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INFRARED PHOTOMETRY AND THE ATMOSPHERIC COMPOSITION OF COOL WHITE DWARFS

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ABSTRACT

JHK photometry is presented for a number of cool white dwarfs, including five of the faintest stars with $M_v \gtrsim 15$. Comparison of the colors is made with the predictions of both hydrogen- and helium-rich model-atmosphere grids, primarily for the purpose of testing for the effects of the pressure-induced dipole opacity of molecular hydrogen. Three conclusions are offered.

1. The coolest observed stars lie near the temperature threshold at which infrared photometry can provide a clear distinction between hydrogen- and helium-rich atmospheres. The two stars Wolf 489 and G107-70 are tentatively suggested as helium-rich, as their $(V - K)$ colors are too red to match hydrogen models near $\log g = 8$.
2. Hydrogen atmosphere fits to the colors yield substantially higher effective temperatures for the cool stars than helium atmosphere fits, and yield higher temperatures than previous investigations fitting hydrogen atmosphere models to optical/near-infrared data.
3. There is a deficiency in the flux at blue wavelengths for all very cool stars relative to model predictions fitting $V - K$ colors. Despite the absence or weakness of spectral features, we argue that this is most likely due to blanketing by neutral metals.

Subject headings: infrared: general — photometry — stars: atmospheres — stars: white dwarfs

I. INTRODUCTION

White dwarfs with surface temperatures below 5000 K may be more numerous than their hotter counterparts (Sion and Liebert 1977), but their basic stellar parameters are only very poorly determined. Since the atmospheres are too cool for Balmer lines to be visible in the optical spectra, it is not even known whether the two distinct sequences among hotter degenerates—with either hydrogen- or helium-dominated atmospheres—extend to these cool stars. Indeed, evolutionary calculations suggest that the deep convective envelopes may have mixed out any thin outer hydrogen layer when $T_{\rm eff}$ has reached 5000 K; this could turn stars with "DA" atmospheres into helium-dominated atmospheres (Koester 1976; Vauclair and Reisse 1977).

If substantial hydrogen does exist in cool white-dwarf atmospheres, most will be in molecular form (Shipman 1977; Wehrse 1977). The first results of a program aimed at testing cool white dwarfs for the presence of H_2 are reported in this *Letter*. The test involves the predicted pressure-induced dipole absorption of H_2 in the infrared.

II. INFRARED PHOTOMETRY

JHK photometry of the coolest accessible white dwarfs was carried out at the KPNO 2.1 m telescope during the period 1978 February to May. A number of hotter stars were included in the program to fully delineate the white-dwarf sequence. The detector (KPNO BT photometer) was a nitrogen-cooled InSb photovoltaic element, preflashed and operated at 20 torr. A 15″ aperture was generally used, except that, when the sky brightness at full Moon and the large image size at f/30 necessitated blind-offset acquisition, the aperture was increased to 22″. In particular, LP 380-5 was never seen at the telescope, but the offset in this case was from a readily detectable M dwarf companion, using the accurate separation given in Luyten (1976), and was probably reliable. Star-sky chopping was performed with a 25″–45″ throw of the secondary oscillating at 10 Hz.

For the present purposes 16 pairs of 10 s integrations are considered to make up an observation. Observations were continued in the natural filter sequence until statistical errors of 0.05 to 0.10 mag were attained. Standards were taken from Table 10 of Frogel *et al.* (1978). Almost all the program stars were observed on more than one night, and the mean colors (weighted inversely as the statistical error) are recorded in Table 1 together with an rms error derived from the scatter in individual observations. Lower weight was given to one night when 10% fluctuations were present due to cirrus cloud. For $J - H$ and $H - K$ these errors are shown bracketed in units of 0.01 mag; the $V - K$ colors should be good to less than 0.07 mag. The number of infrared observations for each star is indicated in the third

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column. On average, more than 2 hours' observing has been accumulated per star.

III. MODEL ATMOSPHERES

Two grids of models for cool white dwarfs have recently been calculated for radically different idealized compositions. Shipman's (1977) models represent atmospheres of pure hydrogen. Pure helium atmospheres have been constructed by Böhm *et al.* (1977, hereafter BCFV). Although this group has tackled the difficult problem of strong Coulomb effects and degeneracy in the equation of state, their models are gray and make no predictions regarding emergent energy distributions.

