

PG 2131+066: A TEST OF PRE-WHITE DWARF ASTEROSEISMOLOGY

M. D. REED,^{1,2} STEVEN D. KAWALER,^{1,3} AND M. SEAN O'BRIEN^{1,4,5}

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ABSTRACT

PG 2131+066 is a composite-spectrum binary with a hot pulsating PG 1159-type pre-white dwarf and an early M-type main-sequence star. Analysis of Whole Earth Telescope observations of the pulsating pre-white dwarf component provided an asteroseismological determination of its mass, luminosity, and effective temperature. These determinations allowed Kawaler et al. to determine the distance to this star. In this paper, we refine the asteroseismological distance determination and confirm the distance by an independent measurement to the system via the spectroscopic parallax of the M star. PG 2131+066 was observed by the *HST* using the original Planetary Camera in 1993 September. Exposures with filters F785LP and F555W both showed the companion at a distance of 0".3. Photometry of the images provides an apparent magnitude for the main sequence companion of $m_v = 18.97 \pm 0.15$, from which we find a distance of 560^{+200}_{-134} pc. We also recalculated the asteroseismological distance to the pre-white dwarf using updated models and new spectroscopic constraints from UV spectra. The new seismological distance is 668^{+78}_{-83} pc, in satisfactory agreement with the distance of the secondary star. These results suggest that this is indeed a physical binary and that the seismological distance determination technique may be the best way to determine the distance to the pulsating hot pre-white dwarf stars.

Subject headings: binaries: spectroscopic — stars: individual (PG 2131+066) — stars: oscillations — white dwarfs

1. INTRODUCTION

Asteroseismology of pre-white dwarfs (PWDs) provides fresh insights into their interior structure and bulk properties. However, because of their extreme temperatures and surface gravities, spectroscopic verification of seismic results has been limited. An independent distance determination would provide a comparison between model and observed luminosities, providing a more confident interpretation of seismic and spectroscopic results. Unfortunately, none of the GW Vir-type stars are close enough to obtain a distance via parallax. However, PG 2131+066 (hereafter referred to as PG 2131) has a red main-sequence companion, which provides an independent test of its distance.

PG 2131 is a member of the PG 1159 spectral class of stars (the pulsating PG 1159 stars are referred to as GW Vir stars). These hot ($T_{\text{eff}} \approx 100,000$ K), luminous ($L \approx 10\text{--}1000 L_{\odot}$) stars represent a link in evolution between planetary nebula nuclei and white dwarfs. As such, by understanding their interior conditions, we provide constraints on both asymptotic giant branch and white dwarf stars.

Spectroscopy by Wesemael, Green, & Liebert (1985) revealed a red component, which they proposed as originating from a companion star (hereafter referred to as the secondary star). Wesemael et al. (1985) deconvolved their spectrum into its constituent components by using a Rayleigh-Jeans approximation to describe the red side of the primary star spectrum. The remaining flux was attributed to the secondary, to which they assigned a spectral type of K5–M0 V and synthesized a V magnitude. From this, they determined a distance to the secondary of $d = 1047^{+1000}_{-500}$ pc.

PG 2131 was discovered to be a variable star by Bond et al. (1984). Pulsations of PG 2131 were investigated in 1992 by the Whole Earth Telescope (WET) collaboration. Seismological analysis by Kawaler et al. (1995) of the WET data, combined with the best available spectroscopic temperature of $T_{\text{eff}} = 80,000 \pm 10,000$ K (Werner, Heber, & Hunger 1991), implied a luminosity of $\log(L/L_{\odot}) = 1.0 \pm 0.2$. Adopting a crude bolometric correction, Kawaler et al. (1995) derived a V magnitude of 16.6, which provided a “seismic” distance to the primary of 470^{+180}_{-130} pc.

PG 2131 provides an important way to “calibrate” seismic results and confirm (or challenge) the reliability of the procedures by which information is extracted from the stellar pulsations. The asteroseismological distance is the end inference of seismic analysis (depending on the other parameters such as stellar mass, luminosity, temperature, etc., determined through earlier steps). Independent testing of this procedure is required to establish the reliability of this distance-determination technique. Such a confirmation has been made for a cooler pulsating white dwarf, GD 358 (Bradley & Winget 1994), via trigonometric parallax, but an independent test of the distance determination of a pulsating GW Vir star is vital.

