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FOUND: THE MISSING BLUE OPACITY IN ATMOSPHERE MODELS OF COOL HYDROGEN WHITE DWARFS

P. M. KOWALSKI[1,2] AND D. SAUMON[2]

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ABSTRACT

We investigate the importance of the far red wing of the Lyα line of hydrogen in the atmospheres of cool white dwarfs of pure hydrogen composition. We find that this absorption process dominates all important sources of opacity in the blue part of the optical spectrum of these stars. Our successful fits to the spectra of cool DA/DC white dwarfs indicate that the far red wing of the Lyα line is the source of opacity that had been missing in the models. The observed sequence of cool white dwarfs in color-color diagrams is very well reproduced by our new pure hydrogen atmosphere models, suggesting that the atmospheric composition of the coolest DC white dwarfs must be revisited.

Subject headings: atomic processes — line: profiles — stars: atmospheres — white dwarfs

Online material: color figure

1. INTRODUCTION

The detection and analysis of large samples of cool white dwarfs over the past decade have led to a significant improvement in our knowledge of the chemical composition and evolution of their atmospheres (Harris et al. 2006; Kilic et al. 2006; Bergeron et al. 1997, 2001). The difficulties in interpreting the spectra of some very cool white dwarfs thought to possess helium-rich atmospheres with small amounts of H (Bergeron et al. 2005; Bergeron & Leggett 2002; Oppenheimer et al. 2001) are most probably related to the extreme physical conditions found in their atmospheres (Kowalski 2006a). On the other hand, the physical conditions in hydrogen-rich atmospheres are much less extreme and the current models should be much more reliable. Nonetheless, models systematically overestimate the flux for $\lambda \lesssim 5000$ Å of hydrogen-rich white dwarfs of $T_{\rm eff} < 6000$ K (Bergeron et al. 2001, 1997; Bergeron 2001). Bergeron et al. (1997) suggested that the mechanism responsible for this phenomenon could be the pseudocontinuum bound-free opacity from hydrogen atoms perturbed by collisions in a relatively dense medium. However, a realistic calculation of this opacity source shows that it is too weak to correct the observed blue flux excess in the models (Kowalski 2006b).

In this Letter, we consider the possibility that the missing opacity is the red wing of the pressure-broadened hydrogen Lyα line. This absorption mechanism results from the perturbations of hydrogen atoms by their interaction with other particles, primarily H and H_2. Such perturbations result in the lowering of the Lyα transition energy and the possibility of a bound-bound transition for photon energies that are smaller than that of an isolated hydrogen atom ($E_{12}^0 = 10.2$ eV). We present a new, semiclassical calculation of this process based on accurate quantum mechanical calculations and a model that has no free parameters. The inclusion of broadening by collisions with H_2 is the key element of this calculation. The resulting pure hydrogen models successfully reproduce the spectral energy distributions (SEDs) and colors of very cool DA and DC white dwarfs.

2. THEORETICAL APPROACH

We are interested in the Lyα opacity far from the line center, at wavelengths $\lambda \gtrsim 2500$ Å. A lowering of the Lyα transition energy by more than ~5 eV is required for a bound-bound absorption from the ground state of a hydrogen atom at these wavelengths. This can occur in rare, close-range collisions that strongly perturb the bound states of the atom. Because the ground-state interactions are strongly repulsive at short range, the probability of such close-range collisions is much smaller than unity. Multiparticle collisions that result in a similar decrease in the Lyα transition energy are therefore insignificant (Kowalski 2006b), and we consider the interaction between a H atom and its closest neighbor only. This approach was used to successfully explain the complex shape of the Lyα line wings detected in the spectra of white dwarfs with $T_{\rm eff} \sim 12{,}000$ K (Allard et al. 2004), the UV flux deficiency observed in the white dwarf star L745−46A (Koester & Wolff 2000), and to model resonance broadening of the Lyα line in the solar spectrum (Sando et al. 1969).