To bridge the gap between the two extremes and to permit a direct comparison of observable colors, we have computed a new grid of models in the temperature range 4000–7000 K. The hydrogen-rich sequence with x (hydrogen fraction by number) = 0.9 was calculated at two gravities ($\log g = 7$ and 8). The helium-rich models have $x = 10^{-5}$. As metal deficiency is quite well established in white dwarfs (Weidemann 1975; Wegner 1972), the metallicity $[z/z_\odot]$ was set to 10^{-5} in both cases. The model-atmosphere program used has been described by Mould (1975, 1976). It is basically the ATLAS code of Kurucz (1970) with modifications very similar to those employed by Shipman (1977). For these compositions atomic line blanketing, TiO and H_2O opacities were not expected to be important and were turned off. One additional change was made in the temperature-correction procedure. The temperature gradient in the convective zone was found to be so close to adiabatic that negligible changes (<1%) in the emergent flux resulted from the substitution $\nabla = \nabla_{ad} + \epsilon$ for $\epsilon \lesssim 0.005$. With this fixed gradient, iteration was only required to converge the radiative layers and stabilize ∇_{ad}.

To permit interpretation of the observations in terms of these models, colors on the Johnson system have been calculated by integration through the filter bandpasses, using the methods of Mould (1976). For comparison with observations on the present system the $J - H$ colors in Table 2 must be reduced by a color term of 1.09 (Frogel *et al.* 1978). The two specific predictions of the grid can be seen from Table 2.

TABLE 1

OBSERVED COLORS

Name	Sp	No. Obs.	$J-H$	$H-K$	$V-K$	$B-V$	V	M_v
W475A........	DA	4	−0.11 (4)	+0.07 (3)	−0.6	0.08	12.30	11.43
LP 101-48......	DA	5	−0.07 (5)	−0.03 (7)	−0.2	0.16	12.24	11.76
Ross 627.......	DA	5	+0.11 (8)	−0.02 (7)	+0.9	0.31	14.24	13.59
L745-46A......	DF	2	+0.03 (2)	+0.19 (3)	+0.55	0.30	13.01	13.77
G195-19.......	DCP	2	+0.05 (7)	+0.21 (6)	+0.85	0.33	13.85	13.85
G99-47........	DAP	2	+0.17 (2)	+0.11 (2)	+1.5	0.61	14.12	14.59
W489..........	DK	6	+0.30 (4)	+0.11 (7)	+2.0	0.96	14.68	15.02
G107-70.......	DC	7	+0.26 (2)	+0.16 (7)	+2.0	0.99	14.62	15.06
LP 44-113......	DCP	5	+0.07 (5)	+0.20 (5)	+1.65	0.40	14.15	15.24
LP 658-2.......	DK	9	+0.16 (3)	+0.07 (5)	+1.7	1.06	14.48	15.26
LP 380-5.......	DC	17	+0.13 (5)	+0.15 (8)	+1.9	1.09	15.63	15.26

NOTES.—(1) Optical magnitudes, colors, and spectral types are taken from the literature. Absolute magnitudes (M_v) are determined from Naval Observatory parallaxes. The letter "P" in the spectral type indicates that a star is polarized and magnetic. (2) G107-70 is apparently a just-resolvable DC white-dwarf pair. The M_v value has a +0.75 correction assuming two equally bright components, as observed (Strand, Dahn, and Liebert 1976).