Though the two distances quoted above are within their rather large error estimates, we sought to improve both estimates using the best available observations, atmospheric models, and seismic models. H. Bond and colleagues imaged PG 2131 in 1993 with the first-generation Planetary Camera (PC) on *HST*. Even with the point-spread function (PSF) problems, they resolved the binary into its two components and reported concordance between the distance determined using the red companion and the asteroseismical distance from Kawaler et al. (1995; H. Bond 1995, private communication). In this paper, we report on our photometric analysis of two *HST* frames that resolve the binary, compare the photometric colors with models of both stars, and reevaluate the seismological analysis. Section 2 describes the *HST* photometry and our analysis. Section 3

¹ Department of Physics and Astronomy, Iowa State University, Ames, IA 50011.

² mreed@iastate.edu.

³ sdk@iastate.edu.

⁴ Space Telescope Science Institute, Baltimore, MD 27701.

⁵ obrien@stsci.edu.

uses the photometric determinations to compare with stellar atmosphere models and obtain spectroscopic parallax distances. In § 4, we review the seismological analysis using updated parameters for the pre-white dwarf component. We compare the results and conclude in § 5.

2. PHOTOMETRY

In 1993, *HST* obtained images of PG 2131 through the F555W and F785LP filters with WFPC1. These images were originally obtained by H. Bond as part of a snapshot project to search for binary planetary nebula central stars. These images confirm the binary nature of PG 2131. As expected, the images show a visual companion that is as extremely red as the primary star is blue. The separation of the pair is $0''.3$, at a position angle of 21° .

We used the IRAF package PHOT to obtain aperture photometry on the stellar cores of both images. To get relative photometry, we chose an aperture that included the stellar core but excluded the first diffraction ring. The small angular separation of $0''.3$ results in the core counts being polluted by their neighbor. This is particularly severe in the F555W image, where nearly half of the secondary core counts can be attributed to the primary. To remove this contamination, we took advantage of the symmetry of the PSF (see Fig. 1). We measured the counts on the opposite side of each star from its companion and subtracted this

from the core counts of the other star; the apertures are illustrated in Figure 1c.

With no other stars in the field, we needed to approximate absolute photometry from this pair alone. To do this, we accumulated all the combined flux by using a large aperture ($\approx 2''.4$) reaching out to points where the signal was indistinguishable from the sky background. Then we used the relative photometry to distribute the total flux to each star. This provided the “absolute” photometry given in Table 1.

In the analysis that follows, the values we obtained were subject to extensive Monte Carlo simulations. These provided most-likely values for all parameters from instrumental magnitudes through the final distance determinations.

TABLE 1
OBSERVED MAGNITUDES

Magnitude/Color	Primary	Secondary
F555W.....	16.84 ± 0.10	19.07 ± 0.12
F785LP.....	17.38 ± 0.11	16.54 ± 0.10
F555W – F785LP.....	-0.54 ± 0.15	2.53 ± 0.16
V.....	16.86 ± 0.14	18.97 ± 0.15
I.....	17.30 ± 0.15	16.85 ± 0.13
V–I.....	-0.46 ± 0.20	2.10 ± 0.19

