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Swift/UVOT Photometry of the Planetary Nebula WeBo 1: Unmasking A Faint Hot Companion Star

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ABSTRACT

We present an analysis of over 150 ks of data on the planetary nebula WeBo 1 (PN G135.6+01.0) obtained with the *Swift* Ultraviolet Optical Telescope (UVOT). The central object of this nebula has previously been described as a late-type K giant barium star with a possible hot companion, most likely a young pre-white dwarf. UVOT photometry shows that while the optical photometry is consistent with a large cool object, the near-ultraviolet (UV) photometry shows far more UV flux than could be produced by any late-type object. Using model stellar atmospheres and a comparison to UVOT photometry for the pre-white dwarf PG 1159−035, we find that the companion has a temperature of at least 40,000 K and a radius of, at most, 0.056 $R_\odot$. While the temperature and radius are consistent with a hot compact stellar remnant, they are lower and larger, respectively, than expected for a typical young pre-white dwarf. This likely indicates a deficiency in the assumed UV extinction curve. We find that higher temperatures more consistent with expectations for a pre-white dwarf can be derived if the foreground dust has a strong "blue bump" at 2175 Å and a lower R_V. Our results demonstrate the ability of *Swift* to both uncover and characterize hot hidden companion stars and to constrain the UV extinction properties of foreground dust based solely on UVOT photometry.

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1. Introduction

The classical barium (or Ba II) stars are red giants with enhanced abundances of carbon and elements such as strontium and barium that are synthesized in the *s*-process of neutron captures. First recognized by Bidelman & Keenan (1951), they are now understood as members of moderately wide binary systems. When the more massive component became an asymptotic-giant-branch (AGB) star, it dredged up carbon and *s*-process elements to its surface and then transferred a portion of this material to the companion through a stellar wind (e.g., McClure 1984; Jorissen et al. 1998; Bond & Sion 2001; and references therein). In this picture the AGB star has now become an optically inconspicuous white dwarf (WD), leaving the optical light of the system dominated by the contaminated cool companion. Strong support for this picture came from the discovery by McClure (1984) that virtually all Ba II stars are single-lined spectroscopic binaries, with fairly long periods and typical orbital separations of about 2 AU.

In almost all cases, it is not possible to provide a direct confirmation of this scenario by proving that the unseen companion star is a WD. Böhm-Vitense (1980) used the *International Ultraviolet Explorer* (*IUE*) satellite to detect a hot WD companion of ζ Cap, the prototypical Ba II star. Gray et al. (2011) recently showed that six barium dwarfs have UV excesses consistent with the presence of a hot WD. However, in the large majority of barium stars the WD—if that is what the companion is—has faded below detectability, even in the UV, and we lack direct proof that the invisible companions are really WDs.

WeBo 1 (PN G135.6+01.0; J2000: 02:40:14.4, +61:09:16) is a faint planetary nebula (PN) that was discovered serendipitously by R. Webbink (see Bond, Pollacco, & Webbink 2003; hereafter BPW03) during examination of Digitized Sky Survey images of the X-ray binary LS I +61 303 (V615 Cas). The X-ray source lies only $4\farcm9$ away from WeBo 1. Deep narrow-band images of the PN have been presented by BPW03 and Smith et al. (2007). The PN appears as a thin elliptical ring, with a prominent 14th-mag central star. Spectroscopic observations by BPW03 revealed that the nucleus is a cool barium star, making WeBo 1 unique among planetary-nebula nuclei (PNNi) known at the time of discovery. More recently, however, a second Ba II PNN, the central star of Abell 70, has been discovered (Miszalski et al. 2012, who list several other cool PNNi that may also have Ba II-like compositions). In the picture of the binary-star origin of Ba II stars outlined above, we can argue that the PN surrounding the barium star in WeBo 1 must not only have been ejected during the pollution process, with some of it accreting onto the optical star, but it must be photoionized by the remnant of the AGB star, now a hot WD at the top of the WD cooling track. Thus the cool star in WeBo 1 would be an extremely young Ba II star, in the sense that the pollution of its surface must have occurred very recently.

The only element missing in this seemingly satisfying story is direct proof that there actually is a hot star present in the WeBo 1 system. This cannot be shown based on ground-based data, because the optical spectrum and colors of the central star show only the cool barium giant. Ultraviolet (UV) observations from space would be necessary to reveal the hot star. WeBo 1 is at too low a galactic latitude to be observed by *GALEX*, and has not been observed by the *Hubble Space Telescope* (*HST*). However, there have been extensive observations of LS I +61 303 and its surrounding field with the *Swift* satellite's Ultraviolet Optical Telescope (UVOT). WeBo 1 was serendipitously within the UVOT field of view for these observations, and thus there are many observations of it in the *Swift* archive.

In this paper, we present *Swift*/UVOT photometry of WeBo 1 in both optical and near-ultraviolet (NUV) passbands, from which we confirm the presence of the expected hot component. §2 describes and presents the UVOT photometric data analyzed in this paper. §3 uses spectral models to reveal properties of the hot companion star and examines the variability of WeBo 1. §4 then summarizes our results. We will use "WeBo 1" to designate both the PN and its central star, but the latter has also been cataloged as V1169 Cas.

2. Observations and Data

Our analysis of WeBo 1 is based on data taken with the UVOT instrument aboard the *Swift* Gamma Ray Burst Mission (Gehrels et al. 2004). UVOT is a modified Ritchey-Chretien 30 cm telescope that has a wide ($17' \times 17'$) field of view, which is imaged by a microchannel-plate intensified CCD operating in photon-counting mode (Roming et al. 2000, 2004, 2005). The camera is equipped with a filter wheel that includes a clear white filter, u, b, and v optical filters, $uvw1$, $uvm2$, and $uvw2$ UV filters, a magnifier, two grisms, and a blocked filter. Figure 1 illustrates the bandpasses of UVOT's filters, and shows that they are well-positioned to separate the UV and optical fluxes from two stars of significantly different temperatures.

Although UVOT's primary mission is to measure the optical/UV afterglows of gamma-ray bursts, the wide field, $2''.3$ resolution, broad wavelength range (1700-8000 Å), and ability