TABLE 2

BROAD-BAND COLORS (Johnson system) OF THE MODEL GRID

T_{eff}	Log g	x	$B-V$	$V-K$	$J-H$	$H-K$	BC
7000......	8	0.9	0.35	0.98	+0.19	0.11	0.12
6000......	8	0.9	0.52	1.41	+0.26	0.10	0.11
6000......	7	0.9	0.51	1.44	+0.28	0.09	0.14
6000......	8	10^{-5}	0.39	0.85	+0.11	0.10	0.05
5500......	8	0.9	0.62	1.67	+0.29	0.12	0.14
5000......	8	0.9	0.74	1.62	+0.13	0.09	0.18
5000......	7	0.9	0.77	2.01	+0.34	0.15	0.26
5000......	8	10^{-5}	0.54	1.37	+0.19	0.15	0.09
4500......	8	0.9	0.79	1.26	−0.08	0.08	0.11
4000......	8	0.9	0.82	0.99	−0.24	0.02	0.09
4000......	7	0.9	0.91	1.31	−0.15	0.06	0.07
4000......	8	10^{-5}	0.82	1.98	+0.27	0.14	0.26
4000*.....	8	0.9	0.82	0.93	−0.27	0.01	0.25
5250......	8	0.9	0.69	1.75	+0.24	0.12	0.18

* This model includes a treatment of pressure dissociation of H_2 (see text).

1. In the hydrogen-rich case ($x = 0.9$) the run of $V - K$ colors indicates that a large infrared deficiency develops at cool temperatures due to the pressure-induced dipole opacity of H_2. A similar effect can be seen in the flux distributions published by Shipman (1977).

2. Effective temperatures derived from the optical continuum will be very different depending on whether the helium-rich or hydrogen-rich case is assumed. This is caused by the switch from H^- to He^- opacity between these cases, and can be seen in the run of $B - V$ colors.

Although our models are undoubtedly compromised by uncertain opacities and idealization of the equation of state, we argue that these two predictions are well founded and qualitatively correct. With regard to (1), the chief concern is the validity of Linsky's (1969) theory of the pressure-induced dipole of H_2. It can be objected that the present temperature regime is far from that of the laboratory conditions in which the absorption coefficients were derived. However, this is not unusual among astrophysical opacity sources for which one tends to rely on the quality of the theoretical extrapolation rather than on direct experimental confirmation. The present understanding of the H_2 dipole opacity can probably be judged from a more sophisticated calculation of the vibration-rotation component by Patch (1971), who obtained an absorption coefficient a factor of 2 larger than that of Linsky. More worrisome is the pure translational component, whose high-frequency exponential cutoff seems very slow at high temperatures. The locus of models in two-color diagrams, however, is not greatly disturbed even if this component is set to zero. A second concern relates to the effects of high pressure on the dissociation equilibrium of H_2. Inclusion of the interaction formulation of Vardya, Giannone, and Virgopia (1969) yielded only small color changes in the coolest model, however. Third, we note that for hydrogen-rich atmospheres in this temperature range, the chief continuous opacity is H^- and, for $[M/H] < -5$, the principal electron donor is hydrogen. Hence, with the above proviso, the predicted IR deficiency will not depend on the degree of purity of the hydrogen atmosphere.[1]

With regard to the second prediction, the main concern is the reliability of the equation of state at very high photospheric pressures. Although with the present temperatures and compositions we do not reach the region of photospheric degeneracy explored by BCFV, it is clear that the Debye-Huckel approximation used in the present ionization equilibria is invalid. Hence we regard the helium-rich models computed here more as calculations of He^--dominated energy distributions than as determinations of atmospheric structure. That He^- remains dominant over He Rayleigh scattering for $x < 10^{-5}$ and $T_{\rm eff} \gtrsim 4000$ K seems assured by the pure helium calculations of BCFV.

[1] For $[M/H] > -5$ models will have a higher electron pressure and a reduced IR deficiency. However, the spectra of cool white dwarfs are generally not consistent with such high metallicities (Shipman 1977).

IV. HYDROGEN OR HELIUM ATMOSPHERES?

The ability of infrared photometry to distinguish between hydrogen and helium compositions is best seen in a ($J - H$, $V - K$) two-color diagram. For the hydrogen-rich sequence, a turnover is predicted due to the onset of the pressure-induced opacity. This occurs near 5500 K, though the position is quite gravity-sensitive. At higher temperatures the colors show little sensitivity to composition. Indeed, in Figure 1 we see that the observed positions of the hotter stars are consistent with the nearly coincident model loci. However, two of the coolest objects with $M_v > 15$ (Wolf 489 and G107-70) lie significantly redward in $V - K$ of the hydrogen model locus for $\log g = 8$. For the location of these objects, we consider three possible explanations.

