, below 7000 Å, and coincidences with these strong laboratory VO bands are found, e.g., $\lambda\lambda$ 5737, 6086, where the signal-to-noise ratio of our spectrum is very low.

Tinney *et al.* (1991) present 4-shooter spectra of eight faint dM’s. Found on the new Palomar 48 in. survey plates, these dM’s were not known as proper-motion stars. In this sample, the two faintest have probable H α emission and strong VO; none have as high a ratio of VO to TiO as does PC 0025. ESO 207 – 61, a member of the Hyades group, is illustrated by Ruiz *et al.* (1991) and suggested as a brown-dwarf candidate. It has a moderate H α emission and its VO to TiO ratio is less than in LHS 2924. The same is true of Gliese 569B (Henry & Kirkpatrick 1990). Of the total of 22 recently published late dM spectra, none are as extreme as LHS 2924 or PC 0025; objects like these are indeed rare (or exceedingly difficult to find).

CaOH: This well-known indicator of low temperature at λ 6230 blends with TiO. In PC 0025 it is a broad noisy band, at low flux level, apparently stronger than in LHS 2924; see Fig. 6.

FeH: Cohen (1978) demonstrated that a tight relation exists between $(V-K)$ and $W(\text{FeH})$, establishing that strong FeH occurs only in cool dM’s. The absence of the infrared Ca II triplet (λ 8500 – 8700 Å) in dwarfs eliminates it as confusing source in the proposed identification of λ 8500 with VO in late dM’s. The Hawkins & Bessell (1988) spectra of red dM’s display strong FeH (0,0) near λ 9910, and confirm its importance as indicator of low T_{eff} . This important feature requires much further study, but unfortunately it lies just past the red limits of our spectra. A weaker FeH (1,0) band near λ 8691 might be suspected in some late dwarfs, but is possibly blended with VO and TiO. As mentioned above, the recent work of Bessell (1991), containing numerous AAT spectra, opens a new door on this subject. Bessell notes

the possibility that λ 8691 contributes to an observed feature in his cooler stars. This may, in fact, become a practically useful blend with VO λ 8500 in the coolest stars. The FeH molecule band spectrum is widely spread out, lacking sharp heads, because of its low moment of inertia. The 1.05 μm feature is in fact seen even at the low resolution of the multi-channel spectrophotometer, 80–160 Å (Greenstein 1991).

H₂O: Is there a possibility that H₂O may appear in the coolest stars? The most accessible feature is a diffuse band at λ 9300 Å present in the Earth’s atmosphere, but sometimes seen in cool late giants. While there are other candidates for blending, in PC 0025 this new band was noted from first inspection as unexpectedly strong. The Hawkins & Bessell (1988) AAT spectra show this feature strong in several of their coolest stars, notably LHS 2397a, LHS 2065, and in their newly found M18, M19, and N1, to which they ascribe the faintest absolute magnitudes. The “steam bands” will be more diffuse than the atmospheric water vapor, requiring higher resolution and observation from a very dry site. Lacking the infrared spectra, it is worthy considering λ 9300 as a possible sign of H₂O.

In the four panels of Fig. 6 we compare the spectra of PC 0025 and LHS 2924, both heavily veiled and having strong VO; PC 0025 differs in its enormously strong hydrogen-emitting chromosphere. A similar comparison of LHS 2930 with the cooler LHS 2924 shows that LHS 2930 has the more normal appearance, with strong TiO throughout the spectrum and weaker VO. The various temperature-sensitive molecules discussed above (except for FeH, not observed) behave as expected, with PC 0025 as an extreme case. *We conclude that PC 0025 continues the spectroscopic evolution from LHS 2930 to LHS 2924, noted by Liebert *et al.* (1984), to still lower temperature and lower luminosity.*