For a given colliding pair, the change in the Lyα transition energy results from the formation of a temporary dimer, whose first transition energy E_{12} differs from that of an isolated hydrogen atom, E_{12}^0. E_{12} is given by the differences in the energies of the ground state and first excited Rydberg state of a H-perturber dimer calculated at a fixed interparticle separation r_c: $E_{12}(r_c) = E_2(r_c) - E_1(r_c) = h\nu_{12}$, where ν_{12} is the frequency of the absorbed photon. This picture is in the spirit of the Franck-Condon principle, which states that the nuclei remain in fixed positions during a radiative transition (Davydov 1965). The differential probability of finding such a dimer with an interparticle separation between r_c and $r_c + dr_c$ is given by (Martynov 1992)

$$dP_c(r_c) = n_{\rm pert} r_c^2\, dr_c \left(\int_{\theta,\phi} e^{-V_{\rm H\text{-}pert}(r_c,\theta,\phi)/k_{\rm B}T} \sin\theta\, d\theta\, d\phi \right), \quad (1)$$

where $n_{\rm pert}$ is a number density of perturbers, $V_{\rm H\text{-}pert}$ is the interaction energy between a hydrogen atom and the perturber localized at the position (r_c, θ, ϕ) in relation to the hydrogen atom. The potential for the interaction of a hydrogen atom with H (H-H dimer) is from Kolos & Wolniewicz (1965) and that for perturbations by H_2 (H-H_2 dimer) is from Boothroyd et al. (1996, 1991; Fig. 1). For the H-H dimer, the allowed bound-bound transition from the ground state with the smallest transition energy (i.e., greatest broadening) at all values of r_c is from $b\,^3\Sigma_u^+ 2p\sigma$ to $a\,^3\Sigma_g^+ 2s\sigma$. Satellite features (Allard et al. 1994) do not appear for this transition because the difference between the two energy curves has no extrema (Fig. 1). Contributions from transitions to other excited levels of the H-H dimer (such as

[1] Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235-1807.

[2] Los Alamos National Laboratory, MS P365, P.O. Box 1663, Los Alamos, NM 87545; kowalski@lanl.gov, dsaumon@lanl.gov.

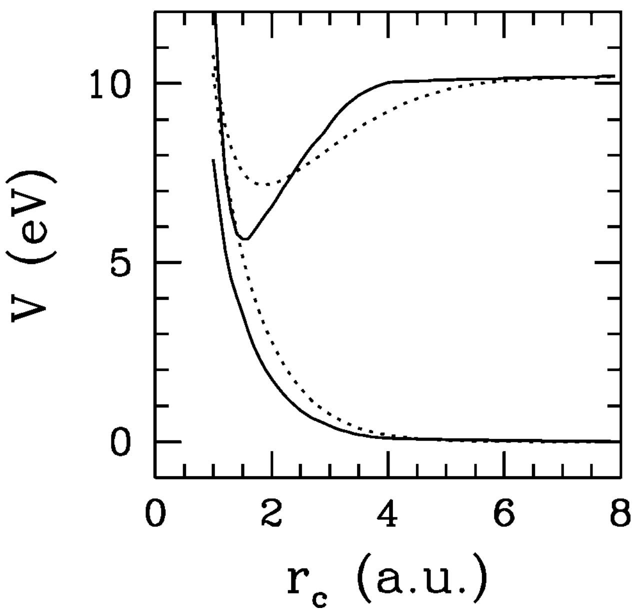

FIG. 1.—Interaction energy curves as a function of the interparticle collision distance for the ground state (*lower curves*) and the first excited Rydberg state (*upper curves*) of H-H_2 (*solid curves*) and H-H (*dotted curves*) dimers. For H-H_2, the energy curves shown are for a collision angle of 90°, where the collision angle is defined between the line connecting the H atom to the center of H_2 and the molecular axis.

$h\,^3\Sigma_g^+ 3s\sigma$ and $i\,^3\Pi_g 3d\pi$) are negligible in the far red wing ($\lambda \gtrsim 2000$ Å) because they always lie above the $a\,^3\Sigma_g^+$ state by at least 2.5 eV in the relevant range of r_c and hence only provide absorption for photons with higher energies than the $a\,^3\Sigma_g^+$ state. For the same reason, transitions from the binding H-H ground state $[X\,^1\Sigma_g^+(1s\sigma)^2]$ are also negligible in the far red wing. We use the $a\,^3\Sigma_g^+ 2s\sigma$ energy curve from Staszewska & Wolniewicz (1999). For the energy of the first excited Rydberg state of the H-H_2 system, we used the H_3 calculations of Boothroyd et al.