1. They have hydrogen atmospheres at $\log g \sim 7$. A surface gravity below 7.5 would be unexpected, however, since recent evidence suggests that hotter white dwarfs have $\log g \sim 8$ with small dispersion, at least for the DA stars (Weidemann 1975, 1977; Schulz 1977; Shipman 1978). The masses and radii of white dwarfs are not expected to change as they cool.

2. They have hydrogen atmospheres, $\log g \sim 8$, and some blanketing ($\gtrsim 0.2$ mag) in the V bandpass, as we argue may exist at bluer wavelengths (§ V). However, a similar two-color plot using Greenstein's multichannel "i" magnitudes at 8000 Å in place of V shows these objects still lying redward of the $\log g = 8$, hydrogen model locus. Furthermore, significant blanketing in V might also be expected to produce curvature in the cool

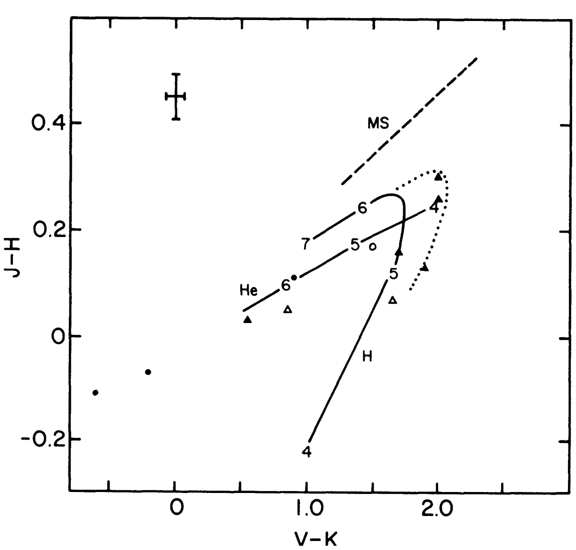

FIG. 1.—The ($J - H$, $V - K$) two-color diagram for white dwarfs with hydrogen spectra (*circles*) and without hydrogen lines (*triangles*). Magnetic stars are denoted by open symbols. The loci of the models is shown transformed in $J - H$ from the Johnson system to that of Frogel *et al.* (1978) by a color term of 1.09. Individual models are denoted by integers representing $T_{\rm eff} \times 10^{-3}$ and the hydrogen- and helium-rich sequences are identified H and He. The $\log g = 7$ hydrogen sequence is shown as a dotted line. The locus of the main sequence is given as MS. The mean photometric errors are estimated (*top left*).

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white-dwarf sequence in the (M_v, $V - I$)-diagram of parallax stars used by the Naval Observatory (see Dahn *et al.* 1978); this is *not* observed, in contrast to the marked curvature at the cool end of the (M_v, $B - V$)-sequence.

3. The stars have helium atmospheres. Both Wolf 489 (DK) and G107-70 (DC) lie very close to the locus of helium models. Given the objections to alternatives (1) and (2), we favor this explanation and tentatively suggest that these stars are helium-rich.[2]

For the three remaining stars with $M_v > 15$, a tentative conclusion on the chemical composition cannot be offered. LP 658-2 (DK) lies close to the turnover of the hydrogen-rich sequence. LP 44-113 = G240-72 is a strongly magnetic star whose energy distribution at V is depressed (e.g., Greenstein 1974); hence its location is difficult to interpret. LP 380-5 (DC) is the faintest star, both apparently and intrinsically, that we have measured to date; it seems too red in $V - K$ for the $\log g = 8$ hydrogen locus, but too blue in $J - H$ for the helium locus.

The temperature estimates for these stars clearly will depend on the assumed atmospheric composition. In Table 3 we present estimates for the coolest stars based on the nearest hydrogen/helium model points plotted in Figure 1. For comparison, Shipman's (1977) values from fitting hydrogen models to optical near-IR spectrophotometry are also shown. Significantly higher temperatures than Shipman's result from hydrogen atmosphere fits to the infrared colors, even if the surface gravities are somewhat lower. Comparison of the optical energy distributions of Shipman's (1977) ATLAS models and these shows that this discrepancy is not due to the models. Our computed Greenstein ($g - r$) colors for 4000, 5000, and 6000 K hydrogen models differ from Shipman's published colors by ≤ 0.015. Significantly higher-temperature hydrogen fits are also indicated if V blanketing is present. We note that the $\sim$4000 K helium atmosphere fits to Wolf 489 and G107-70 lead to radii $\sim 0.019\ R_\odot$, significantly greater than the mean for white dwarfs and consistent with $\log g \sim 7.7$; the locus of helium model colors is insensitive to changes in $\log g$.