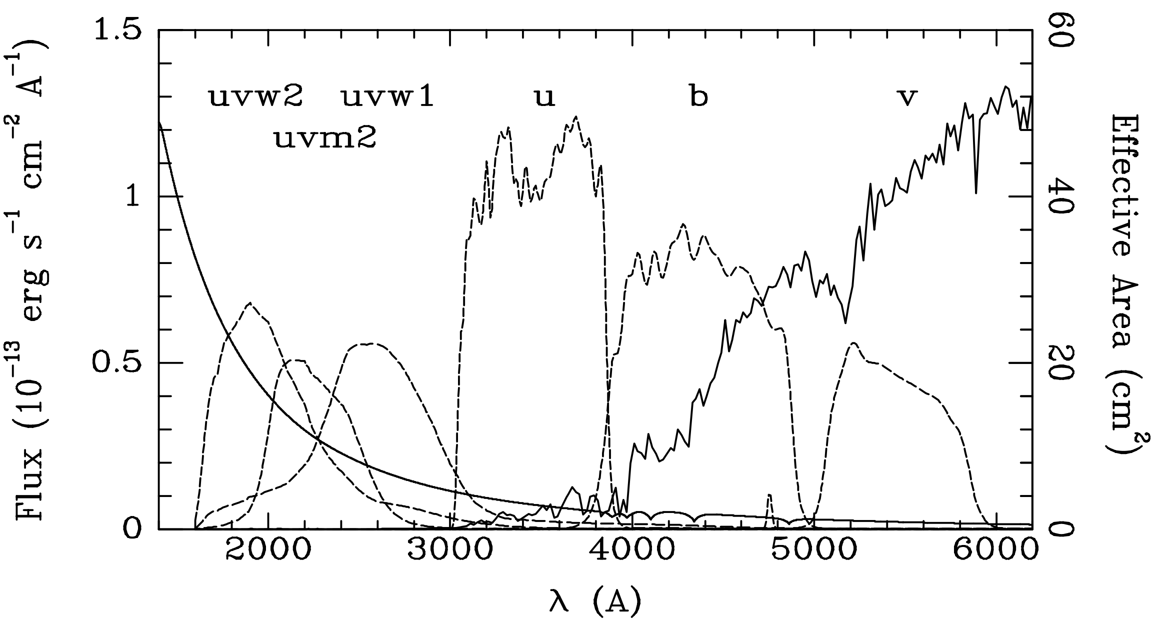

Fig. 1.— A comparison of the spectra of a hot white-dwarf (WD) star to that of a K giant in the bandpasses of the *Swift* UVOT camera. The WD spectrum (solid line on left) is a model of the DA-type UV standard star SDSS J150050.71+040430.0 (WD 1458+042) from Siegel et al. (2010). The model spectrum is from the TLUSTY code (Lanz & Hubeny 1995), with parameters set to $T_{\rm eff} = 23,300$ K, $\log g = 7.8$. The K-giant spectrum (solid line on right) is taken from the atmospheric models of Castelli & Kurucz (2003), using $T_{\rm eff} = 4250$ K and $\log g = 2$. It has been arbitrarily scaled to match the flux of the WD at about 3800 Å. The dashed lines are the effective areas of the six *Swift*/UVOT filters used in this study.

to observe simultaneously with *Swift*'s X-Ray Telescope (XRT; Burrows et al. 2005) allow a broad range of investigations, including the study of hot or energetic stars. Our recent catalog of UV photometric standard stars (Siegel et al. 2010) demonstrates the ability of UVOT to measure the properties of hot compact stars, such as the one suspected to be a companion to WeBo 1.

WeBo 1 has never been deliberately targeted by *Swift*. However, as noted above, the nearby high-mass X-ray binary LS I +61 303 *has* been monitored extensively, and WeBo 1 is well within the 17′ UVOT field of view. Our search of the *Swift* archive yielded a total of 160 ks of full-frame UVOT exposure time on WeBo 1, taken between 2007 November 1 and 2012 February 3. A large fraction of these observations was performed using a UV-weighted six-filter mode, while others were performed with UVOT in "Filter of the Day"—a mode in which only one of the u, $uvw1$, $uvm2$, or $uvw2$ filters is used, both to save on filter-wheel rotations and to slowly build a UV sky survey. The result is that the accumulated exposure time on WeBo 1 is heavily weighted toward the UV filters.

Photometry for WeBo 1 was measured from deep stacked UVOT images using the UVOTSOURCE program. UVOTSOURCE, an FTOOL released as part of the HEASOFT *Swift* suite of software programs[1], measure aperture photometry and then corrects the count rates for the flat-field correction, coincidence losses and sensitivity loss over time. It then transforms the instrumental magnitudes to a standard AB- and Vega-magnitude systems, using formulae and calibration data from Poole et al. (2008) and Breeveld et al. (2010, 2011)[2].

[1]HEASOFT software can be found at: http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/

[2]The most recent UVOT zero points are available online from the UVOT Digest at `http://heasarc.gsfc.nasa.gov/docs/swift/analysis/uvot_digest/zeropts.html`

Table 1. *Swift*/UVOT Observations of WeBo 1

Filter	Exposure Time (ks)	AB Mag	Var
v	8.8	$14.52 \pm 0.02 \pm 0.01$	1.11
b	9.2	$16.03 \pm 0.02 \pm 0.02$	1.14
u	22.4	$18.09 \pm 0.02 \pm 0.02$	1.14
$uvw1$	28.3	$19.62 \pm 0.02 \pm 0.03$	1.05
$uvm2$	44.0	$21.18 \pm 0.03 \pm 0.03$	1.17
$uvw2$	47.2	$20.24 \pm 0.02 \pm 0.03$	1.14

In Table 1 we list the total exposure times in each UVOT filter, and the mean magnitudes for WeBo 1 with both random and systematic errors given. The fourth column gives an index of variability, which is the ratio of the observed photometric scatter to the calculated formal error. Non-variables should have an index near 1.0, while strongly variable stars will have an index of 3.0 or more. The tight clustering of these measures near 1.0 (with a mean of 1.13) indicates that we detected little evidence for variability of WeBo 1 to within 0.03-0.05 magnitudes, a point we address further in §3.4.

To check on potential X-ray emission from the binary system, we ran the automated analysis pipeline of Evans et al. (2009) on the data from the *Swift* XRT, which were taken simultaneously with the UVOT observations. While there are several X-ray sources in the field (most notably LS I +61 303 itself), we do not find any X-ray emission at the position of WeBo 1.

The WeBo 1 PN has an expansion age of about $12,000 \pm 6,000$ yr (BPW03). The putative hot companion star would be expected to be a hot central star or a WD near the top of the WD cooling sequence, with its exact location on its post-AGB evolutionary track depending on the exact age of the star and its mass. While Siegel et al. (2010) demonstrated an ability to constrain the properties of hot WD stars (10,000–30,000 K) from UVOT data, WeBo 1 is expected to be hotter than their calibration stars in order to ionize the surrounding PN (see, e.g., Hugelmeyer et al. 2007). A search of the *Swift* archive identified only a handful of known WDs with both extreme temperatures ($T_{eff} > 50,000$ K) and low reddening ($E(B - V < 0.1)$ for comparison. The latter requirement is particularly critical, given the uncertainties in the UV extinction curve discussed below. We settled on PG 1159−035 (GW Virginis) as the best object with which to test our ability to constrain the properties of extremely hot degenerate objects. PG-1159 is hot (140,000 K, Jahn et al. 2007), well-studied, has published spectra and, most important, has minimal foreground reddening. PG 1159−035 is a prototype of a rare class of very hot, hydrogen-deficient WDs and is known to display non-radial pulsations with an amplitude of approximately 0.02 mag (Winget 1991; Costa & Kepler 2008). PG 1159−035 is not surrounded by a PN, but many of the PG 1159 class are known PNNi (e.g., Kohoutek 1-16, Grauer & Bond 1984; RX J2117.1+3412, Motch et al. 1993; PG 1520+525, Jacoby & van de Steene 1995; and several others). While the WeBo 1 core is unlikely to be, like PG 1159−035, deficient in hydrogen, PG 1159−035 defines a probable the upper limit on its potential properties, with the WDs of Siegel et al. (2010) defining the lower limit.

PG 1159−035 has never been specifically targeted for *Swift* observations. However, like WeBo 1, it was observed serendipitously by UVOT on 2005 December 12 and 2011 July 28, during observations of the fortuitously nearby active galaxy Mkn 1310. Table 2 lists the photometry measured at both epochs of PG 1159−035. We find no significant difference in the magnitudes at the two epochs, as expected given the relatively low pulsation amplitude of PG 1159.

3. Analysis

3.1. A UV-bright Companion

BPW03 estimated a spectral type of K0 III:p Ba5 for WeBo 1, indicative of a cool K giant with C_2 absorption bands and a very strong line of Ba II at 4554 Å. From the spectral type and the observed color, they estimated an intrinsic $(B-V)_0$ color of 1.15 and a foreground reddening of $E(B-V) = 0.57$. Our broadband optical colors from *Swift* (Table 1) are consistent with the BPW03 measures.