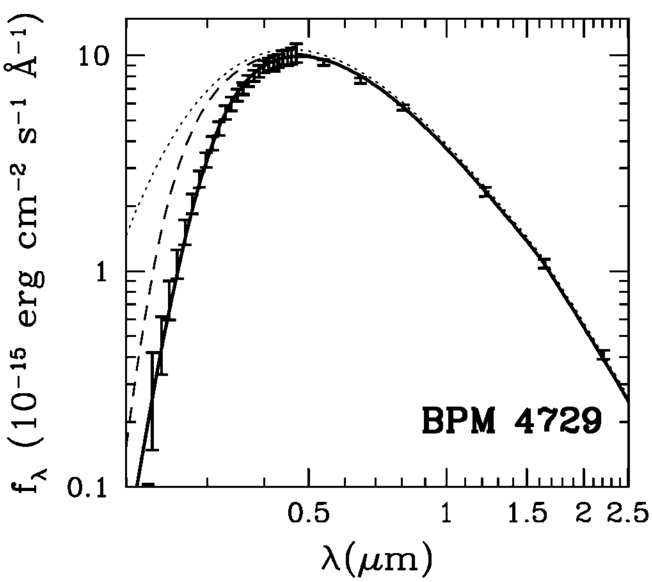

FIG. 2.—Spectral energy distribution of the DA white dwarf BPM 4729 (WD 0752−676). The UV spectrum of Wolff et al. (2002) extends up to 4500 Å. Additional measurements are broadband fluxes from *U* (McCook & Sion 1999) and *BVRIJHK* (Bergeron 2001) photometry. The solid and dotted lines represent the pure hydrogen models with and without the opacity from the red wing of the Lyα line, respectively. The fit parameters are $T_{\rm eff} = 5820$ K and $\log g = 8.30$. The dashed line represents the spectrum obtained when only H-H collisions are considered in the Lyα opacity calculation. All model spectra shown are computed from the same atmospheric structure.

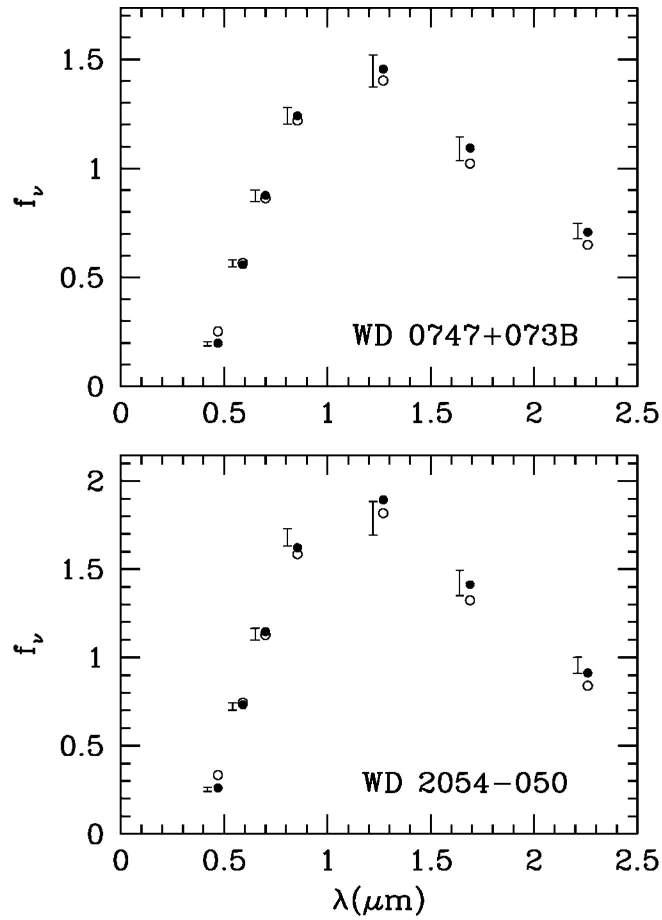

FIG. 3.—Fits to the spectral energy distributions of two very cool white dwarfs from the sample of Bergeron (2001). Bars represent the observed *BVRIJHK* fluxes with $\pm 1\ \sigma$ errors (Bergeron 2001). Circles, shifted by 0.05 μm for clarity, represent the best-fitting pure hydrogen models. Models with the Lyα opacity (*filled circles*) give the following ($T_{\rm eff}$, $\log g$): (4255, 7.78) for WD 0747+073B and (4260, 7.84) for WD 2054−050. Models computed *without* the Lyα opacity (*open circles*) give (4240, 7.75) for WD 0747+073B and (4260, 7.83) for WD 2054−050. The units of flux are 10^{-26} ergs cm^{-2} s^{-1} Hz^{-1}. Bergeron et al. (2001) classified WD 2054−050 as a He-rich star.