[2] G107-70 is, however, a double star [see note (2), Table 1]. While we are thus presenting composite colors for two stars which may differ significantly in their energy distributions, we note that the observed $(V - K) \approx +2.0$ would not be produced by any combination of two hydrogen-rich stars with colors near the $\log g = 8$ model locus.

TABLE 3

$T_{\rm eff}$ ESTIMATES FOR THE COOL STARS*

Name	This Work H	This Work He	Shipman H
LP 658-2	5200	5400	4270
G107-70	5500	4000	...
Wolf 489	5500	4000	4070
LP 380-5	5000	4300?	...
LP 44-113	4800?	5000?	5100
G99-47	6000	...	5850

* An accuracy of ±300 K is estimated for our values not followed by a question mark.

V. EVIDENCE FOR LINE BLANKETING AT BLUE WAVELENGTHS

In Figure 2 we present the ($B - V$, $V - K$) two-color diagram for the program stars, again compared with the predictions of the model grids. For the hotter helium- and hydrogen-rich stars, we note an approximately linear increase in $V - K$ with $B - V$ for decreasing effective temperatures, in agreement with the models. However, the four coolest nonmagnetic stars are apparently too red in $B - V$ to match unblanketed hydrogen or helium models. That is, the coolest stars seem to have a relative deficiency of blue light.

One possible explanation for this blue deficiency is that the stars have nearly pure helium atmospheres so deficient in metals and free electrons that helium Rayleigh scattering dominates over the He^- opacity. On the basis of the results of BCFV, however, we rejected this hypothesis in § III. A much more likely explanation is that the blue deficiency is due to blanketing by numerous lines of the neutral metals, most of which occur at ultraviolet and blue wavelengths. The cool white dwarf LP 701-29 (Dahn *et al.* 1978) provides an extreme example of such line blanketing below 4500 Å. The individual lines are so broadened and blended in this star as to be individually unrecognizable, yet they block out most of the blue light. Weidemann (1966) and Eggen and Greenstein (1967) first discussed blanketing as a likely cause of the significant deviations of the *UBV* colors of cool white dwarfs from the blackbody colors. Liebert's (1977) scanner energy distributions showed a substantial deficiency of blue flux relative to blackbody curves fitting red optical fluxes. In Figure 2, however, the effect is shown more conclusively by comparison with unblanketed model predictions over a longer baseline in color.

This result indicates that the coolest white dwarfs are generally not totally free of heavier elements in their atmospheres. It is plausible, however, that only modest

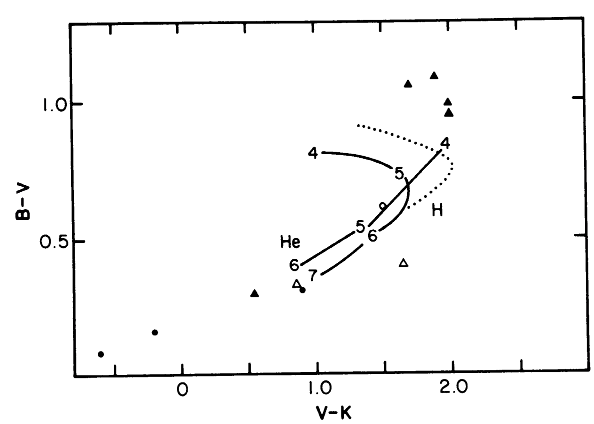

FIG. 2.—The ($B - V$, $V - K$) two-color diagram. The key is the same as for Fig. 1.

abundances of these elements are required to produce the blue flux deficiency, not necessarily metal abundances higher than those found in hotter white dwarfs. We note that the metal abundances suggested for even the extreme case of LP 701-29 (Cottrell, Bessell, and Wickramasinghe 1977) are still very low relative to the Sun.

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