5. CONCLUSION AND SPECULATION

The interpretation of the observed L , T_{eff} for the faintest, well-studied stars has been historically difficult. A good temperature scale is still lacking. Berriman & Reid (1987) discuss the problems of fitting stars with fully known parameters to the theoretical main sequence (their Fig. 3). Mainly these arise from the uncertainty of T_{eff} , coupled with the effect of H₂O blanketing on L_{bol} . Berriman and Reid find that low mass stars, $< 0.10 M_{\odot}$ (on hydrogen-burning tracks) and $0.06 M_{\odot}$ “brown dwarfs” (contracting towards their ultimate low luminosity), lie close together in their L_{bol} , T_{eff} diagram. The data for real stars could belong on either (or neither) locus.

It is difficult to define what a “brown dwarf” is (Stevenson 1991) and even more difficult to suggest observational criteria that permit recognition. This is especially true when the individual stellar masses are unknown. To define one, we depend on the refined theoretical calculation of low mass evolution, by Burrows *et al.* (1989, hereafter referred to as BHL). They test models with a wide variety of composition, opacities, and mixing-length ratios, and for a given mass and age predict T_{eff} and L . The radii, and therefore temperatures, vary between their models; luminosity, as function of mass and age, is less model-dependent. Above $0.085 M_{\odot}$ the model shrinks and cools somewhat towards an ultimately stable main-sequence configuration. Below a certain mass ($\approx 0.075 M_{\odot}$), nuclear energy is never tapped and the star cools and fades as a hydrogen-rich degenerate. Let us follow a star with $0.07 M_{\odot}$, insufficient for hydrogen ignition, truly