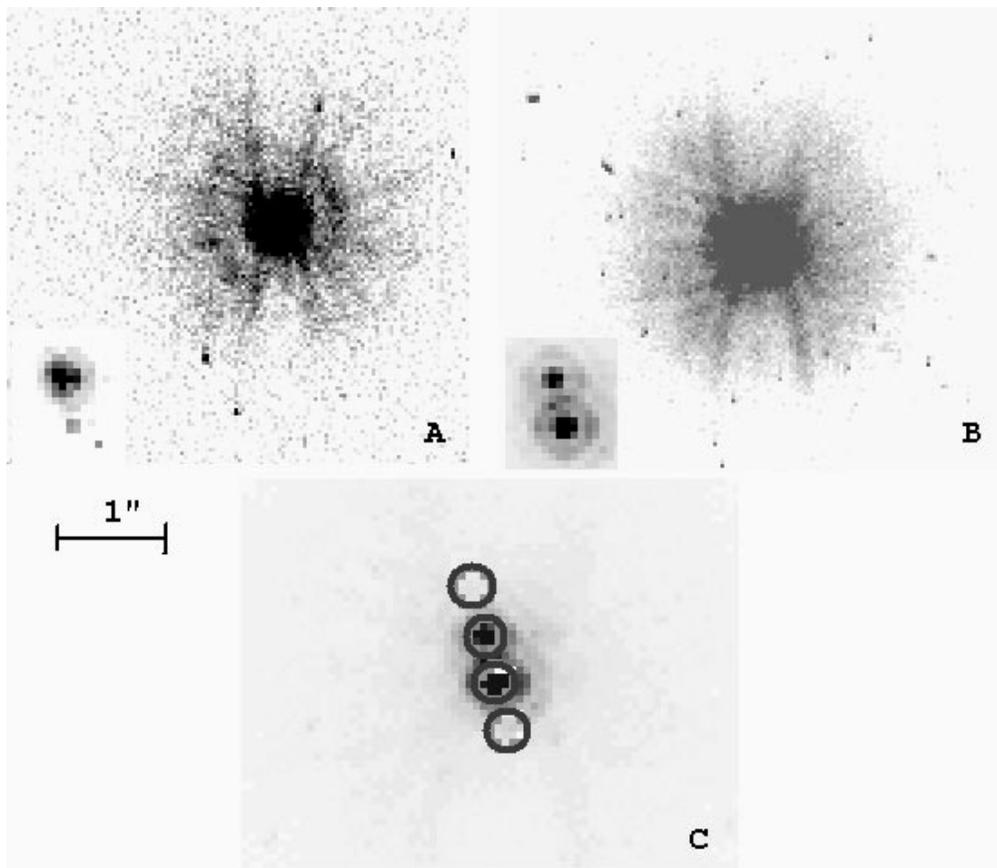


FIG. 1.—*HST* PC images of PG 2131. Panel A is the F555W image, and panel B is the F785LP image. The inset to the lower left of these two panels shows, with a different stretch, the core of the image, revealing the two components. Panel C is the F785LP image of the PG 2131 system, with overlays showing the apertures used.

We simulated all photometric measurements (i.e., counts and count rates) using Poisson statistics. Uncertainties in color corrections and other expressions were modeled as Gaussian distributions with the standard deviations given in the sources of these relations, as cited. Errors were not propagated analytically but were determined throughout the sequence by the distribution of values returned by the Monte Carlo trials. The errors quoted are the 1σ errors derived from the Monte Carlo probability distributions.

Using filter conversions from Holtzman et al. (1993), we iteratively determined the V and I magnitudes listed in Table 1 from the *HST* F555W and F785LP filter bandpasses. It should be noted however that the Holtzman et al. (1993) conversions do not include stars as blue or red as the components of PG 2131, but they do contain the widest range available in the literature, from $V-I$ of 0 to approximately 1.7. We estimate conversion errors of 0.1 mag for each filter.

If the secondary is a main-sequence star, the $V-I$ color of the secondary may be used to determine the absolute magnitude using an empirical main-sequence (M_V , $V-I$) relation. Several are available from the recent literature. Clemens et al. (1998) used nearby stars, combined with *Hipparcos* data, to determine such a relationship for the lower main sequence. Using their composite fit, we find that $M_V = 10.01 \pm 0.68$, yielding a distance of 560^{+200}_{-134} pc. Error estimates combine the uncertainty for the relationship quoted by Clemens et al. (1998) as well as the photometric errors. It is important to note here that if the companion is not a main-sequence star, but is a luminosity class III star of the same color, it would have an absolute magnitude of -0.6 , placing it over 78,000 pc away!

We also obtained an absolute magnitude for the secondary from Figure 6 of Baraffe et al. (1998). Using this figure, we find $M_V = 9.68 \pm 0.1$. With this absolute magnitude we calculate a distance for the secondary of 688 ± 65 pc. Even though this error is smaller, it is based on a region where the Baraffe et al. (1998) sample contains few stars and, therefore, is more prone to systematic effects that are not in the error estimate. (We use the value of $M_V = 10.01 \pm 0.68$ from the Clemens et al. 1998 relation for the rest of the paper.)