Based on the optical spectral type, we can use stellar-atmosphere models to predict the UV flux of the K0 star. We used the ATLAS9 compilation of Castelli & Kurucz (2003). For our model star, we adopted [Fe/H] = 0, $T_{\rm eff} = 4750$ K, $\log g = 2.0$, $v_{\rm turb} = 2\,{\rm km\,s^{-1}}$, and a mixing length of $1/H = 1.25$. This model spectrum was used to generate synthetic photometry, following the method described in Siegel et al. (2010) and using the AB-mag zero points of Breeveld et al. (2011). We then estimated the foreground reddening by applying the Pei (1992) Milky Way extinction curve to the model spectrum and forcing the predicted $b-v$ color to match the observed value. The $b-v$ index is our longest-wavelength *Swift* color and should have minimal contamination from the anticipated hot companion. We deduced an intrinsic $b-v$ color of 1.10 and a foreground reddening of $E(B-V) = 0.70$, somewhat higher than obtained by BPW03.

Barium stars are known to have a broad absorption feature in their spectral energy distributions, centered near 4000 Å (Bond & Neff 1969). The Bond-Neff absorption lies partially within the b filter (see Figure 1) and it would be expected to be strong in WeBo 1. This may explain the higher inferred $E(B-V)$, compared to that estimated from the $B-V$ color, since the B band has a longer effective wavelength than b. However, our neglect of the Bond-Neff effect in the following discussion should have a minimal impact.

While the main bandpasses of the NUV filters are in the near-UV, $uvw2$ and $uvw1$ have significant red leaks at optical wavelengths. These leaks have been well characterized using *HST* spectrophotometry of cool late-type stars (Breeveld et al. 2011). The red leak is not a significant problem for hot stars, but a cool and reddened K giant would have such minimal intrinsic UV emission that almost any detection in the NUV filter would be due to red leak. To indicate the scope of the problem, we used methods detailed in Brown et al. (2010) to generate synthetic magnitudes for the K giant using the entire filter curve given in Breeveld et al. (2011), and compared them to synthetic magnitudes generated using filter curves truncated at 2500, 3000, and 3300 Å for the $uvw2, uvm2$, and $uvw1$ filters, respectively. We find that a cool K giant would have so little intrinsic UV flux that, in the absence of a hot companion, the red leak would contribute 99%, 65%, and 90% of the signal detected in $uvw2$, $uvm2$, and $uvw1$. By comparison, for a hot (40,000 K) companion star, only 13%, 1%, and 8% of its signal would come from the red tail. Thus, a K giant would be almost undetectable in the NUV filters without a red leak, faint but detectable in all but $uvm2$ with the red leak, and easily detectable in all filters with a hot companion star. These calculations indicate that the properties of any complex system in the UVOT filters can be understood only if careful attention is paid to the red-leak contribution, an ability we demonstrated in Siegel et al. (2010).

Table 3 compares the synthetic and observed NUV magnitudes of WeBo 1 with model magnitudes normalized to match the v-band brightness. The comparison shows that WeBo 1, in comparison to the model, has a strong flux excess in all of the UV passbands, *well above the flux predicted from the well-characterized red leak.* This excess is particularly notable in the $uvm2$ filter, which has minimal red sensitivity and is therefore the filter most sensitive to the presence of a hot companion star. *The dramatic excess of UV flux clearly indicates that WeBo 1 has a hot companion.*

Our measured properties for the WeBo 1 primary are somewhat sensitive to the assumed model parameters. The fit reddening, in particular, varies from 0.3 to 1.1 magnitudes if the temperature is allow to vary from 4000 K to 5500 K. Is it possible that a different type of single star could produce the observed optical and NUV photometry, especially given the interplay with the red leak?

Figure 2 shows the intrinsic (unreddened) $b-v$ and $u-uvm2$ colors of *all* of the Kurucz model atmospheres with [Fe/H] = +0.0 and $v_{turb} = 2.0\,\mathrm{km\,s^{-1}}$. The models range from $\log g = 0.0$, $T_{\rm eff} = 3500$ K to $\log g = 5.0$, $T_{\rm eff} = 50,000$ K. Also shown for comparison is UVOT photometry of the open cluster M67 (Siegel et al., in prep). Note that with the filter curve properly modeled, the photometric sequence in M67—an old cluster of solar metallicity—matches the locus of synthetic magnitudes, lending confidence to our ability to model the UVOT filters, including any red sensitivity.

No stellar model can reproduce both the optical and NUV colors of WeBo 1 (starred point). And no amount of assumed reddening can move WeBo 1 onto the Kurucz locus. The arrow shows the reddening vector calculated from the Pei models with the length equal to the maximum reddening along the line of sight from the Schlegel et al. (1998) maps ($E(B-V) = 1.48$). Only a significant and large change to both the amount of foreground

Table 2. *Swift*/UVOT Photometry of PG 1159−035

Filter	2005 December 12 Exposure Time (ks)	2005 December 12 AB Mag	2011 July 28 Exposure Time (ks)	2011 July 28 AB Mag
v	1.29	$14.75 \pm 0.02 \pm 0.01$	0.08	$14.71 \pm 0.04 \pm 0.01$
b	1.29	$14.26 \pm 0.02 \pm 0.02$	0.08	$14.26 \pm 0.03 \pm 0.02$
u	1.29	$13.72 \pm 0.02 \pm 0.02$	0.19	$13.68 \pm 0.03 \pm 0.02$
$uvw1$	2.46	$13.17 \pm 0.02 \pm 0.03$	0.16	$13.13 \pm 0.02 \pm 0.03$
$uvm2$	···	···	0.30	$12.95 \pm 0.02 \pm 0.03$
$uvw2$	···	···	0.31	$12.69 \pm 0.02 \pm 0.03$

Table 3. Comparison of Observed WeBo 1 Magnitudes to a Synthetic K Giant

Filter	WeBo 1 Observed	Synthetic[a]
v	14.52	14.52
b	16.03	16.03
u	18.09	18.64
$uvw1$	19.62	20.40
$uvm2$	21.18	25.64
$uvw2$	20.24	21.80

[a]Model properties: [Fe/H] = 0, $T_{\rm eff}$ = 4750 K, $\log g = 2.0$, $v_{\rm turb} = 2\,{\rm km\,s^{-1}}$, $1/H = 1.25$; reddened by $E(B-V) = 0.70$ and normalized to the v magnitude of WeBo 1.