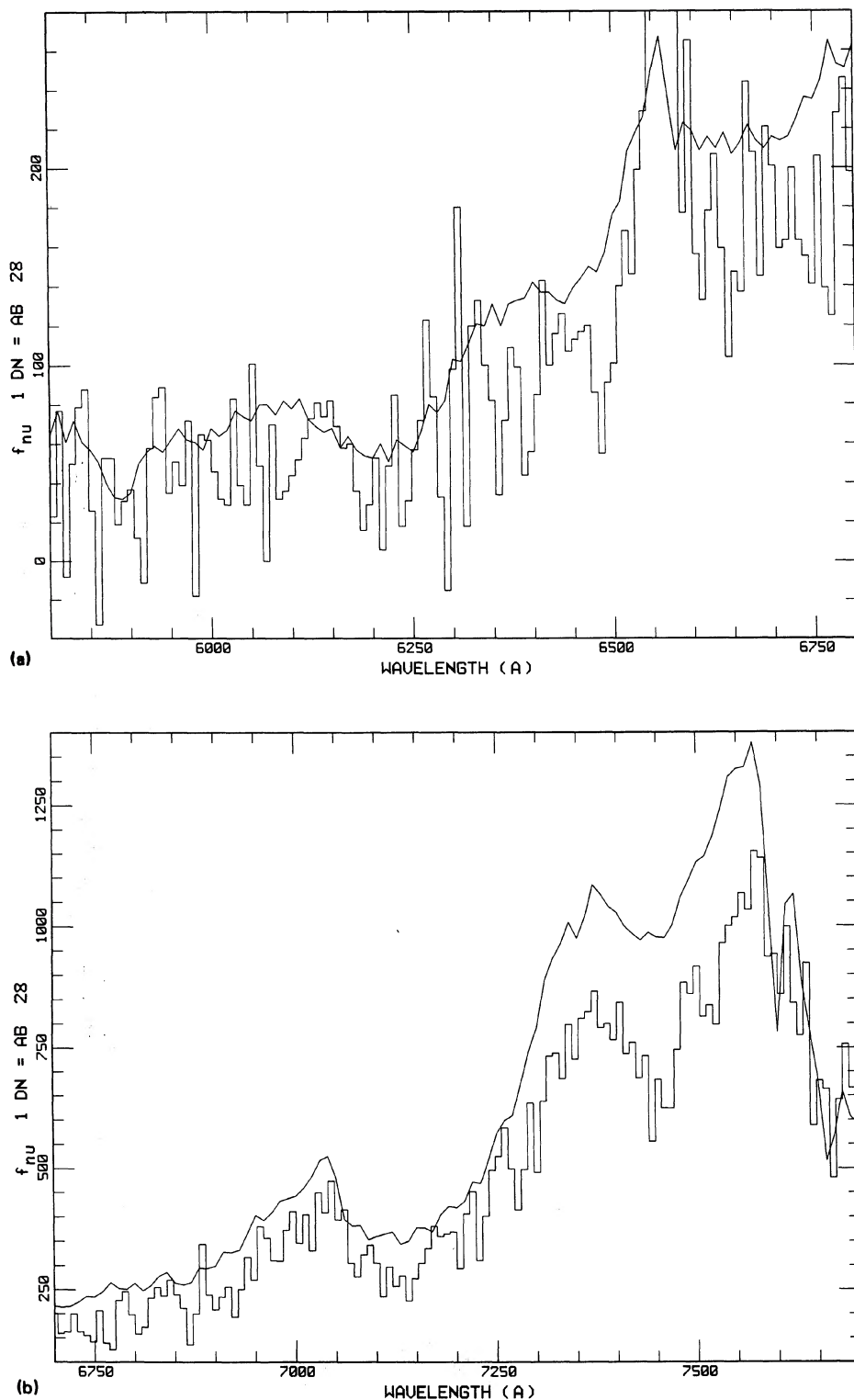


FIG. 6. (a)–(d) Comparison of 4-shooter spectra of PC 0025 (histogram) and the faintest known dM, LHS 2924 (solid line). The fluxes of PC 0025 are on the same scale as that of Figs. 2 and 3. Fluxes for LHS 2924 are scaled by a constant factor to match PC 0025 near λ 9100 Å. Each of the four panels covers a wavelength range of 1000 Å; there is a 100 Å overlap between successive graphs. The enormous H α emission line is far off scale in the first panel, reaching DN = 2000. At shorter wavelengths H β emission (not shown) reaches DN = 260 and the CaOH absorption band near λ 6230 is strong. PC 0025 + 0447 is redder over all than LHS 2924, has weaker TiO bands, weaker λ 8192 of Na I, stronger K I (7665, 7699 Å) and VO (7400, 7900, 8500 Å). The noisy feature near 9300 Å might possibly include H₂O in these stars, as well as in our atmosphere.

