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A Very Low-Luminosity, Very Cool, DC White Dwarf[1]

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ABSTRACT

The star LHS 3250 is found to be a white dwarf at a distance of 30 pc. Its absolute magnitudes ($M_V = 15.72$; $M_{\rm bol} = 16.2$) put it among the least-luminous white dwarfs known. Its optical spectrum shows no features, indicating it has a DC classification, and it shows no detectable polarization, indicating it does not have a very strong magnetic field. However, its broadband colors show it to have a unique spectral energy distribution, and it stands out from all other stars in BVI and other broadband photometric surveys.

We discuss these properties, and conclude that LHS 3250 must be an extremely cool white dwarf with strong collision-induced absorption at red-infrared wavelengths from molecular hydrogen, in accord with models for very cool white dwarf atmospheres. If so, it is the first such star known, and the first star to provide observational evidence supporting these models. It suggests that other very cool white dwarfs, both halo white dwarfs and the oldest disk white dwarfs, also may have colors affected by similar absorption. The atmospheric composition of LHS 3250 is not known, and therefore its temperature is poorly determined. It may be a helium-core star with a mass $0.3 < M < 0.45 M_{\odot}$, and to be a product of mass-transfer in a close binary system. However, until its temperature is better known, its mass and age remain uncertain.

Subject headings: Astrometry; Stars: Hertzsprung-Russell Diagram; Stars: Individual - LHS 3250; Stars: White Dwarfs

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1. Introduction

The star LHS 3250 (LP70-238; WD1653+630) is a faint star discovered by Luyten (1970; 1976) to have a proper motion of 0.512 arcsec yr^{-1} in a position angle of 275.2° and a color-class "f". These properties indicate that it is likely to be a white dwarf, and it was observed spectroscopically by Hintzen (1986) who verified it as being a white dwarf with a classification of DC9. USNO parallax observations began in 1992, and they have now confirmed that the star has the very low luminosity of a cool white dwarf (discussed in Section 2). However, in the process of measuring its colors accurately, we have found it to have a unique spectral energy distribution. Optical spectra and polarization data have been obtained, and lead us to conclude that most likely it has an extremely low temperature. This conclusion is of particular interest because low-temperature, low-luminosity white dwarfs in the Galactic disk can constrain the early star-formation history of the disk, and because such stars in the Galactic halo potentially can contribute significant mass to the halo. In this paper, we discuss the unusual properties of this star, and attempt to arrive at a plausible description of its nature.

2. Observational Constraints

2.1. Astrometry

LHS 3250 was observed with the 1.5 m Strand Telescope and a Tektronix 2048x2048 CCD camera as part of the USNO parallax program during 1992–1998. This configuration gives typical errors of ±0.5 mas in the relative parallax with 50 observations or more. LHS 3250 was observed with 84 images taken on 81 nights. The general observing and reduction procedures for the Tek2048 astrometry are described by Monet et al. (1992). The astrometric results are shown in Table 1. Future observers should note that the coordinates given in the LHS Catalogue are incorrect by 1.6 arcmin – the LHS Atlas has the correct star marked, and the correct coordinates are given in Table 1. Also, the proper motion given in the LHS Catalogue differs from that given in Table 1 by much more than is normally found for LHS stars. We know of no reason for this discrepancy unless the star was near the faint limit on one of Luyten's plates.

2.2. Photometry

Visual $UBVRI$ photometry of LHS 3250 was obtained with the USNO 1 m telescope using a Tektronix 1024x1024 CCD on four nights (two in 1995 and two in 1998). Infrared JHK photometry was obtained with the KPNO 4 m telescope using the ONIS infrared imager with an ALADDIN InSb detector on three nights in 1998 for J and H and one night for K. The results are shown in Table 2. The RI data are on the Cousins system, and the JHK data are on the CIT system. Comparison of the data from different nights shows no evidence for variability larger than about 2%.

Some of the observed color combinations are displayed in Figure 1, where the colors of LHS 3250 are compared to the sample of cool white dwarfs published by Bergeron et al. (1997) and Leggett et al. (1998). The $U-B$ colors for this sample of stars were taken from McCook & Sion (1998). The colors of LHS 3250 contrast strongly with other white dwarfs, providing the first evidence for the unusual properties of this star. (LHS 1126 is also marked in the figure because it may be a similar type of star, as we discuss in Section 3.) The $U-B$ and $B-V$ colors are both consistent with a cool white dwarf with $T_{\rm eff} \sim 5000$ K, while the $V-I$ and $V-K$ colors would normally indicate a much hotter temperature. The flux distribution in Table 2 is strongly peaked near 6000 Å. To the eye, this star would appear distinctly orange.

The colors shown in Figure 1 cannot arise from a composite spectrum, as could be produced by a physical binary system or a chance alignment with a field star. Therefore, this region of the color-color plots in Figure 1 is usually empty. In fact, no other objects are known to fall near LHS 3250 in Figure 1b other than QSOs with redshift near 3.5-4.0 (Hawkins & Véron 1996). Therefore, stars like LHS 3250 should be identified easily in a broadband survey using BVI filters or the Sloan $g'r'i'$ filters.

2.3. Spectroscopy and Spectropolarimetry

Low-resolution spectra have been obtained with the Steward Observatory 2.3 m Bok telescope, the Palomar 5 m telescope, and the Keck II 10 m telescope. All data show a continuous spectrum with no detectable features, confirming the DC classification made by Hintzen (1986). The spectrum with the highest signal/noise is that from the Keck telescope, a 15-minute exposure taken with the Low-Resolution Imaging Spectrograph (Oke et al. 1995), with a resolution of 9 Å. It is displayed in Figure 2. (This spectrum was converted from counts to a flux scale using the other three flux-calibrated spectra and the broad-band photometry. Finally, 3-pixel smoothing was applied.) Beside the wavelength coverage shown in this spectrum, the spectrum from the Steward 2.3 m telescope with 60 min integration includes 3600-4000 Å (albeit with lower signal/noise). It is included in Figure 2, and shows no detectable calcium features. We also note that Hintzen's spectra covered only the blue spectral region (3600-5400 Å) and that he mentioned no calcium features.

The spectral energy distribution shown in Figure 2 is unlike any other known white dwarf. A comparison with other spectra of DC and other cool white dwarfs (e.g., Wesemael et al. 1993, Figure 15; Bergeron et al. 1997, Figure 18) shows that the sudden decline in flux redward of 6000 Å is contrary to the normal behavior of cool white dwarfs, where F_ν reaches a maximum redward of 1μ.