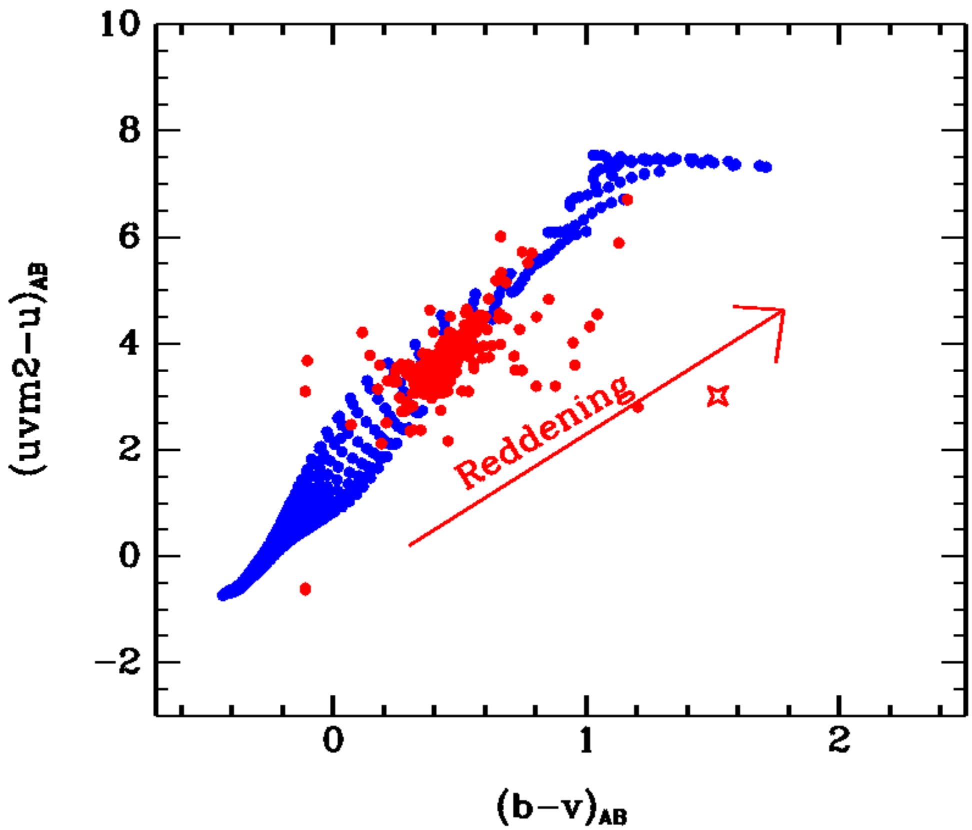

Fig. 2.— A comparison of the optical and NUV colors of WeBo 1 to the intrinsic colors of the Kurucz models of stellar atmospheres. The blue points represent the predicted color for all of the available models with [Fe/H] = 0 and $v_{\rm turb} = 2.0\,{\rm km\,s^{-1}}$. The star is WeBo 1. Red points represent photometry of the open cluster M67. The line shows the reddening vector, with the length of the line indicating the full Schlegel et al. (1998) extinction value along this line of site. Magnitudes are on the AB system.

reddening *and* the reddening law could possibly move WeBo 1 even close to the locus of model stars. Varying the metallicity of the model family shifts the intrinsic color locus only slightly and not nearly enough to capture WeBo 1. There is simply no method by which the observed optical and NUV photometry can be fit by a single star. Two bodies—one cool and one faint but hot—are required.

3.2. Comparison to PG 1159−035

As discussed in §2, we settled on PG 1159−035 as both a test of our ability to constrain the properties of extremely hot compact objects and as a baseline against which to compare WeBo 1. However, confirming the nature of WeBo 1 is more complicated than simply adding PG 1159−035 to the K giant, even assuming that such a comparison were appropriate. Shifting PG 1159's photometry to account for the difference in reddening and distance does not reproduce the magnitudes and colors measured for WeBo 1 (Table 4). This may be due to differences between the two objects but is even more likely due to the additional reddening. Accounting for 0.70 magnitudes of reddening in the NUV passbands is more complicated than simply adding an offset to the photometry as we have done in Table 4. The NUV extinction curve is uncertain, particularly the strength of the blue bump at 2175 Å. Moreover, the curve is steep and extinction can vary depending on spectral type.

Properly accounting for all the potential confounding factors—red leak, UV extinction curve, differences between the secondary star and PG 1159−035—requires spectral synthesis, in which theoretical and observational models are used to recreate the observed photometric measures, a method we used with notable success in creating WD UV standard stars (Siegel et al. 2010) and which we used in §3.1 to rule out a single star.

3.3. Spectral Modeling of the Companion Star

Revealing the origin of the UV excess in WeBo 1 requires careful modeling of both the cool giant, and the putative hot companion. Modeling of the K giant is informed by spectroscopic identification of the star. As discussed earlier, the K giant is modeled using a Kurucz model stellar atmosphere with $T_{\rm eff} = 4750$ K, log $g = 2.0$, and $v_{turb} = 2\,{\rm km\,s^{-1}}$. This model spectrum was used to generate synthetic magnitudes following the method described in Siegel et al. (2010) and using the AB zeropoints of Breeveld et al. (2011).

The UV excess suggests a companion to the K giant which is similar to the pre-WD PG 1159 star. Unlike the K giant, the temperature of the companion is a free parameter.

Ideally, one would measure the properties of the companion by comparison to a spectral library of extremely hot WD and pre-WD stars, such as the one published from *IUE* data (Holberg et al. 2003). However, these spectra only go as red as 3150 Å, which does not cover all of the UVOT filters and does not cover the red leak in the $uvw1$ and $uvw2$ filters.

However, a simpler model may be sufficient for modelling the companion. UV spectra of hot compact WDs and PG 1159 stars (Feibelman 1996; Kruk & Werner 1998; Marcolino et al. 2007) indicate that the hottest stars should have few absorption features in the UVOT wavelength range, which occupies the Rayleigh-Jeans tail of the spectral energy distribution. We ran two models of PG 1159−035 through our spectral modeling software, one using a pure black body of 140,000 K, the other using the published *IUE* spectrum over the 1100-3150 Å range and a blackbody curve for the remainder. In both cases, we re-normalized the photometry to minimize χ^2. Figure 3 shows the results. Both the hybrid model and the pure blackbody model provide a reasonable fit to the photometric measures, with reduced χ^2 values of 3.2 and 3.5, respectively, with the most significant discrepancy in the u-band measure. For simplicity's sake, we used blackbody models for the companion star.

The K giant and hot companion models were fit to the observed photometry simultaneously using the double-star χ^2 method described in Hoversten et al. (2008). A standard χ^2 fit to a model can be expanded to include two models as follows:

$$\chi^2 = \sum_i \left[\frac{F_{o,i} - a f_{A,i} - b f_{B,i}}{\sigma_i} \right]^2 , \qquad (1)$$

where $F_{o,i}$, $f_{A,i}$ and $f_{B,i}$ are the fluxes of the observed object, first template model and second template model in the ith bandpasss, σ_i is the photometric uncertainty in the ith band, and a and b are the flux weighting coefficients that minimize the χ^2. This equation can then be expressed in terms of magnitudes

$$\chi^2 = 1.086^2 \sum_i \left[\frac{1 - a10^{\left(m_{o,i} - m_{A,i}\right)/2.5} - b10^{\left(m_{o,i} - m_{B,i}\right)/2.5}}{\sigma_{m_i}} \right]^2 , \qquad (2)$$

where $m_{o,i}$ and σ_{m_i} are the observed magnitude and magnitude error in the ith band, $m_{A,i}$, and $m_{B,i}$ are the model magnitudes of the first and second models in the ith band, and a and b are again weighting coefficients that minimize χ^2.

The relative weighting of the two models appears to be a free parameter, adding extra degrees of freedom to the χ^2 minimization. However, this in not the case as a and b can be analytically determined by setting $\partial\chi^2/\partial a$ and $\partial\chi^2/\partial b$ equal to zero and solving the simultaneous system of equations. The result is that