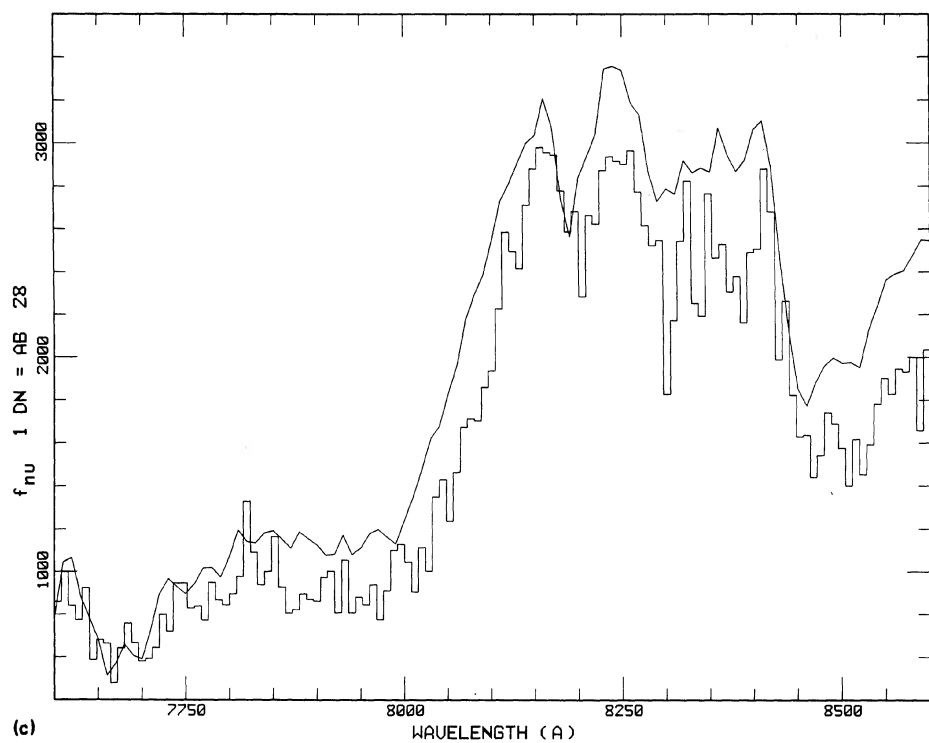
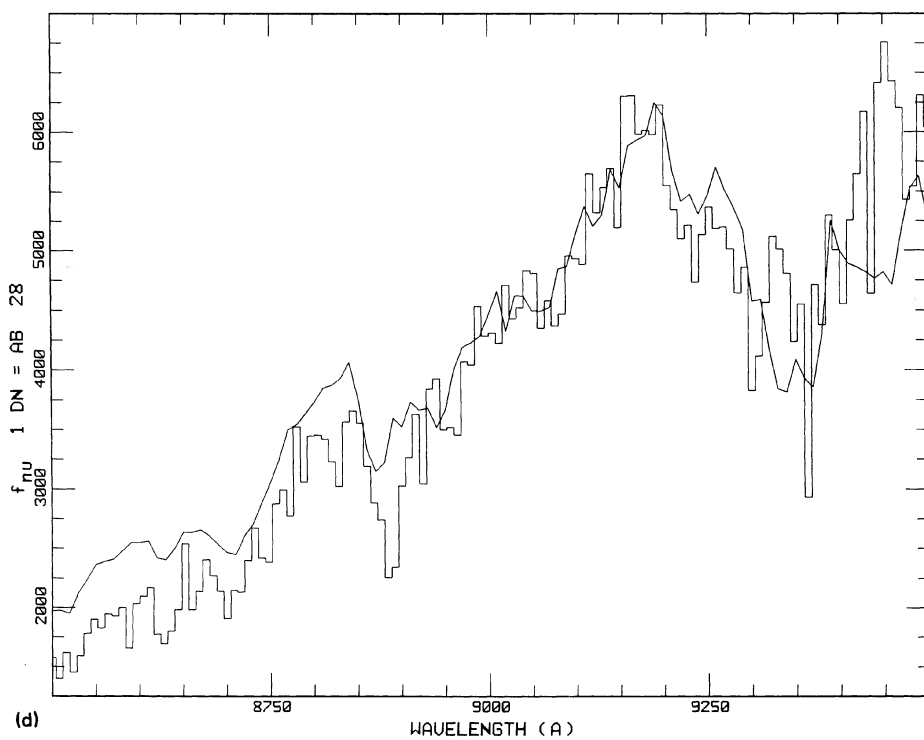


FIG. 6. (continued)