White dwarfs with unusual colors are often found to have both distorted spectra and significant circular polarization due to photospheric emission in a strong magnetic field ($B > 10^8$

G). To investigate this possibility, data were also obtained with the CCD Spectropolarimeter (Schmidt et al. 1992) on the Steward Observatory 2.3 m Bok telescope on two occasions in 1998. In Figure 3 are displayed polarization spectra as $V/I(\%)$ resulting from sequences totaling 40 min and 53 min on 1 Apr. and 23 Sep., respectively. Both occasions show a distinct lack of significant circular polarization on either side of the 6000Å spectral break, and the 3σ upper limit for the spectrum-added polarization is $V/I < 0.4\%$ in each dataset. We conclude that magnetism is a very unlikely explanation for the peculiar energy distribution of LHS 3250.

2.4. Color-Magnitude Diagram

With the absolute magnitude (Table 1) and observed colors (Table 2), we can construct color-magnitude diagrams that are usually indicative of the approximate temperature and mass of white dwarfs. Figure 4 shows the M_V vs. $B-V$ diagram in panel (a) and M_V vs. $V-I$ in panel (b). In this figure, LHS 3250 is compared with other white dwarfs with accurate parallaxes obtained with CCDs at USNO, plus the unusual low-luminosity star ESO439-26 (Ruiz et al. 1995). The points include all white dwarfs from Monet et al. (1992) plus other white dwarfs with parallaxes determined since 1992 but not yet published; all points are shown with their formal one-sigma error bars. The curves show the model-atmosphere colors of white dwarfs with pure hydrogen and pure helium atmospheres (Bergeron et al. 1995b). The four white dwarfs known to have high surface gravity and high mass from spectrophotometric studies are labelled; they stand out from other stars in both panels. From this figure, one would derive for LHS 3250 a somewhat high mass (near 0.8 $M_\odot$) and a cool temperature from the $B-V$ color, but an extraordinarily-high mass (near 1.4 $M_\odot$) and high temperature from the $V-I$ color. This discrepancy is another symptom of the peculiar colors of LHS 3250 shown in Figure 1. In the following discussion, we conclude that probably neither diagram gives a correct understanding of the star because its colors are far from being indicative of its temperature or gravity.

2.5. Luminosity

In order to establish the luminosity of LHS 3250, the bolometric correction (BC) is needed. Using

$$\mathrm{BC} = \mathrm{BC}_\odot + 2.5\ \log\left(\frac{\int F_{\lambda_\star} S_V(\lambda)\mathrm{d}\lambda}{\int F_{\lambda_\star}\mathrm{d}\lambda}\right) - 2.5\ \log\left(\frac{\int F_{\lambda_\odot} S_V(\lambda)\mathrm{d}\lambda}{\int F_{\lambda_\odot}\mathrm{d}\lambda}\right)$$

where $S_V(\lambda)$ is the transmission function of the V filter, we derive BC $= 0.45 \pm 0.10$. The uncertainty is due to the coarse sampling of the spectrum shown in Figure 5. This value is quite different from that for normal cool white dwarfs which have BC $= -0.2$ at $T_{\rm eff} = 5000$ K to BC $= -1.0$ at $T_{\rm eff} = 4000$ K (Bergeron et al. 1995b). However, positive values of BC are reproduced in the models of very cool white dwarfs with strong collision-induced absorbtion (CIA; see Section 3.2) owing to their large infrared flux deficiency. We then derive $M_{\rm bol} = M_V + \mathrm{BC} = 16.17 \pm 0.11$

and $\log(L/L_{\odot}) = -4.57 \pm 0.04$. With the exception of the high-mass star ESO439-26, this is the lowest luminosity known for any white dwarf.

2.6. Stellar Population

The low luminosity of LHS 3250 raises the question of its membership in the Galactic disk or halo. Can we otherwise determine its origin, and perhaps thereby place some constraints on its age? Its tangential velocity (Table 1) is typical of a white dwarf in the old disk. However, its Galactic coordinates ($l = 94°$, $b = 38°$) mean that its proper motion reflects primarily its U and W space velocities, while its V velocity is mostly projected into the unknown radial velocity. One could hypothesize a radial velocity in the range –170 to –220 km s^{-1} which would result in V velocity components in the range –180 to –220 km s^{-1}, respectively, and W velocity components in the range –50 to –80 km s^{-1}, respectively, values typical of stars in the Galactic halo. However, the DC nature of the spectrum offers no possiblity for testing this hypothesis. Therefore, its kinematics do not identify its population of origin.

3. Temperature Constraints

Despite the fact that the luminosity of LHS 3250 is well determined, its effective temperature must be defined more accurately before we can proceed further. Everything else about the star (the mass, the radius, the cooling age, and the evolutionary state) depends on determining $T_{\rm eff}$ accurately. In this section, we attempt to constrain the temperature from the observed spectral energy distribution. Then in the following section (Section 4), we discuss further constraints imposed from the accurate luminosity and other considerations.

The unique spectral energy distribution is given in Table 2 and shown in Figure 5. A comparison with white dwarf model colors (Bergeron et al. 1995b) shows that a model star with $T_{\rm eff} \sim 5000$ K matches the $UBVR$ data for LHS 3250 quite well, while a model star with $T_{\rm eff} \sim 15000$ K and a helium-dominated atmosphere matches the $RIJHK$ data. Apparently strong absorption is occuring in the atmosphere of LHS 3250, either at blue wavelengths if the star is hot, or at red/near-infrared wavelengths if it has a cool temperature. First we consider the possibility that it is hot.

3.1. A High Temperature?

Hot white dwarfs normally have hydrogen or helium lines visible: DA stars with hydrogen atmospheres have Hα present with an equivalent width of >1 Å when the temperature is > 5300 K (Bergeron et al. 1997), while DB stars with helium atmospheres have HeI lines present at $\lambda\lambda$4471, 5876, and 6678 when the temperature is > 11000 K (Wesemael et al. 1993). In contrast, DC stars are known with classifications as hot as class DC5, with $B - V$ colors $\sim$0.00, indicating temperatures ~ 12000 K for helium-dominated atmospheres; at hotter temperatures helium lines become visible. Because LHS 3250 shows neither hydrogen nor helium lines, its temperature must be < 12000 K, but this temperature is not hot enough to match the $RIJHK$ data.