$$a = \frac{AB^2 - BC}{A^2B^2 - C^2} \qquad (3)$$

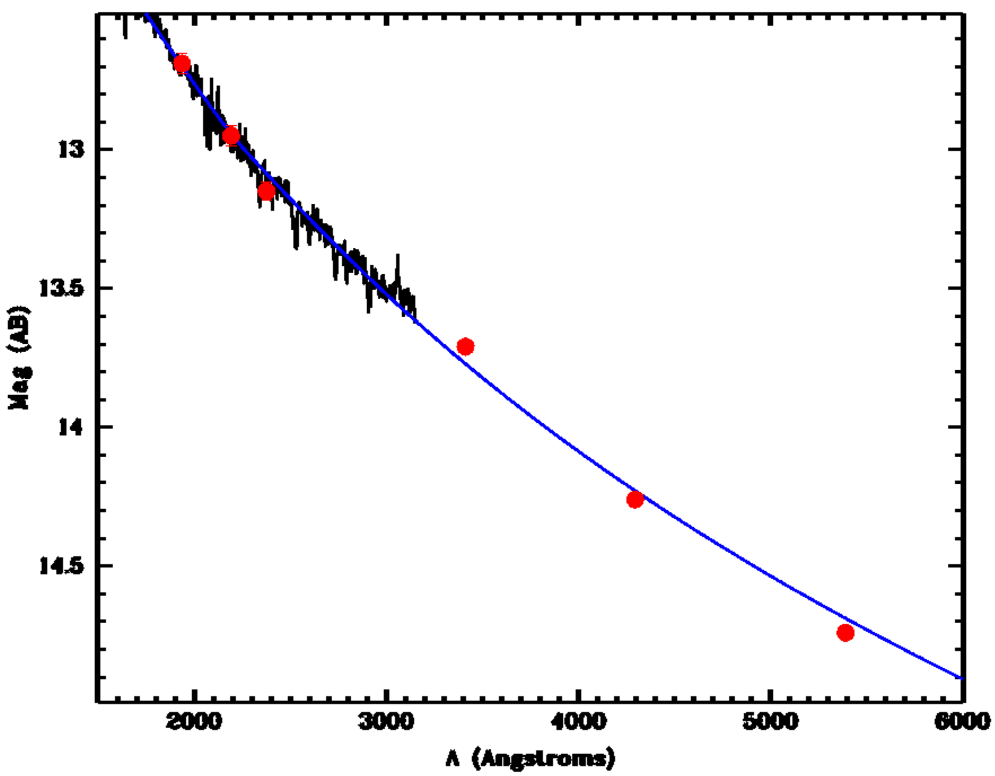

Fig. 3.— Comparison of observed photometry and synthetic spectra for the pre-white dwarf star PG 1159−035. Solid red points are the photometric measures at the effective wavelengths for a 140,000 K blackbody. Point sizes are comparable to the observational uncertainties. The blue line is the blackbody curve for a 140,000 K blackbody while the solid black line is the *IUE* spectrum of PG 1159−035 taken from Holberg et al. (2003).

and

$$b = \frac{BA^2 - AC}{A^2B^2 - C^2}\,, \tag{4}$$

where

$$A = \sum_i \left(\frac{10^{(m_{o,i}-m_{A,i})/2.5}}{\sigma^2_{m_i}} \right), \tag{5}$$

$$B = \sum_i \left(\frac{10^{(m_{o,i}-m_{B,i})/2.5}}{\sigma^2_{m_i}} \right), \tag{6}$$

and

$$C = \sum_i \left(\frac{10^{(2m_{o,i}-m_{A,i}-m_{B,i})/2.5}}{\sigma^2_{m_i}} \right). \tag{7}$$

This shows that under the assumption of χ^2 minimization there exists an optimal weighting of two spectral models. Once a and b have been calculated it is only necessary to consider one combination of any two models.

Figure 4 shows the χ^2 space assuming Milky Way dust in the foreground while Figure 5 shows a similar plot assuming SMC dust (without a blue bump at 2175 Å). The models using Milky Way dust and a strong blue bump are notably superior to those using an SMC dust model without a blue bump. For the former, the minimum χ^2 is reached for a companion temperature of 40,000 K and a foreground extinction of $A_V = 2.43$. This is slightly higher than the extinction calculated just from the K giant itself ($A_V = 2.17$).

Figure 6 compares the best fitting black body and K giant models to the observed photometry of WeBo 1, again illustrating that neither star can provide an adequate representation of the measured photometry. However, the combined photometry matches the data points well. We also show the unextincted spectra to demonstrate just how dramatically the foreground dust obscures the hot companion star. Note the significant downturn in the UV flux in the *uvm*2 passband; a result of the strong blue bump in the foreground dust. Note also that, under this model, we should see some emission from the companion star near the H and K lines. BPW03 did not see this and this could indicate that WeBo's 1 companion is fainter and hotter than our fit models.

If the WeBo 1 companion is a WD, having passed the turnaround point in the H-R diagram, the 40,000 K temperature is problematic. It would imply a low mass for the companion star (below 0.3 $M_\odot$; Schönberner et al. 1989; Panei et al. 2007) and therefore a rather high WD age (at least several 10^7 years). This would be incompatible with the 12,000 yr age of the nebula. At 40,000 K, it would be more likely that the WeBo 1 companion is in a young PNN phase still evolving to higher temperature and not having yet reached the turnaround point.

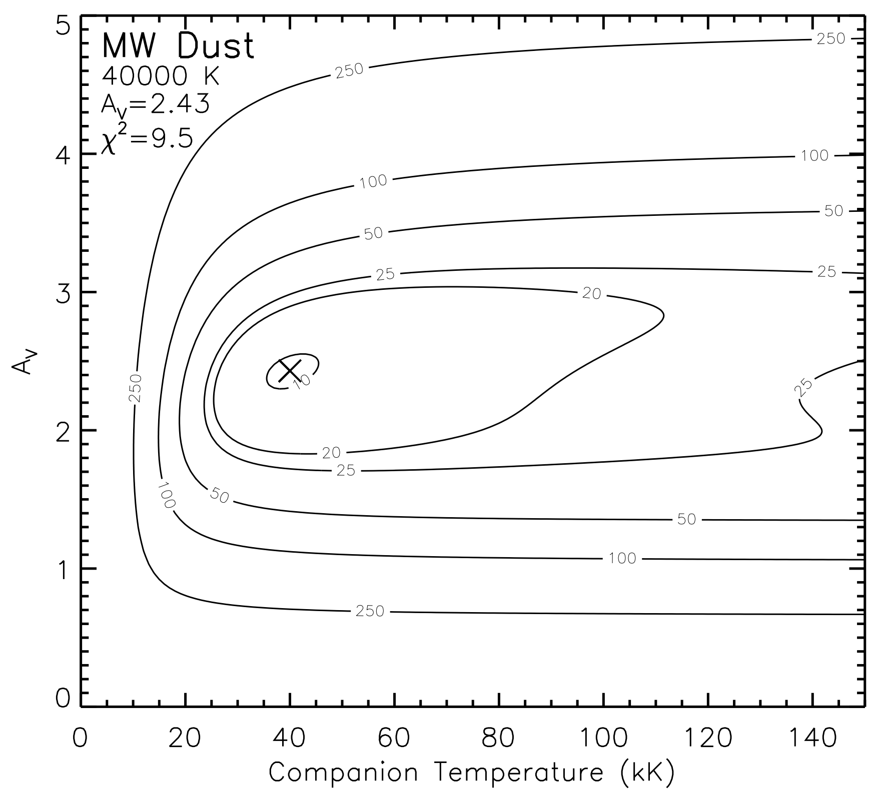

Fig. 4.— Minimized χ^2 values for WeBo 1 assuming a K giant and a black body companion as a function of temperature and foreground extinction. This plot uses Milky Way dust with a strong 2175 Å bump. Temperatures are in units of 1000 K. The cross shows the best fitting companion model at 40,000 K and $A_V = 2.43$.

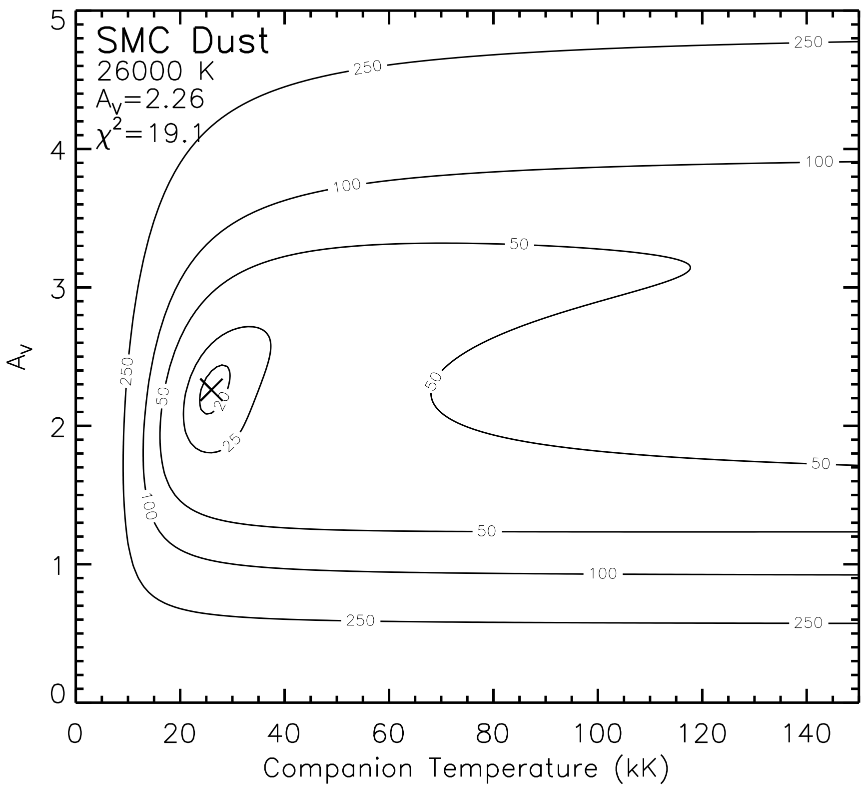

Fig. 5.— Minimized χ^2 values for WeBo 1 assuming a K giant and a black body companion as a function of temperature and foreground extinction. This plot uses SMC dust without a strong 2175 Å bump. Temperatures are in units of 1000 K. The cross shows the best fitting companion model at 26,000 K and $A_V = 2.26$.