The only published ground-based photometry of PG 2131 is a magnitude given by Green, Schmidt, & Liebert (1986) of 16.63; this entry in their tabulation is denoted as uncertain. This is a multichannel V magnitude, which approximates Johnson V . For comparison, the combined V magnitude of the two stars on the *HST* frame is 16.79 ± 0.10 . Given the large uncertainty in the Green et al. (1986) value, this represents consistency between the ground-based photometry and the PC photometry. We note that Bond et al. (2000) have obtained newer ground-based photometry for comparison with the *HST* images.

3. MODEL FITTING

Given the $V-I$ color and distance for the secondary, we were ready to determine if the pair were an optical binary or a physical binary. To do this, we used the data for the secondary to calibrate models to the *HST* WFPC1 system. Then we determined the distance for the primary by convolving models with the now-calibrated system, where the only free parameter is distance.

Starting from the $V-I$ versus T_{eff} relationship of Monet et al. (1992), we found $T_{\text{eff}} = 3600 \pm 250$ K for the second-

ary. Next we processed a grid of Kurucz models⁶ from the tabulation by Lejeune, Cuisinier, & Buser (1997) for comparison with our derived $V-I$ color and chose a model with $T_{\text{eff}} = 3500$ K and $\log g = 4.5$ as the best match, in good agreement with our Monet et al. (1992) derived temperature.

To calibrate our synthetic *HST* system, we first adopted stellar radii for the two stars. For the secondary, this was a radius appropriate for an M2 V star, while the radius used for the primary is $0.0182 R_{\odot}$. We convolved our M2 V model with the WFPC1 system throughputs for the two filters, assuming the distance determined in § 2. Comparing this flux with the observed flux provided the appropriate zero point, so the model magnitudes match the observed magnitudes for the secondary. With these zero points, we “observed” models for the primary, adjusting the distance until our synthetic magnitudes matched the *HST* observations. Using this method, we derived a distance of 681^{+170}_{-137} pc for the primary.

Though Paunzen, Konig, & Dreizler (1998) claim evidence for a possible third component in this system, the *HST* photometry shows that such a close companion to the white dwarf would produce much redder colors than are observed for it. The spectroscopic signature of $H\alpha$ most likely comes from the M2 V star visible on the *HST* images; this is reasonable considering the relative youth of this system (the “newly minted” white dwarf started out as a star of about $2.3 M_{\odot}$ about 7.5×10^8 yr ago).

4. SEISMOLOGICAL ANALYSIS

The primary of PG 2131 is a member of the GW Vir class of pulsating pre-white dwarfs. These stars are multiperiodic nonradial g -mode pulsators. The periods present allow asteroseismological determination of bulk stellar properties such as mass and rotation rate. In some cases, the period spectrum is rich enough to allow determination of the internal structural parameters such as the thickness of various composition layers. Perhaps the best example of this procedure is that shown for PG 1159 by Kawaler & Bradley (1994).

Knowledge of stellar properties from other sources (such as spectroscopy or broadband photometry) frequently provides key input in the seismic analysis. For example, a given set of pulsation periods can be matched by a model of a given mass (within a limited mass range) at discrete values of T_{eff} . Figure 2 shows the least-squares fit between model periods and the observed periods in PG 2131 as a function of T_{eff} for four different stellar masses. Clearly, the fit is temperature-dependent within a given mass, but each shows a pronounced minimum at a well-defined effective temperature. To see the quality of the fit in a different way, we present Figure 3. This figure shows the observed periods of PG 2131 as dark horizontal lines; periods of successive overtones of three models ($0.60 M_{\odot}$, $0.61 M_{\odot}$, and $0.62 M_{\odot}$) are shown as thinner lines. The intersection of the model periods with the observed are marked as points; a perfect fit would be a precise vertical alignment of points at the temperature of the best model. The departures from a perfect fit could be the result of mode trapping by a sub-

⁶ The models included in our grid ranged from models corresponding to K5 V stars to M5 V stars.