The hot-star alternative also requires some *continuous* absorption at blue wavelengths to explain the energy distribution in Figure 5. However, possible sources of continuous absorption (molecules, for example), will not be present in a high-temperature atmosphere. The DZ (metallic-lined) and DX (peculiar) white dwarfs sometimes have broad absorption features [e.g., G99-44, LP701-29, and G240-72 (Wesemael et al. 1993)], but only when they are cool; hot white dwarfs never show such broad absorption so as to be classified DC. Most of the stars with broad (often unidentified) features also have identified metallic features, primarily Ca lines, which are not seen in LHS 3250 (Section 2).

A further consequence of a high temperature for LHS 3250 would be that it would have a high mass, probably near the Chandrasekhar limit, as shown in Figure 4(b). This would be required by its faint absolute magnitude, which places it 2-3 mag fainter than any white dwarfs of similarly high temperature. ESO439-26, for example (see Figure 4), has a temperature near 4500 K and a mass $\sim 1.2 M_{\odot}$ (Ruiz et al. 1995). A high mass (and resulting high gravity) is possible, but it probably would not help explain the peculiar colors, as gravity has virtually no effect on the colors of hot, helium-dominated atmospheres (Bergeron et al. 1997). Therefore, we believe that a high temperature for LHS 3250 is unlikely.

3.2. A Cool Temperature?

Can the unusual energy distribution be explained with a cool temperature? Molecular opacities are potentially important in the high gravity of a cool white dwarf atmosphere and might supply the continuous opacity apparently needed to understand LHS 3250. A possible explanation is that collision-induced absorption (CIA) by molecular hydrogen[3] is dominating the opacity for wavelengths >6000 Å.

The effects of CIA on the colors of cool white dwarfs with various hydrogen/helium compositions have been described by Bergeron et al. (1995a) and Hansen (1999). Various models for white dwarfs with extremely low temperatures and pure hydrogen atmospheres (Bergeron et al. 1997; Hansen & Phinney 1998; Hansen 1998; Hansen 1999; Saumon & Jacobson 1999; Chabrier

[3]Collisions of H_2 molecules with other H and He atoms and molecules become important in a high-density atmosphere. These collisions induce a temporary dipole moment in the H_2 molecule that creates permitted dipole transitions and a greatly increased opacity at red and near-infrared wavelengths (Linsky 1969; Lenzuini et al. 1991; Saumon et al. 1994). The effect is greatest in a helium-dominated atmosphere that is otherwise very transparent.

1999) agree in predicting strong flux-deficiencies for $\lambda > 1\mu$, a peak in the flux distribution near $\lambda \sim 6000 - 9000$ Å, and blue $V - I$ and $V - K$ colors. However, high-density helium atmospheres are difficult to model, and no models of mixed-composition atmospheres are presently available for temperatures below 4000 K. The models that are available predict stronger infrared absorption, and a bluer wavelength at which the flux reaches a maximum, for lower temperatures and for He/H ratios of roughly 10 to 100. The blue $V - K$ color of LHS 1126 (a star noted in Figure 1c) was explained by this mechanism (Bergeron et al. 1994; Schmidt et al. 1995; Bergeron et al. 1997). Here, we see that LHS 3250 has much more extreme colors than LHS 1126, so the effect of CIA must be much stronger if it is the explanation for the colors of LHS 3250.

A start at fitting the spectral energy distribution of LHS 3250 has been made by Bergeron (1999), and the result kindly made available to us. The composition was assumed to be pure hydrogen. A grid of model atmospheres extending from 4000K to 1500K was calculated at intervals of 250K for log g = 7.0, 7.5, 8.0, 8.5, 9.0. The models were calculated as described in Bergeron et al. (1995a). The equation of state was modified to include molecular H_2, H_2^+ H_3^+ as in Saumon et al. (1994), utilizing the opacity calculations of Lenzuini et al. (1991) with the CIA coefficients for H_2, H and He species from Borosow et al. (1989). Similar models were used previously for detailed analyses of cool white dwarfs (Bergeron et al. 1997; Leggett et al. 1998). Due to the lack of evolutionary models (such as the C/O core grid of Wood used in earlier papers), zero temperature results for helium cores were adopted (Hamada & Salpeter 1961), and should provide an adequate mass-radius relation at these low temperatures.

An approximate fit to the $VRIJHK$ flux distribution, using a pure hydrogen atmosphere, is shown in Figure 5 (middle panel). The result is an extremely low temperature ($T_{\rm eff}$ = 2020 K), where the fit has been done assuming a plausible value of log g = 6.8. The model is qualitatively close to the data, and shows that strong CIA in a hydrogen atmosphere with very low temperature is possible. A similar temperature near 2100 K would be derived from the models with pure hydrogen by Saumon & Jacobson (1999), and presumably with those by Chabrier (1999), but temperatures are not included for the latter models.

However, we discuss below some difficulties that arise with a temperature this low and a pure hydrogen atmosphere. Instead, helium-dominated atmosphere models (Bergeron et al. 1995a) may be more realistic. In these models, CIA is strong at temperatures as high as 4000 K, and becomes strongest (at a given temperature) for He/H compositions of 10-100. One such model is also shown in Figure 5 (bottom panel). It *does not* reproduce the flux distribution of LHS 3250 in detail, but it does reproduce the strong infrared flux deficiency seen. Apparently a temperature lower than 4000 K is required to give increased CIA opacity to match the data. Therefore, we conclude that the temperature is in the range $2000 \leq T_{\rm eff} < 4000$ K, and the He/H ratio is near zero if the temperature is at the low end of the range, and is large (perhaps 10-100) if the temperature is at the high end of the range.