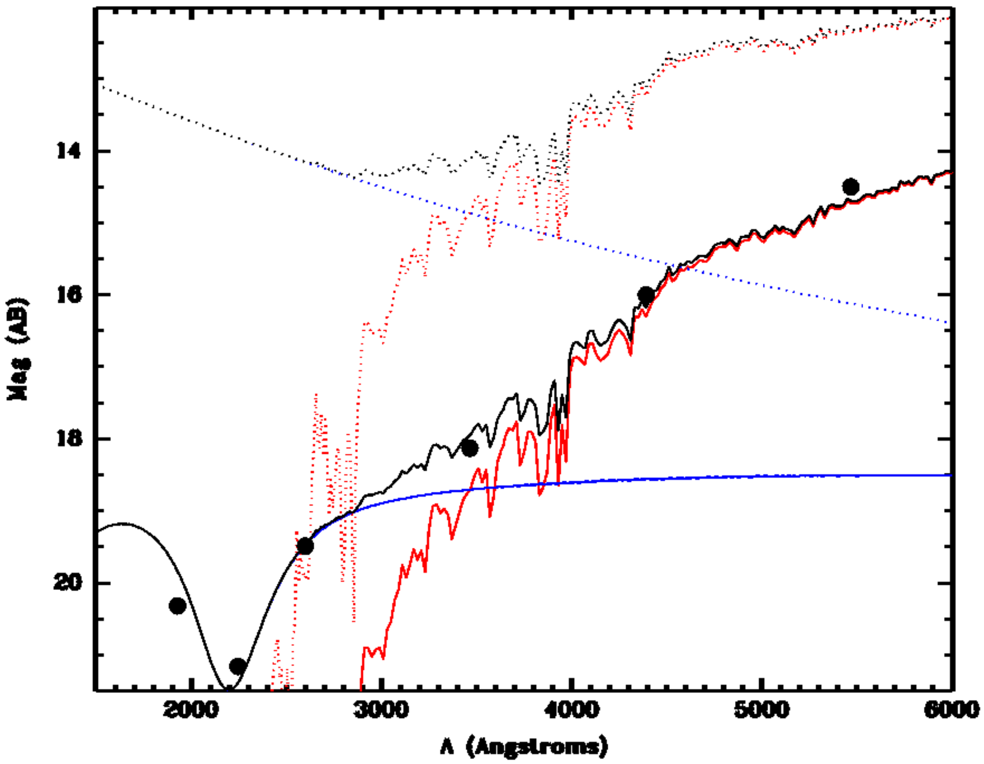

Fig. 6.— Comparison of observed WeBo 1 photometry to best fitting K giant plus hot companion model. Solid points are the data, with error bars smaller than the size of the points. Magnitudes are on the AB system. The lines are the spectral models—blue for the hot companion, red for the K giant and black for the combined system. Dotted lines denote the spectra in the absence of foreground extinction. Note the dramatic effect of the foreground dust, particularly the 2175 Å bump.

However, there are a number of reason to believe that the temperature of WeBo 1 is higher than our nominal estimate. At this temperature, WeBo 1 is at the limit of UVOT's ability to constraint the properties of extremely hot stars. Note in Figures 4 and 5 that the χ^2 contours are elongated in the temperature direction. A star as hot as WeBo 1's companion is far brighter in the FUV than the NUV and we are likely probing the Rayleigh-Jeans tail of the spectral energy distribution, which has limited leverage on the temperature. Running PG 1159−035 through the software shows that we can establish a strong lower limit on the temperature ($\sim$ 100,000 K) but no upper limit. A small change in the underlying models would not lower our estimated temperature significantly, but could increase it dramatically.

It is worth noting that simply running a 140,000 K blackbody through our engine provides a perfectly adequate fit to the photometry of PG 1159−035. This indicates that we *should* be able to measure the temperature of WeBo 1 or at least place a better lower limit if it is indeed as hot as PG 1159−035. However, PG 1159−035 is a simple system—a single star with minimal foreground reddening. WeBo 1, by contrast, involves an unusual barium star with a high degree of chromospheric activity (BPW03), a pre-WD star companion in an early stage of evolution, and a high amount of foreground dust. This system may simply be too complex for the modelling software.

The most likely culprit for this sabotage is the foreground dust. The extinction curve in the UV is still poorly known. Simply adding in the blue bump increases the estimated temperature of the companion by 14,000 K and cuts the reduce χ^2 in half. Using techniques developed in our study of the Milky Way dust (Hoversten et al., in prep), we varied the strength of the blue bump and the assumed extinction law (R_V). We find that for a blue bump strength of 1.25 and a R_V of 2.5, the derived temperature of the star shoots up to 184,000 K and the foreground extinction is more consistent with that derived from the K giant and by BPW03 (Figure 7). These parameters are well within the range of extinction laws described by Cardelli et al. (1989). The implication is that the inferred properties of such a hot star are uniquely sensitive to the assumed properties of the foreground dust. If this is the case, studies of more hot pre-WDs could provide powerful insight into the Milky Way's extinction law in the UV.

At a temperature of 184,000 K, WeBo 1's properties would be consistent with a young WD or pre-WD. Its exact evolutionary state would depend on its mass.

The normalization used for the spectral models intrinsically includes both the radius and distance to the WeBo 1 system. Assuming a distance of 1600 pc (BPW03), a Milky Way dust model, and calculating radii based on the b and v magnitudes for the cool primary star and the $uvm2$ magnitudes for the companion, we calculate stellar radii of 5.3 and 0.057 $R_\odot$, respectively. This is broadly consistent with expectations for a red giant and WD star.