(1996). To obtain the H-H_2 potential from the H_3 potential surface, we assumed a fixed internuclear separation for H_2 of 1.4 a.u. This approach is justified by the fact that the atoms in H_2 vibrating in the ground state spend most of the time at the equilibrium internuclear separation. At the temperatures of interest ($T < 6000$ K), the vibrational excitation is small, and so is the amplitude of vibration ($\lesssim 0.4$ a.u.). We have verified that such a small change in the intermolecular separation does not affect our results significantly.

The line profile is calculated in the quasi-static approximation, which is suitable for a calculation of the far line wings perturbed by classical particles (Allard & Kielkopf 1982). The profile of the line $\alpha(\nu)$ is given by equations (13) and (61) in Allard & Kielkopf (1982):

$$\alpha(\nu)d\nu \sim dP_c(r_c(\nu))|\langle 2|\boldsymbol{d}|1\rangle|^2, \tag{2}$$

where $\langle 2|\boldsymbol{d}|1\rangle$ is the r_c-dependent transition dipole moment between the ground state and the first excited Rydberg state of the colliding pair, and ν is the frequency. The dipole transition moments, which vary with separation r_c, are from Staszewska & Wolniewicz (1999) for H-H and Peng et al. (1995) for H-H_2. For a given Lyα transition energy, the H-H_2 ground-state interaction is much less repulsive than the H-H ground-state