4. Discussion and Conclusions

In this section, we explore the physical parameters of LHS 3250 (the radius, mass, and cooling age) and its evolutionary state. These quantities are directly related to its well-determined luminosity and its approximately-known temperature. A detailed analysis will require mixed-composition model atmospheres at cooler temperatures than are available now, and is beyond the scope of this paper. Our present goal is to constrain the physical parameters (if possible) by considering a range of possible temperatures ($2000 \leq T_{\rm eff} < 4000$ K, as determined above), and exploring the consequences of each temperature. Table 3 gives a summary of these results. Here, the second column lists the radius derived for each possible temperature, using the measured luminosity above. This is followed by the mass, as derived from mass-radius relations for white dwarfs with different core and atmospheric compositions. For this purpose, we give the mass for each value of the radius found using different models listed in the footnotes to Table 3. Finally, the table gives the (very approximate) cooling time to reach $L/L_{\odot} = -4.6$, taken from the same models. Table 3 shows that (1) the mass depends strongly on the adopted temperature, (2) the exact mass depends on the presence and thickness of a hydrogen atmosphere, and (3) a helium core and a mass lower than normal for a white dwarf are very possible, but a normal mass and a carbon/oxygen core are also possible.

Because a helium core and a reduced mass must be a result of mass transfer in a binary system, and because such mass transfer often leaves a double white dwarf system with the two stars having nearly equal masses, we have added a second set of values to Table 3 for the case of a composite of two equal-luminosity white dwarfs. For such a composite system, the luminosity of each star at a given possible temperature is less than for the single-star case by a factor of 2, the radius is less by a factor of $\sqrt{2}$, the mass is greater by a factor of $\sim$1.5-2.5, and the cooling age to reach $L/L_{\odot} = -4.9$ is generally much greater.

Table 3 indicates that LHS 3250 could have a wide variety of states. First, if LHS 3250 has a C/O core, it could be a single star with a mass near 0.50-0.55 $M_{\odot}$, a temperature near 3800 K, and a cooling time of about 9 Gyr. A helium-dominated atmosphere would be required to reproduce the observed spectral energy distribution at this relatively high temperature (Section 3). Second, if LHS 3250 has a helium core with a helium-dominated atmosphere, Table 3 shows that it could have a wide range of temperatures ($2000 < T_{\rm eff} < 3500$ K) and masses ($M < 0.45 M_{\odot}$). It could be a single visible star or a composite double white dwarf with somewhat lower temperatures and masses. Finally, if LHS 3250 has a helium core and a hydrogen atmosphere, then the spectral energy distribution requires a temperature near 2000 K. Then Table 3 shows that a very low mass, $< 0.15 M_{\odot}$, is required to give the large radius demanded by such a low temperature.

Evolutionary models for He-core stars by Driebe et al. (1999) may further limit the states that are possible for LHS 3250. These models are intended to include a realistic thickness of hydrogen envelope on low-mass stars based on when and how fast mass is lost during evolution on the red giant branch. These authors argue that a thick hydrogen envelope will inevitably survive on He-core stars with $M < 0.3M_\odot$, and that the structure of the stars will give prolonged H-burning, resulting in the cooling times being extended significantly. If these evolutionary models are correct, then a mass $\leq 0.25M_\odot$ would result in a cooling time greater than the age of the universe to reach the low luminosity of LHS 3250, and must be ruled out. This conclusion eliminates all states with very low-mass, including all states with a hydrogen atmosphere. Only two remaining states are allowed: a single He-core white dwarf with a temperature in the range $3200 < T_{\rm eff} < 3500$ K, a mass 0.3-0.45 $M_\odot$, and a cooling time of roughly 12 Gyr; or a composite of two He-core white dwarfs with a temperature close to 2700 K, a mass $\sim 0.3M_\odot$, and a cooling time $\sim$15 Gyr. Only if somehow the predicted thick H envelope has been lost (or perhaps some H has been accreted since the white dwarf formed with a helium atmosphere), then perhaps a thin H atmosphere, with the very low temperature and low mass, is still possible. Both "thin atmosphere" models (Hansen & Phinney 1998; Benvenuto & Althaus 1998; Benvenuto & Althaus 1999) predict that convection will mix helium up into the atmosphere, diluting the hydrogen as a low-mass star cools. However, below roughly 4000 K, a radiative zone develops (Hansen & Phinney 1998) and diffusion should remove the helium, again leaving a pure-H atmosphere. This scenario appears to be the only possibility that LHS 3250 has a hydrogen-dominated atmosphere.

Applying these constraints, we can place LHS 3250 in the H-R diagram. Figure 6 shows LHS 3250, again compared with the same sample of cool white dwarfs shown in Figure 1 (Bergeron et al. 1997; Leggett et al. 1998). LHS 3250 has a lower luminosity than any star except the massive white dwarf ESO439-26 (Ruiz et al. 1995). LHS 3250 is plotted with the possible temperatures derived above.

A He-core white dwarf must have lost mass during its giant-branch evolution through mass transfer in a close binary system. Also, the composite double white dwarf states discussed above might have the two stars comprising a close binary system, and possibly having exchanged mass. Therefore, LHS 3250 may be (or may once have been) a binary. The companion could be a neutron star, and thus not detectable unless it was also a pulsar; then LHS 3250 would be like an older version of the low-mass white dwarfs found to be the visible companions of some millisecond pulsars. Alternatively, we may be seeing a composite of two white dwarfs, both with similar low temperatures. Close binaries which undergo common-envelope evolution are believed to be the likely progenitors of double-degenerate stars with a He-core component (e.g. Iben & Livio 1993; Iben et al. 1997). These progenitors can, and apparently often do, produce a pair of nearly identical stars. Examples are the pair of C/O white dwarfs L870-2 (Saffer et al. 1988), and the pairs of He-core white dwarfs L101-26 (Moran et al. 1997) and Ton1323 (Marsh et al. 1995). Of the other known close double-degenerate stars, most have a He-core primary star (Saffer et al. 1998), with a secondary star of unknown type. Therefore, arriving at a close binary system with both components being such very cool (and very old) He-core stars is plausible.

Stars related to LHS 3250 have recently been found in the globular cluster NGC 6397 (Cool et al. 1998; Edmunds et al. 1999). Three "non-flickering" stars appear to be He-core white dwarfs with masses $< 0.4M_\odot$, and the one with an observed spectrum has a hydrogen atmosphere with

$T_{\rm eff} \sim 17000$ K and a mass $\sim 0.25 M_{\odot}$. All three stars are much hotter and more luminous than LHS 3250, and are much younger (more recently formed) white dwarfs. Thus the three may eventually evolve to be similar to LHS 3250.