a brown dwarf; adopt parameters of opacity and mixing length that seem typical, BHL Model C. Such a star is actually in transition, with 10% of its luminosity thermonuclear even after 10^{10} yr. At age 10^8 yr, BHL model C has $M_{\text{bol}} = 11.82$, $T_{\text{eff}} = 2910$ K; at 10^9 yr, $M_{\text{bol}} = 14.88$, $T_{\text{eff}} = 1810$ K. In a time interval of 9×10^8 yr, the M_{bol} increases by 3.06, and the temperature drops by 1100 K. The radius shrinks from 10^{10} cm to 0.63×10^{10} cm, releasing gravitational energy. Lower mass accelerates the speed and magnitude of the evolution; for $0.06 M_{\odot}$, only 1% of the luminosity is ever thermonuclear. $M_{\text{bol}} = 12.14$, $T_{\text{eff}} = 2780$ K at 10^8 yr, and $M_{\text{bol}} = 15.53$, $T_{\text{eff}} = 1560$ K at 10^9 yr, the radius shrinkage about the same. Here the increase in M_{bol} is 3.39 and the temperature drops by 1220 K. Were younger models available, useful isochrones could be drawn (see D'Antona & Mazzitelli 1985). Lower mass results in T_{eff} too low even at 10^8 yr. To explain the intense chromospheric activity (suggesting youth) in PC 0025 may require a mass below $0.08 M_{\odot}$ observed at an earlier epoch. In order to obtain a $T_{\text{eff}} \approx 2100$ K at 10^8 yr, BHL models suggest a mass of $\approx 0.035 M_{\odot}$. Given the poorly known parameters of PC 0025, a wide range of mass and age thus seems possible. But if PC 0025 is now in a dynamic, pre-brown dwarf stage, one should not use the BHL tracks.

The radii of these hydrogen-core degenerates far exceed those of helium-carbon core degenerate white dwarfs, while the mass is about one-tenth as large. At 10^{10} yr the surface gravity ($\log g = 5.3$) is not sufficiently larger than the Sun's to introduce pressure broadening, and the surface gravity is even lower when the star is younger. Similarly, the scale height of the chromosphere would be nearly normal, but at typical chromospheric temperatures would constitute a larger fraction of the star's radius. The arguments for chromospheres in youth are familiar; winds, mass loss or accretion, rapid rotation, and magnetic fields often accompany youth, providing sources of hydromagnetic heating. The very strong emission lines suggest that PC 0025 + 0447 is a recently formed low-mass star. From its low effective temperature, we expect a mass so low that it will be unable to burn hydrogen.

Since PC 0025 was discovered in a survey with well-defined detection criteria, it is possible to make an estimate of the space density of such objects. Combining the results from our transit and scan grism surveys, PC 0025 could have been detected in a volume

$$V = \frac{4\pi d^3}{3f^{3/2}} \left(\alpha_s + \frac{\alpha_t}{l^{3/2}} \right),$$

where d is the distance, f is the ratio between the detected flux and the limiting flux of the scan survey, α_s and α_t are the fractions of the sky covered in the scan and transit surveys, respectively, and l is the ratio of the limiting fluxes of the transit to the scan surveys. Using the observed values of $f = 1.07$, $l \approx 4$, $\alpha_s = 0.6$ sq. deg, and $\alpha_t = 62$ sq. deg., the number density is

$$N = 0.005 \left(\frac{63 \text{ pc}}{d} \right)^3 \text{ pc}^{-3}.$$

The contribution of such objects to the local mass density is

$$\rho = 1.8 \times 10^{-4} \left(\frac{63 \text{ pc}}{d} \right)^3 \left(\frac{M}{0.035 M_{\odot}} \right) \left(\frac{t_{\text{Gal}}}{t_{\text{PC}}} \right) M_{\odot} \text{ pc}^{-3},$$

where t_{Gal} and t_{PC} are the ages of the Galaxy and the line emitting phase of PC 0025, respectively. If objects like PC 0025, in a steady state, are not to constitute too large a fraction of the local mass density, the duration of this luminous H α line phase must not be less than $\approx 10^8$ yr. Similarly, if its true distance is considerably less than our estimated 63 pc, we could face an excessive local mass density.

As the previous paragraph shows, our current data base places but limited constraints on several important properties of PC 0025. Our understanding of this source would be greatly increased by (1) accurate infrared photometry, (2) a moderate resolution, high signal-to-noise spectrum that extends out to one micron, and (3) astrometry (obviously in the infrared) to place some limits on its distance.

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