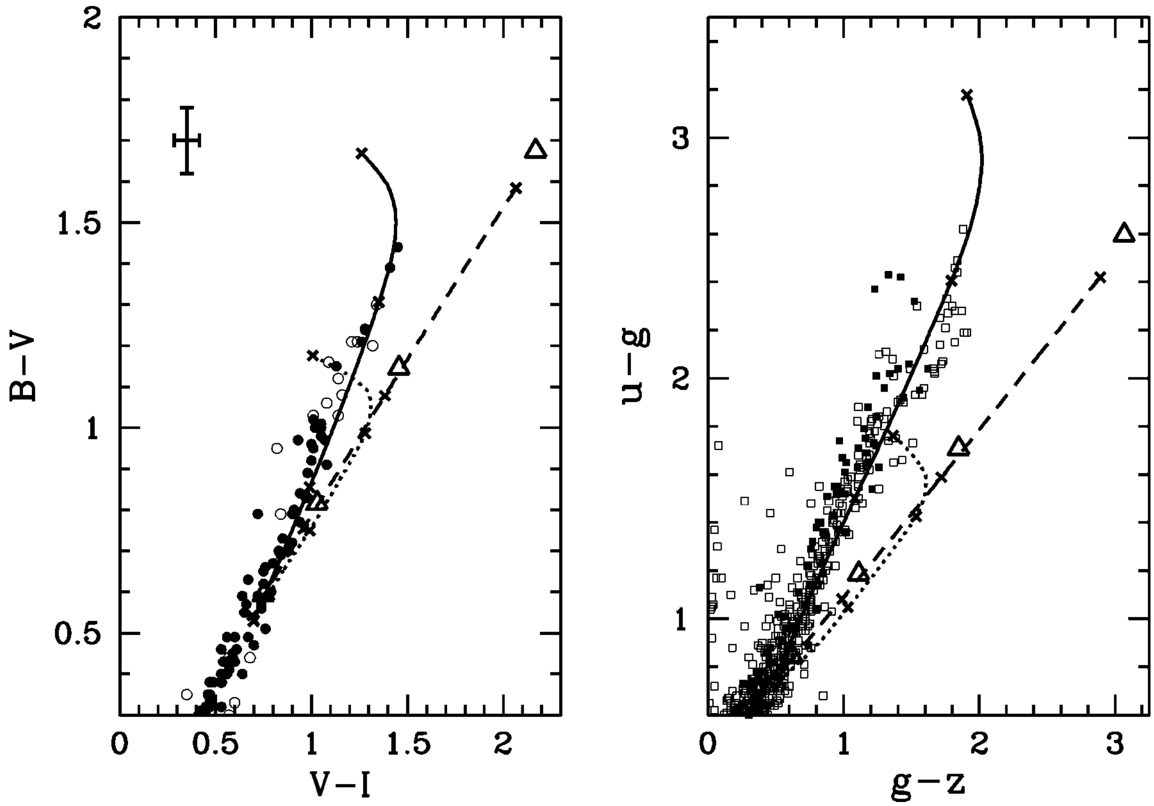

FIG. 4.—Color-color diagrams for cool white dwarfs. *Left panel*: The sample of Bergeron (2001). The composition as determined by Bergeron (2001) is shown by filled circles (hydrogen-rich) and open circles (helium-rich), and the photometric uncertainties are shown by the error bars in the upper left. *Right panel*: The SDSS white dwarf sample of Kilic et al. (2006; *filled squares*) and Harris et al. 2006 (*open squares*). The photometric error bars vary widely from star to star in these two samples and are not shown. The lines represent the synthetic colors of the models: pure hydrogen with the Lyα line opacity (*solid lines*) and without (*dotted lines*). A pure He sequence is also shown (*dashed lines*). The $T_{\rm eff}$ along each curve is indicated by crosses at 3000, 4000, 5000, and 6000 K from top to bottom. All models have $\log g = 8$. The corresponding colors of blackbodies are shown by open triangles. DQ, DZ, and known or suspected double degenerate stars have been removed from the samples. [*See the electronic edition of the Journal for a color version of this figure*.]

interaction (Fig. 1), and the probability of a close H-H_2 interaction is much larger than that of a close H-H interaction [dP_c(H-H_2) $\gg$ dP_c(H-H)]. Hence, the H-H_2 collisions are the dominant contributors to the Lyα line red wing opacity in the atmospheres of cool H-rich white dwarfs with a significant abundance of H_2 ($T_{\rm eff} < 6000$ K).

3. APPLICATIONS TO COOL WHITE DWARF ATMOSPHERES

3.1. *The Spectral Energy Distribution of Cool DA's*

BPM 4729 (WD 0752−676) is the only cool DA white dwarf observed in the near-UV (Wolff et al. 2002). When complemented with the *BVRIJHK* photometry of Bergeron et al. (2001) and the *U* magnitude (McCook & Sion 1999), the complete SED of this cool white dwarf is obtained. The UV spectrum extends well into the wing of the Lyα line and thus provides an excellent measure of the strength and profile of the line. Our fit of a pure H model ($T_{\rm eff} = 5820$ K, $\log g = 8.30$) to the entire SED of BPM 4729 is excellent (Fig. 2). These values of $T_{\rm eff}$ and g agree with the values of Bergeron et al. (2001) at the 1 σ level. The high quality of the fit of the UV spectrum demonstrates the validity of our model for the far red wing of the Lyα line under the conditions encountered in BPM 4729. At the photosphere, the composition is $\log n({\rm H}) = 19.8$ and $\log n({\rm H}_2) = 19.0$, where n is the number density in units of cm^{-3}. Despite the lower abundance of H_2, it is an important contributor to the Lyα line opacity in the far red wing (Fig. 2). Wolff et al. (2002) obtained a good fit of the UV and blue spectrum with a He-rich model with H/He $= 3 \times 10^{-5}$. They point out that such a low H abundance fails to reproduce the Balmer lines of BPM 4729, however. Wolff et al. (2002) required a large amount of He to match the UV spectrum because the broadening of Lyα by collisions with He is weaker than with H or H_2. They also considered a pure hydrogen model, but its Lyα line extends only up to ∼2400 Å. In view of the difference between the potential curves for the $b\,^3\Sigma_u^+$ to $a\,^3\Sigma_g^+$ states of the H-H dimer (Fig. 1), this indicates that this particular transition was not included in the model of Wolff et al. (2002). The main reason for our success with a pure H model is our inclusion of the broadening of the Lyα line by collisions of hydrogen atoms with H_2 and using the $b \rightarrow a$ transition for the H-H dimer.

We have also fitted *BVRIJHK* photometry of most of the coolest DA/DC white dwarfs in the Bergeron et al. (2001) sample. Two typical fits are shown in Figure 3. Our models have no difficulty in reproducing the observed *B* flux, and excellent fits are obtained for most stars with either pure H or pure He. The importance of the Lyα line opacity in the models is revealed by comparing with fits of models that exclude this opacity source. The improvement in fitting the *B* flux with our Lyα opacity model is clearly visible. The star WD 2054−050 (vB 11; lower panel of Fig. 3) was assigned a pure helium composition by Bergeron et al. (2001). We return to this point in § 3.2. The success of the pure H models indicates that the Lyα red wing opacity is the missing blue opacity source in models of cool H-rich white dwarf atmospheres.