In conclusion, we find LHS 3250 to have a temperature sufficiently low that its colors are strongly affected by some continuous absorption, probably CIA from molecular hydrogen. As such, it provides the first example of a very cool white dwarf with blue $RIJHK$ colors, and it supports models of white dwarfs with H or H/He atmospheres (Bergeron et al. 1995a; (Bergeron et al. 1997; Hansen & Phinney 1998; Hansen 1998; Hansen 1999; Saumon & Jacobson 1999; Chabrier 1999) that show their $RIJHK$ colors becoming bluer with decreasing temperature and luminosity. Finding other white dwarfs with low (and lower) luminosities and temperatures is currently of interest for determining the density and luminosity function of old disk and halo white dwarfs. The population (disk or halo) to which LHS 3250 belongs is not known. It may be a product of mass transfer in a close binary system, not a result of single-star evolution. Nevertheless, its noteworthy colors at this very low temperature support the conjecture that many low-luminosity white dwarfs in the halo will have blue colors. Stars like LHS 3250 will be easy to identify in photometric surveys, so we should soon measure how frequently they occur.

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Fig. 1.— Color-color diagrams showing LHS 3250 is easily distinguished from a sample of cool white dwarfs.

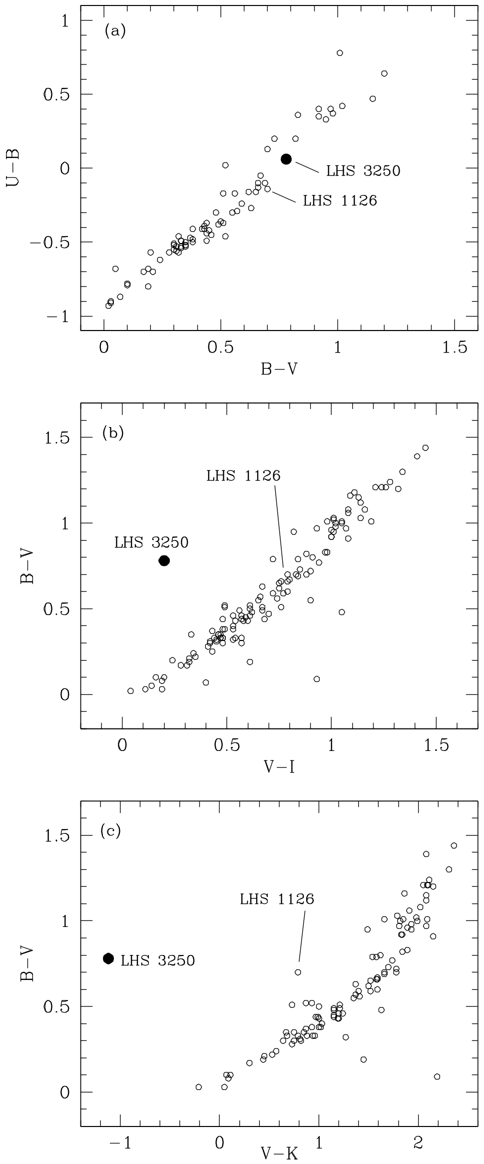
Fig. 2.— Spectrum of LHS 3250 taken with the Keck II telescope, plus the blue end of a spectrum taken with the Steward 2.3 m telescope (shifted vertically by 10 flux units for clarity) in order to show wavelengths blueward of 4000 Å.

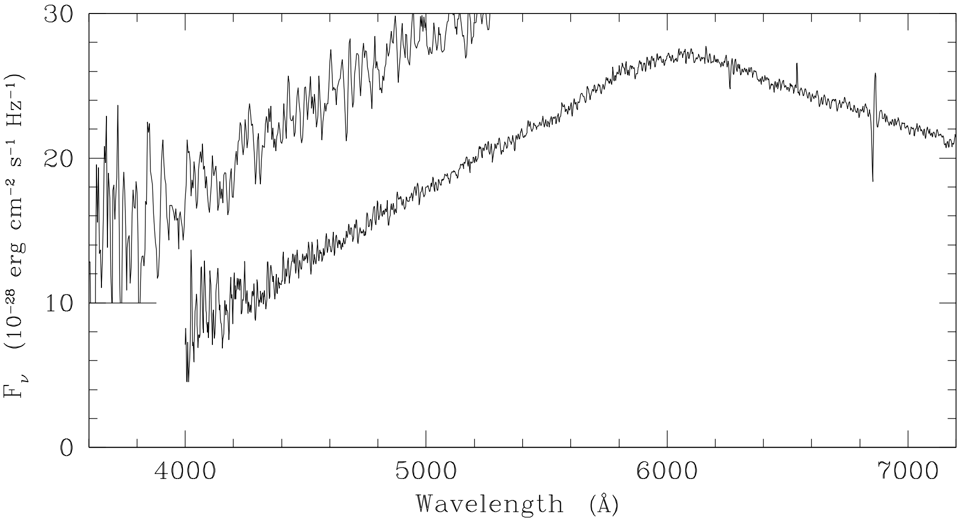
Fig. 3.— Spectropolarimetry of LHS 3250 taken with the Steward 2.3 m telescope. The data for 23 Sep. have been displaced upward by 20% for clarity.

Fig. 4.— Color-absolute magnitude diagrams of LHS 3250 compared to white dwarfs with accurate CCD parallaxes. Curves show model atmosphere colors (Bergeron et al. 1995b) for pure hydrogen atmospheres (solid curves) and pure helium atmospheres (dashed curves). Four stars known to have high mass are labelled (see text). Note the discrepant position of LHS 3250 between the two panels.