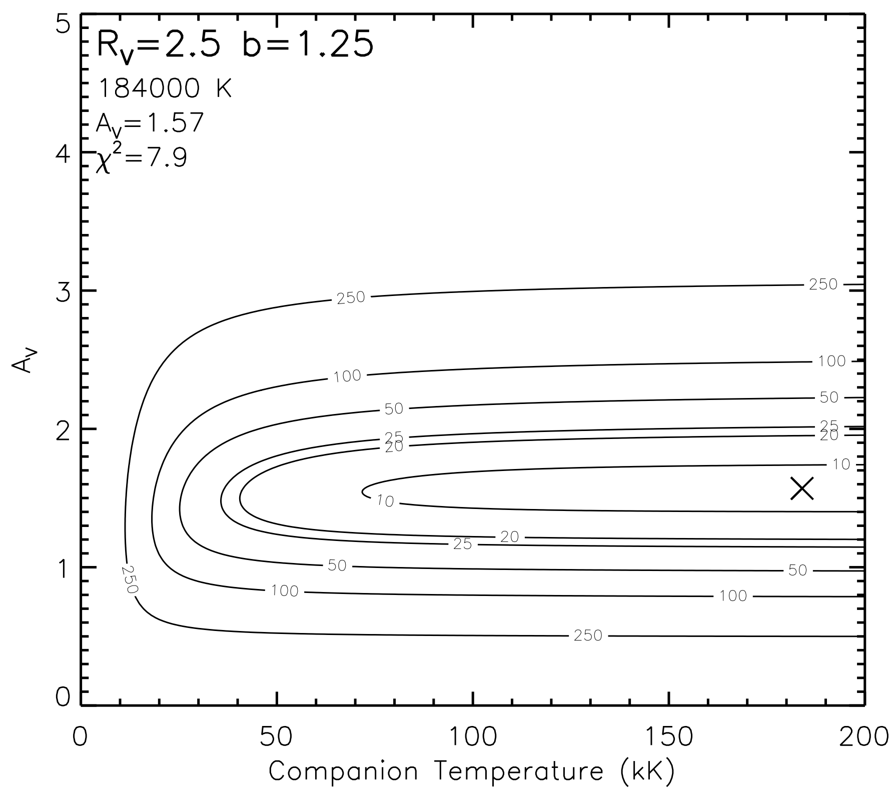

Fig. 7.— Minimized χ^2 values for WeBo 1 assuming a K giant and a black body companion as a function of temperature and foreground extinction. This plot uses Milky Way dust with a slightly stronger 2175 Å bump and a lower R_V, resulting in a steeper extinction in *Swift*'s NUV passbands. Temperatures are units of 1000 K. The cross shows the best fitting companion model at 184,000 K and $A_V = 1.57$. Not that the contours are narrowly elongated in the temperature direction, indicating we are at or beyond the limit of UVOT's sensitivity to stellar temperature.

Applying this method to PG 1159−035 correctly recovers the known stellar radius of 0.025 $R_\odot$. If the alternative dust model is assumed, the radii of the stars shrinks to 3.7 and 0.028 $R_\odot$ for the K giant and pre-WD, respectively.

In sum, although our spectral models calculate a lower temperature of the WeBo 1 secondary than expected, the data are inconsistent with anything other than a small, compact, hot object as the companion to the red giant star. However, even a fairly small change in the assumed foreground dust results in a WeBo 1 secondary that is similar in temperature and size to PG 1159−035.

3.4. Photometric Stability

BPW03 indicated that WeBo 1 showed variability on a timescale of 4.7 days, possibly as a result of starspots on a rotating primary star. As noted above, column four of Table 1 shows the ratio of observed to expected scatter. In all six passbands, WeBo 1 shows minimal scatter beyond that expected from the photometric errors. However, this broad and somewhat inhomogeneous dataset may not be ideal to detect the variability. If the variability is indeed the result of starspots, that signal may be blurred if the starspots changed over the five years.

We investigated this further by calculating a Welch-Stetson (1993) variability index for all two-filter combinations in our photometry. The Welch-Stetson index measures the correlation of photometric residuals from the mean flux. Pulsating stars should have positive residuals or negative residuals simultaneously in different passbands. Non-variable stars should have an index near zero. We found numerous correlations among the filter combinations, ranging from 0.04 to 0.42. Much of this correlation is the result of a long-term fading of 1-2% per year in all passbands except b and $uvm2$. It's not clear what would cause this trend – whether it is something secular connected with the WeBo 1 primary or something related to the calibration. The decline in UVOT's sensitivity is well-characterized by Breeveld et al. (2011) and incorporated into the current FTOOLS build. However, a small error in sensitivity decline or large scale sensitivity could potentially produce this signal.

However, this long-term decline does not explain all of the variability. The left panel of Figure 8 shows the residuals for the b and v passbands for the entire data set while the right panel shows those from 2011 October to 2012 February, when *Swift* was monitoring LS I +61 303 at least every week and, during 2012 December, every day. For the latter time span, we see a correlation between the residuals, which hints at potential variability in the WeBo 1 primary. We attempted to fit this period using phase dispersion minimization with the IRAF task PDM over periods between 0.1 and 100 days. We found multiple solutions, none of which were particularly superior or showed a particularly clear light curve.

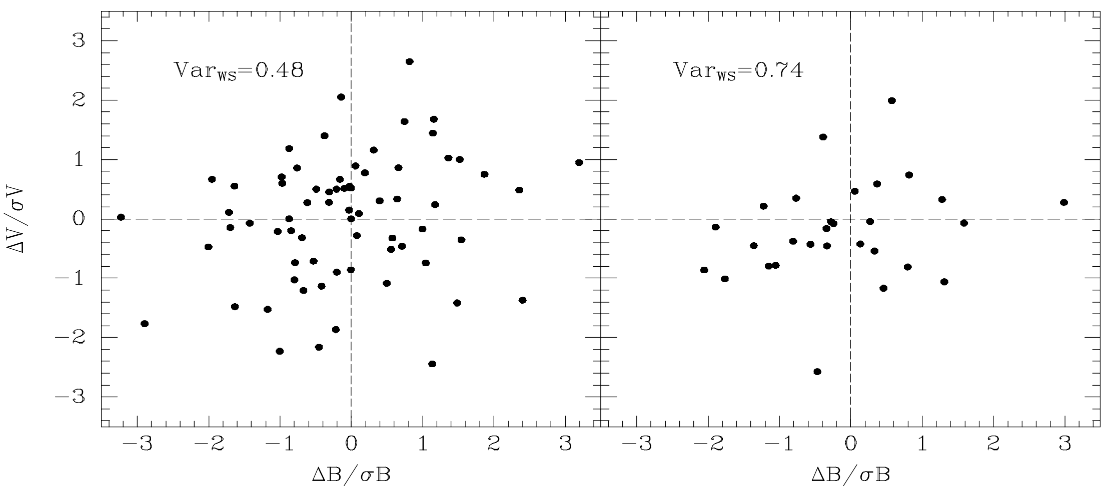

Fig. 8.— Residual correlation in *Swift*/UVOT b and v photometry of WeBo 1. The points represent b and v photometric measures taken within 0.5 day of each other. The axes measure the ratio of photometric residuals to photometric uncertainties (Δ/σ where $\Delta_V = V_i - \langle V \rangle$. For a truly variable star, the residuals should be correlated resulted in a diagonal line from the lower left to upper right (see, e.g., Figure 1 of Welch & Stetson (1993). The residuals of WeBo 1 show a slight correlation with a positive variability index. Narrowing the data to those taken in late 2011 and early 2012 shows a stronger correlation.

It should be noted that the variability detected by BPW03 was of order 30 mmag. This is less than the random errors on individual observations of WeBo 1, which have a mean of 95, 46, and 41 mmag in the *ubv* passbands, respectively. Even binning observations made on the same day reduces the mean error of the measures only to 77, 37, and 32 mmag, barely sufficient to measure the variability. Furthermore, the *Swift*/UVOT data are not optimized for the detection of the primary star's variation. There are gaps in the phase coverage when *Swift* was either not observing V615 Cas or not observing it in the optical filters that are the most sensitive to WeBo 1's primary star. The modes it has been observed in are weighted heavily toward the NUV. All of these factors make the detection of WeBo 1's variability difficult.

However, Figure 9 shows the v- and b—-band photometry from late 2011 and early 2012 folded with a period of 4.686 days, the periodicity identified by BPW03. As can be seen, while a 30 mmag variation is close to the level of the noise, the data hint at a slight correlation in the magnitudes that could be the rotation of WeBo 1's primary star. While we cannot claim to have definitely detected this variability, the data suggest that it is real.