3.2. *Color-Color Diagrams*

Color-color diagrams allow a broader comparison with data. Figure 4 shows two large samples of cool white dwarfs, that of Bergeron et al. (2001) and a combination of two samples culled from the Sloan Digital Sky Survey (SDSS; Kilic et al. 2006; Harris et al. 2006). The atmospheric composition of the stars in the first sample, as determined by Bergeron et al. (2001), is indicated in the left panel of Figure 4. Colors computed from our pure H model sequence, both with and without the Lyα opacity, are shown. Our sequence of new pure hydrogen atmospheres follows the observed sequence of stars very well in these two color-color diagrams. Equally good agreement is found in all other color-color diagrams involving *BVRIJHK* and *ugriz* colors (not shown here).

On the other hand, the sequence of pure helium models of Bergeron et al. (1995a; see also Bergeron et al. 1995b) used in the analysis of Bergeron et al. (1997, 2001) also reproduces the observed sequence in the *BVI* color-color diagram. This potential ambiguity in the atmospheric composition of cool DC stars is resolved with a new sequence of pure He models. We have computed pure He models based on much improved constitutive physics for dense helium, including a better calculation of the ionization equilibrium and of the He^- free-free (ff) and Rayleigh scattering absorptions (Iglesias et al. 2002; Kowalski & Saumon 2004; Kowalski et al. 2005, 2006). A detailed description of these models will be the subject of a future publication. Qualitatively, the correlations in dense fluid He reduces the contribution of Rayleigh scattering by a factor of ~10 (Iglesias et al. 2002), and the strong interactions in the fluid increase the ionization fraction (and hence, the He^- ff opacity) by 2–3 orders of magnitude (Kowalski et al. 2005, 2006). The combination of these effects make He^- ff the only important source of opacity in these models. On the other hand, because of a lower ionization fraction and the higher Rayleigh scattering opacity in a dilute gas, the pure He model spectra of Bergeron et al. (1995a) are affected by both opacities (see their Fig. 13). Since He^- ff is a nearly gray opacity, our pure He atmosphere models are essentially gray and the emergent flux is close to that of a blackbody. The colors of this pure He sequence are shown in Figure 4 along with those of blackbodies. Compared to the Bergeron et al. (1995a) pure He sequence, to our pure H sequence, and to the observed sequence of very cool white dwarfs, this new pure He sequence is much redder for $T_{\rm eff} \lesssim 4500$ K. As the ionization fraction is sufficiently large for the He^- ff opacity to dominate, the colors of our new He sequence are insensitive to modest pollution by metals since increasing the fraction of free electrons will only increase the He^- ff opacity without any effect on the emergent spectrum. On the basis of the location of the pure H and pure He model sequences in the color-color diagrams (Fig. 4) and the excellent fit we obtain for WD 2054−050 with a pure hydrogen model, it appears that the atmospheric composition of the coolest DC stars needs to be revisited.

4. CONCLUSIONS

The existence of an unidentified absorption mechanism in cool hydrogen white dwarf atmospheres was reported a decade ago (Bergeron et al. 1997). The interpretation of this missing opacity as the pseudocontinuum absorption from hydrogen atoms has been recently shown to be incorrect (Kowalski 2006b). On the other hand, the red wing of the Lyα line opacity from hydrogen could provide the required absorption (Wolff et al. 2002). We present a new calculation of the extreme pressure-broadening of the Lyα line by both H and H_2. When these were included in our new pure hydrogen atmosphere models, we obtained an excellent agreement with the UV/optical/near-IR SED of the cool DA white dwarf BPM 4729 and we successfully fitted the *B* through *K* SEDs of stars with hydrogen-rich atmospheres, as determined by Bergeron et al. (1997, 2001). The inclusion of broadening by collisions with H_2 is essential to reproduce the SED of very cool hydrogen white dwarfs.

In color-color diagrams, the new pure hydrogen models follow the observed sequences of cool white dwarfs very well, while an improved physical description of dense helium moves the cool end of the helium sequence to the red, near the locus of blackbody colors. This suggests that detailed fitting of the SED of the coolest DC white dwarfs will result in a number of them, and perhaps most, having hydrogen-rich composition rather than helium-rich. An example is provided by our fit to WD 2054−050. This has direct implications for the spectral evolution of very cool white dwarfs and for the physical mechanisms responsible for their atmospheric composition.

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