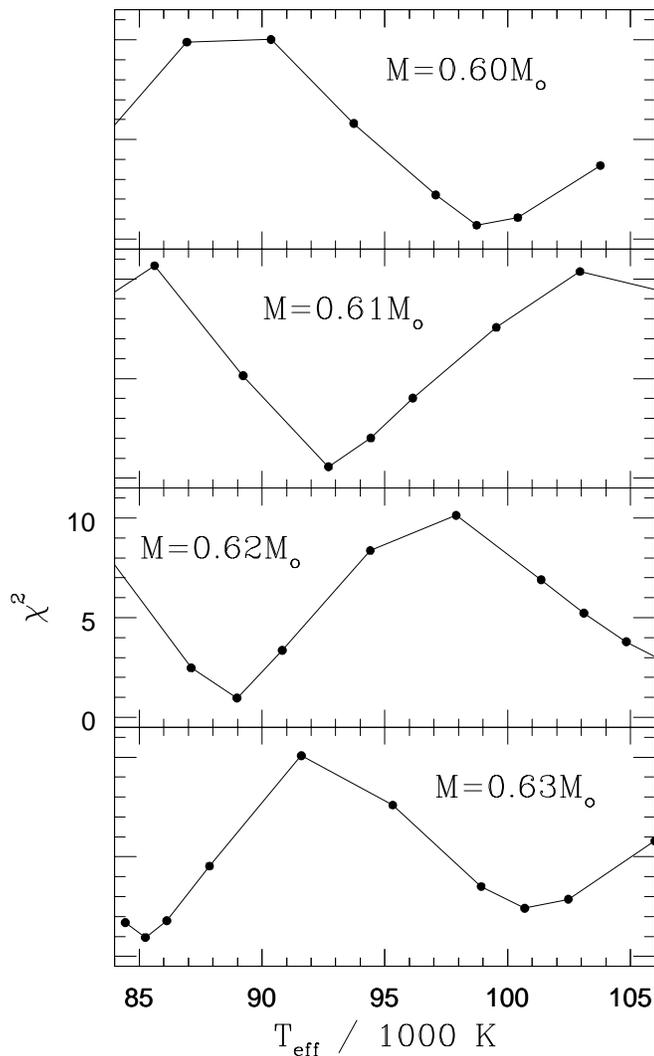


FIG. 2.—Comparison between the observed periods of PG 2131 and model periods. The χ^2 difference between the observed and model periods is plotted against the effective temperature of evolutionary models of the masses indicated. Pronounced minima occur at well-defined effective temperatures.

surface composition transition, as discussed in Kawaler & Bradley (1994). We did not make an effort to match these small departures with the models, but clearly these departures could be reduced with such efforts without affecting the T_{eff} fit significantly.

Considering the range of possible masses, as limited by the spectroscopic temperature determination and its uncertainty, the period-matching constraint results in a relation between bolometric luminosity and effective temperature (as shown by the dashed line in Fig. 4). In the case of PG

TABLE 2
SEISMIC RESULTS

Parameter	Value
Mass (M_{\odot})	0.608 ± 0.011
Luminosity (L_{\odot})	26_{-8}^{+10}
Radius (R_{\odot})	0.0186 ± 0.0012
M_v	$7.69_{-0.18}^{+0.25}$