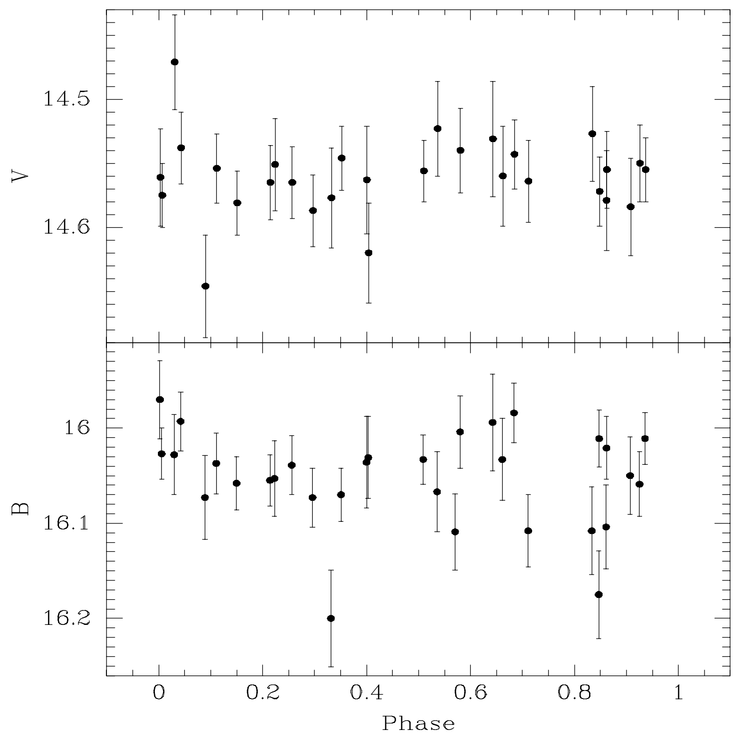

Fig. 9.— v- and b-band photometry of WeBo 1 folded with the 4.686 day periodicity detected by BPW03. Photometric measures are binned by calendar day.

If—as speculated by BPW03—the variability is the result of starspots on a fast-rotating primary, the starspots may have changed over the course of five years of observing, therefore muddying any periodicity in the full data set. But the variation would be marginally detectable over the short time span of the most recent observations. Only more regular and systematic observations will be able to confirm WeBo 1's variation as well as any long-term changes.

4. Conclusions

Using archival *Swift*/UVOT images of the planetary nebula WeBo 1, we have detected a surplus of ultraviolet flux that cannot be explained by any single-star system. Using spectral models, we estimate that the system consists of a K giant (previously identified by BPW03) and a hot compact object with a temperature of at least 40,000 K and a radius of less than 0.056 $R_\odot$. This temperature is significantly lower than expected for a young planetary nebula, which is likely due to inadequacies in the foreground dust model. The spectral models provide an excellent reproduction of the photometry of PG 1159−035, a hydrogen-deficient pre-WD with a similar extreme temperature but minimal reddening. Modifying the assumed extinction curve to a lower R_V and a stronger blue bump improves the fit to the photometry and increases the derived temperature to well over 100,000 K. UV spectroscopy and/or FUV imaging would be needed to provide a firm constraint on the pre-WD temperature (as well as the foreground extinction). Our results do, however, confirm the speculation of BPW03 that WeBo 1 is a binary system, consisting of a cool barium star and a hot pre-WD companion.

We detect some variability in the optical passbands which would be consistent with the variability reported by BPW03. This variability is most clearly shown in the subset of the data during which WeBo 1 was more regularly monitored. The long-term data are more ambiguous. If this result is confirmed, it would rule out regular pulsations, companion heating or ellipsoidal variation as explanations for the variability seen by BPW03. Only changing starspots would produce a clear signal over a short period of time but a blurred signal over a longer epoch. However, the measured variation of WeBo 1 is comparable to the precision afforded by our photometry. More thorough and precise photometric monitoring is needed to determine if WeBo 1's putative variation is the result, as speculated by BPW03, of starspots on a rapidly rotating primary.

Finally, it is worth noting that all of the data in this study were obtained serendipitously during the study of other objects. This hints at the promise held by the ongoing UV sky survey for discovering and characterizing serendipitous sources.

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REFERENCES

Bidelman, W. P., & Keenan, P. C. 1951, ApJ, 114, 473

Böhm-Vitense, E. 1980, ApJ, 239, L79

Bond, H. E., & Neff, J. S. 1969, ApJ, 158, 1235

Bond, H. E., & Sion, E. 2001, Encyclopedia of Astronomy and Astrophysics, p. 290

Bond, H. E., Pollacco, D. L., & Webbink, R. F. 2003, AJ, 125, 260 [BPW03]

Breeveld, A. A., Curran, P. A., Hoversten, E. A., et al. 2010, MNRAS, 406, 1687

Breeveld, A. A., Landsman, W., Holland, S. T., et al. 2011, American Institute of Physics Conference Series, 1358, 373

Brown, P. J., Roming, P. W. A., Milne, P., et al. 2010, ApJ, 721, 1608

Burrows, D. N., et al. 2005, Space Science Reviews, 120, 165

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245

Castelli, F., & Kurucz, R. L. 2003, Modelling of Stellar Atmospheres, 210, 20P

Costa, J. E. S., & Kepler, S. O. 2008, A&A, 489, 1225

Feibelman, W. A. 1996, ApJ, 464, 910

Gehrels, N., et al. 2004, ApJ, 611, 1005

Grauer, A. D., & Bond, H. E. 1984, ApJ, 277, 211

Gray, R. O., McGahee, C. E., Griffin, R. E. M., & Corbally, C. J. 2011, AJ, 141, 160

Holberg, J. B., Barstow, M. A., & Burleigh, M. R. 2003, ApJS, 147, 145

Hoversten, E. A. 2008, Ph.D. Thesis, The Johns Hopkins University

Hügelmeyer, S. D., Dreizler, S., Werner, K., et al. 2007, 15th European Workshop on White Dwarfs, 372, 249

Jacoby, G. H., & van de Steene, G. 1995, AJ, 110, 1285

Jahn, D., Rauch, T., Reiff, E., et al. 2007, A&A, 462, 281

Jorissen, A., Van Eck, S., Mayor, M., & Udry, S. 1998, A&A, 332, 877

Kruk, J. W., & Werner, K. 1998, ApJ, 502, 858

Lanz, T., & Hubeny, I., 1995, ApJ, 439, 905

Marcolino, W. L. F., Hillier, D. J., de Araujo, F. X., & Pereira, C. B. 2007, ApJ, 654, 1068

McClure, R. D. 1984, PASP, 96, 117

Miszalski, B., Boffin, H. M. J., Frew, D. J., et al. 2012, MNRAS, 419, 39

Motch, C., Werner, K., & Pakull, M. W. 1993, A&A, 268, 561 s

Panei, J. A., Althaus, L. G., Chen, X., & Han, Z. 2007, MNRAS, 382, 779

Pei, Y. C., 1992, ApJ, 395, 130

Poole, T. S., et al. 2008, MNRAS, 383, 627

Roming, P. W., Townsley, L. K., Nousek, J. A., et al. 2000, Proc. SPIE, 4140, 76

Roming, P. W. A., Hunsberger, S. D., Mason, K. O., et al. 2004, Proc. SPIE, 5165, 262

Roming, P. W. A., et al. 2005, Space Science Reviews, 120, 95

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Schonberner, D. 1989, Planetary Nebulae, 131, 463

Siegel, M. H., et al. 2010, ApJ, 725, 1215

Smith, N., Bally, J., & Walawender, J. 2007, AJ, 134, 846

Welch, D. L. & Stetson, P. B. 1993, AJ, 105, 1813

Winget, D. E., Nather, R. E., Clemens, J. C., et al. 1991, ApJ, 378, 326

Table 4. Comparison of Observed WeBo 1 to Synthetic K-Giant and Shifted PG 1159−035 Photometry

Color	WeBo 1 Observed	Synthetic[a]
v	14.52	14.52
b	16.03	15.94
u	18.09	17.83
$uvw1$	19.62	18.46
$uvm2$	21.18	20.18
$uvw2$	20.24	19.36

[a]Magnitude generated by adding a scaled model from Table 3 to PG 1159−035 magnitudes from Table 2. The latter were shifted by 1.4 magnitudes to account for difference in distance and by UV extinction values for $E(B-V) = 0.70$.