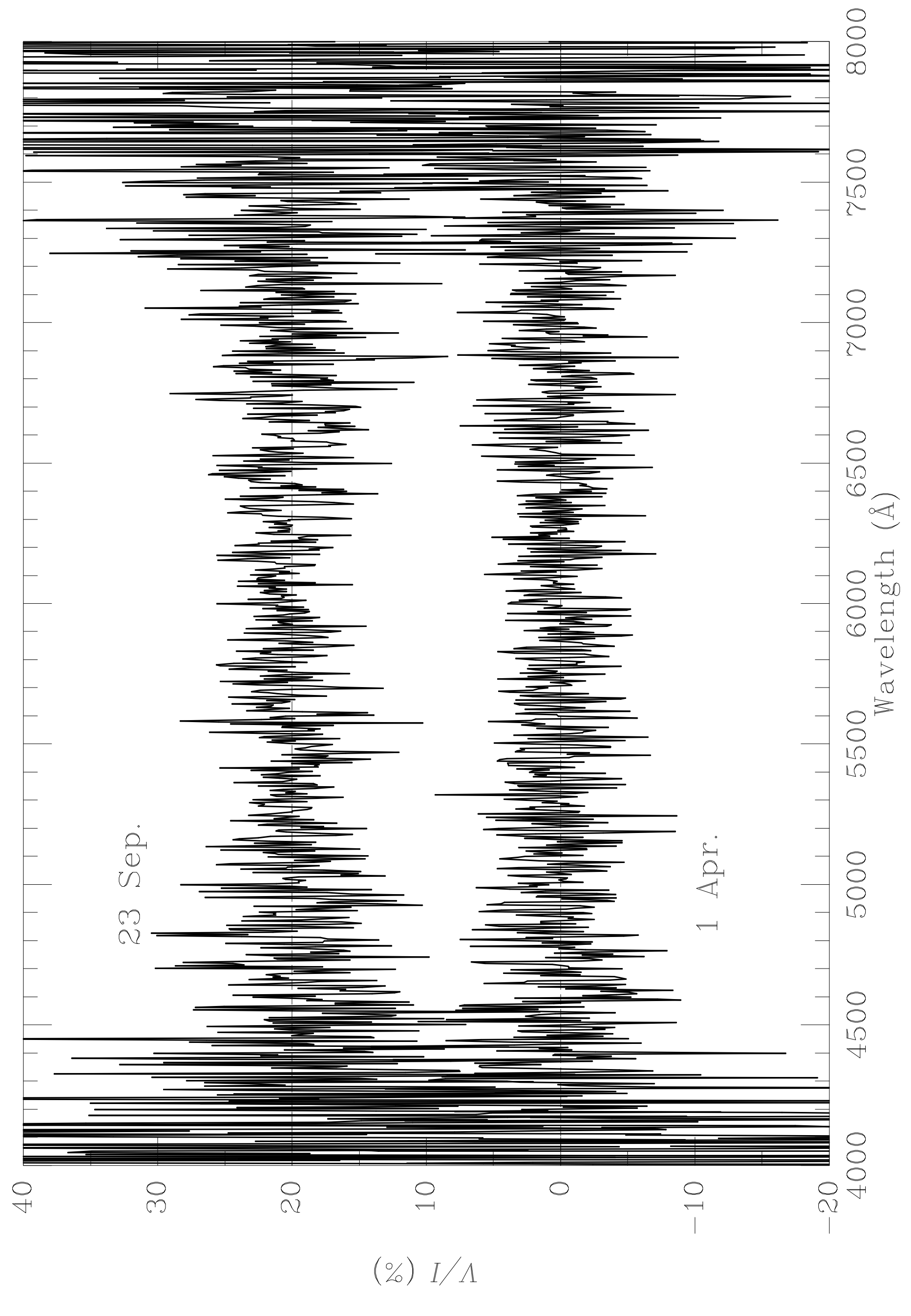
Fig. 5.— Spectral energy distribution of LHS 3250. The top panel gives the observed distribution, with error bars. The middle and bottom panels show the observed data compared with two models having strong CIA opacity.

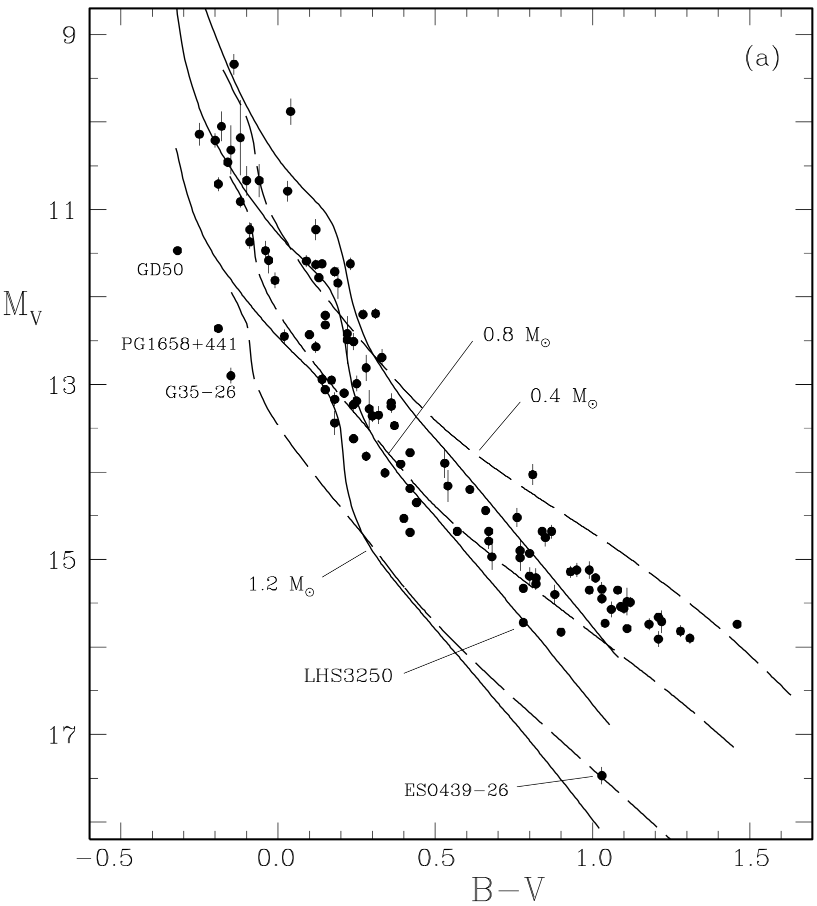
Fig. 6.— H-R diagram showing LHS 3250 with a sample of cool white dwarfs. LHS 3250 is plotted with two filled circles to show a plausible range of (cool) temperatures.

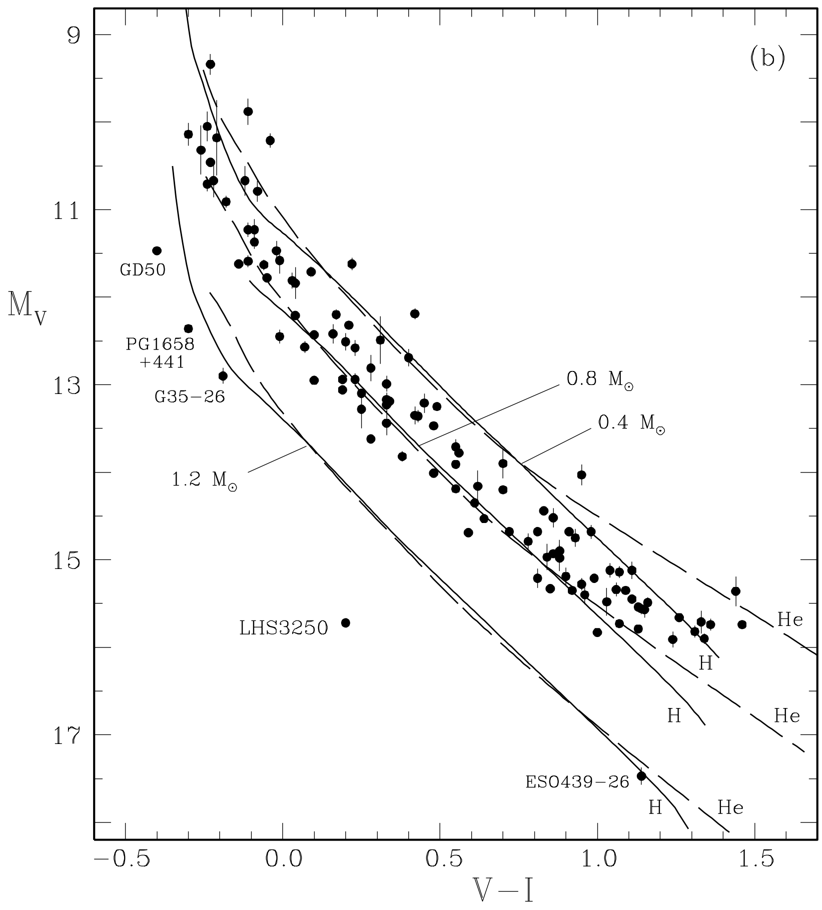

(a)
U−B
B−V
LHS 3250
LHS 1126
(b)
B−V
V−I
LHS 1126
LHS 3250
(c)
B−V
V−K
LHS 1126
LHS 3250

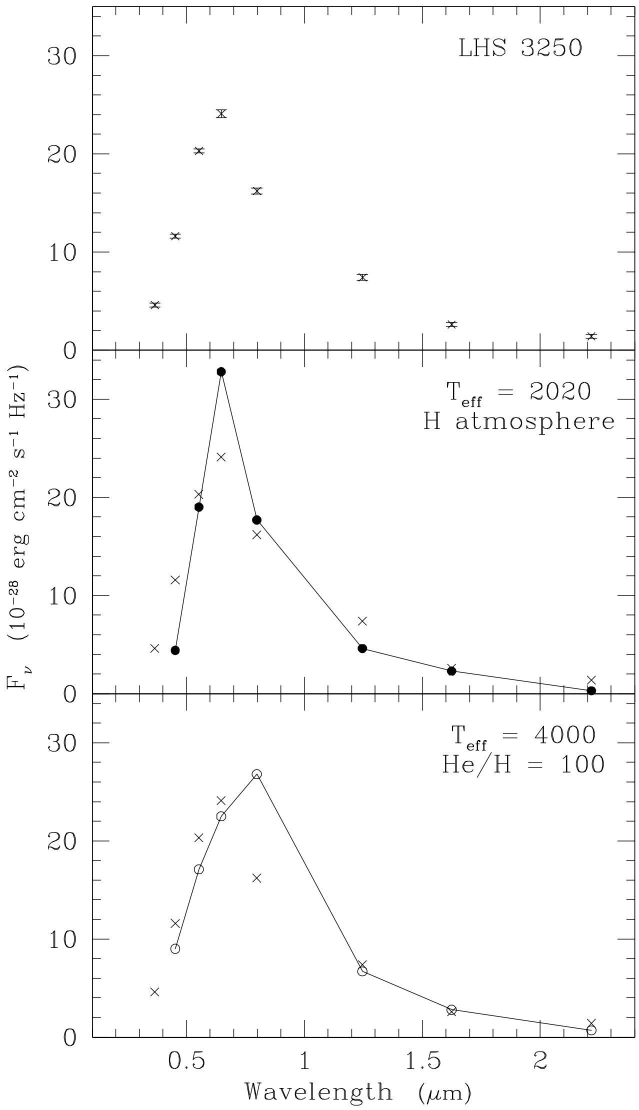


30
20
10
0
4000
5000
6000
7000
Wavelength (Å)
F_ν (10^{-28} erg cm^{-2} s^{-1} Hz^{-1})


23 Sep.
1 Apr.
Wavelength (Å)
V/I (%)
4000
4500
5000
5500
6000
6500
7000
7500
8000
40
30
20
10
0
−10
−20


(a)
M_V
B−V
GD50
PG1658+441
G35−26
0.8 M⊙
0.4 M⊙
1.2 M⊙
LHS3250
ESO439−26
9
11
13
15
17
−0.5
0.0
0.5
1.0
1.5


(b)
M_V
V−I
9
11
13
15
17
−0.5
0.0
0.5
1.0
1.5
GD50
PG1658
+441
G35−26
LHS3250
ESO439−26
0.8 $M_\odot$
0.4 $M_\odot$
1.2 $M_\odot$
He
H
H
He
H
He


LHS 3250
T_{eff} = 2020
H atmosphere
T_{eff} = 4000
He/H = 100
F_ν (10^{-28} erg cm^{-2} s^{-1} Hz^{-1})
Wavelength (μm)
0
10
20
30
0.5
1
1.5
2

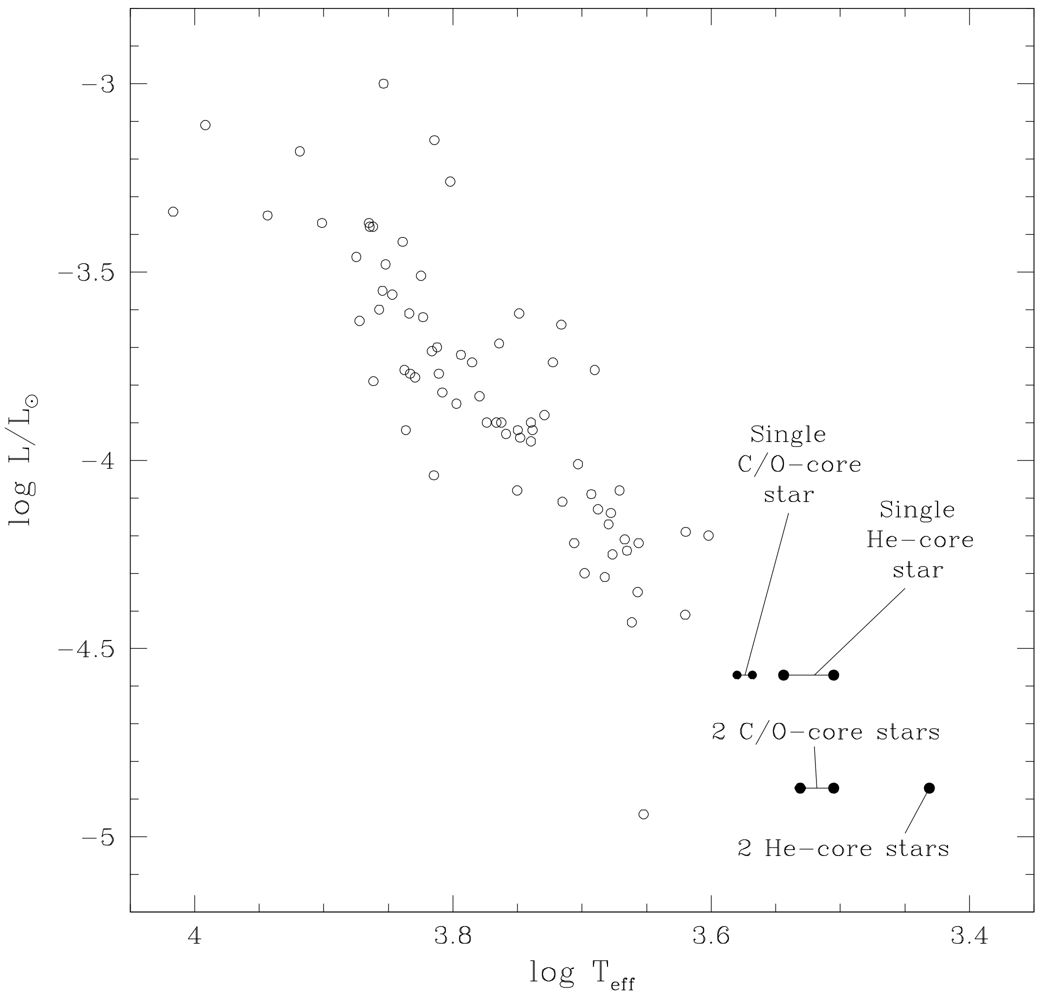

Single
C/O-core
star
Single
He-core
star
2 C/O-core stars
2 He-core stars
log L/L$_\odot$
log T$_{eff}$
−3
−3.5
−4
−4.5
−5
4
3.8
3.6
3.4

Table 1. Astrometric Data

Parameter	Value
RA[a]	$16^{\mathrm{h}}\ 54^{\mathrm{m}}\ 01.3^{\mathrm{s}}$
Dec[a]	$62^{\mathrm{o}}\ 53'\ 55''$
π_{rel}	32.26 ± 0.49 mas
$\Delta\pi$	0.78 ± 0.11 mas
π_{abs}	33.04 ± 0.50 mas
Distance	30.3 ± 0.5 pc
μ_{rel}	565.7 ± 0.1 mas yr^{-1}
PA	286.11 ± 0.02 degrees
V_{tan}	81.2 ± 1.2 km s^{-1}
M_V	15.72 ± 0.04

[a]Coordinates are given for equinox and epoch 2000, derived from the USNO-A Catalog.

Table 2. Photometric Data

Color[a]			Magnitude	f_ν[b]
		U	18.91±0.05	4.6±0.2
$U-B$	0.06±0.05	B	18.85±0.02	11.6±0.2
$B-V$	0.78±0.02	V	18.07±0.01	20.3±0.2
$V-R$	0.33±0.02	R	17.74±0.02	24.1±0.4
$R-I$	−0.13±0.03	I	17.87±0.02	16.2±0.3
$I-J$	−0.46±0.05	J	18.33±0.05	7.4±0.3
$J-H$	−0.61±0.07	H	18.94±0.06	2.6±0.2
$H-K$	−0.25±0.15	K	19.19±0.14	1.4±0.2

[a] RI are on Cousins system; JHK are on CIT system.

[b] Units are 10^{-28} erg cm^{-2} s^{-1} Hz^{-1}.

Table 3. Possible Radius, Mass, and Cooling Age

$T_{\rm eff}$	$R/R_\odot$	$M/M_\odot$	Age	$M/M_\odot$	Age	$M/M_\odot$	Age	$M/M_\odot$	Age
		C/O core H/He atmosphere[a]		He core He atmosphere[b]		He core Thin H atmosphere[c]		He core Thick H atmosphere[d]	
For single white dwarf:									
4000	0.0110	0.69	9 Gyr						
3750	0.0124	0.52	9 Gyr						
3500	0.0143			0.43	13 Gyr			0.45	12 Gyr
3250	0.0166			0.30	11 Gyr	0.37	14 Gyr	0.34	13 Gyr
3000	0.0194			0.20	9 Gyr	0.23	10 Gyr	0.24	>15 Gyr
2750	0.0231			0.13	7 Gyr	0.14	8 Gyr	0.18	>15 Gyr
2500	0.0280					0.09	6 Gyr	<0.15	>15 Gyr
2250	0.0346								
For double white dwarf:[e]									
4000	0.0078	0.95	9 Gyr						
3750	0.0088	0.87	9 Gyr						
3500	0.0101	0.76	10 Gyr						
3250	0.0118	0.59	11 Gyr						
3000	0.0138			0.46	20 Gyr			0.5	~15 Gyr
2750	0.0164			0.31	16 Gyr	0.38	>15 Gyr	0.35	~15 Gyr
2500	0.0198			0.19	13 Gyr	0.21	~15 Gyr	0.23	>15 Gyr
2250	0.0244			0.11	10 Gyr	0.12	9 Gyr	0.18	>15 Gyr

[a]Models from Wood (1995) and Hansen (1999).

[b]Models from Althaus & Benvenuto (1997).

[c]Models from Hansen & Phinney (1998).

[d]Models from Driebe et al. (1999).

[e]Values for each star, assuming two identical stars.