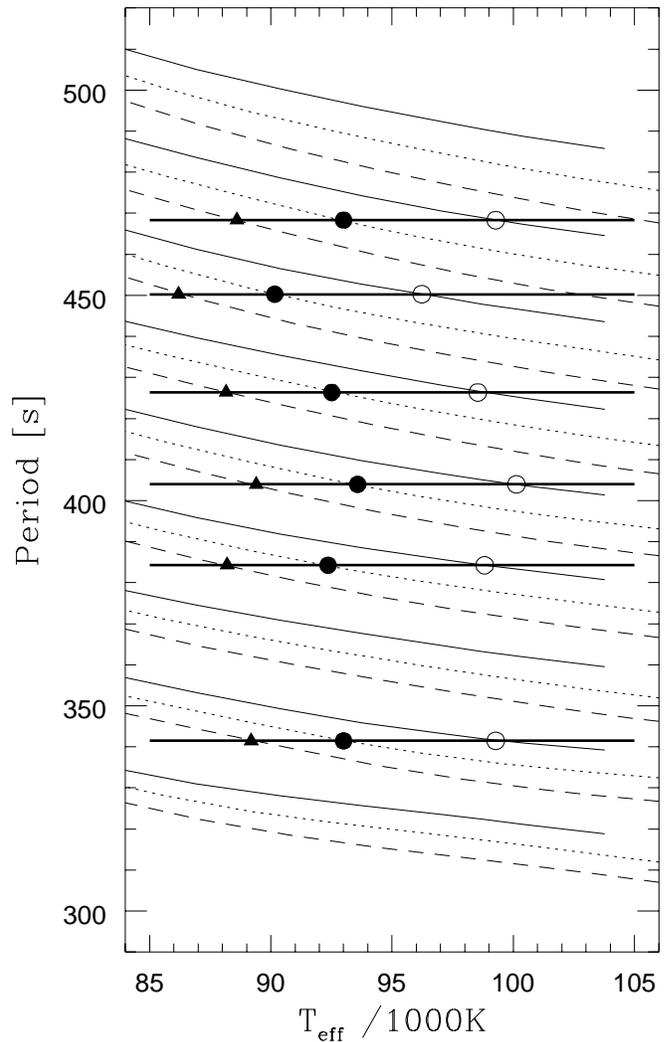


FIG. 3.—Periods of PG 2131 compared with model periods. The thick horizontal lines represent the observed periods, while thinner lines are model periods for $0.60 M_{\odot}$ (solid line), $0.61 M_{\odot}$ (dashed line), and $0.62 M_{\odot}$ (dotted line). Points of intersection are highlighted; a perfect-fit model would produce a vertically aligned set of highlighted points.

2131, a specific value of T_{eff} , combined with the requirement of matching the observed pulsation period, breaks the degeneracy of the models and isolates a model at a given mass and luminosity.

Kawaler et al. (1995) used this procedure, along with the then-current spectroscopic temperature of 80,000 K, to determine the mass and luminosity of PG 2131 and, therefore, its seismic distance. Later, Dreizler & Heber (1998) revised the temperature upward to 95,000 K. We used the revised temperature and the models shown in Figures 2–4, to recalculate the parameters of PG 2131. Using Dreizler’s atmospheric models, we calculated bolometric corrections to determine the “seismic” distance to PG 2131 of 668_{-83}^{+79} pc. Most of the uncertainty in the seismic distance lies in the bolometric correction. Table 2 shows the properties of the best-fit seismic model of PG 2131.

5. SUMMARY

Though the *HST* images show the 0.3 separation between the two stars, obtaining accurate photometry with

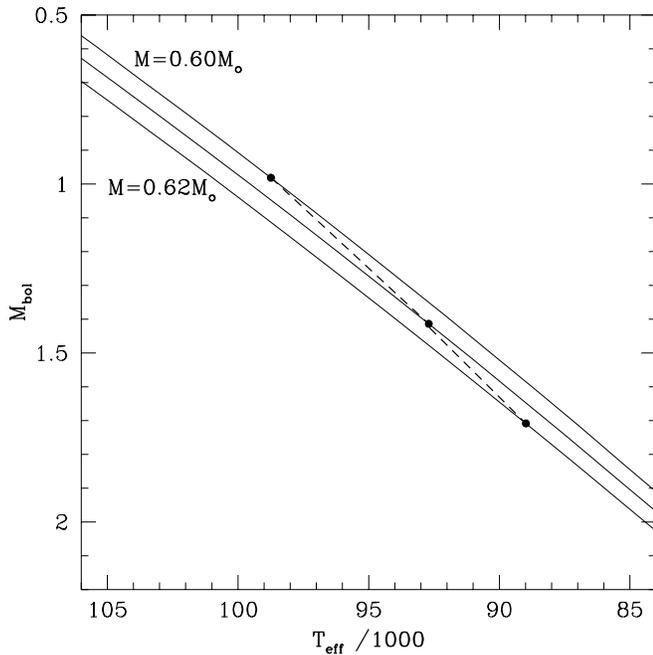


FIG. 4.—Theoretical H-R diagram for models of PG 2131. The dashed line connects models that provide a good fit to the observed periods of PG 2131 as a function of temperature and which lie on the evolutionary tracks. Thus the dashed line represents a period-luminosity relation for PG 2131.

these images requires separating the flux into its constituent components. We have used aperture photometry on the stellar cores and the entire field to obtain apparent magnitudes. From the photometry and a transformation to $V-I$ colors, we deduced that the secondary is an $M2 \pm 1$ V star and determined its distance to be 560^{+200}_{-134} pc. We used these data to calibrate models of the WFPC1 system for use with stellar models.

By convolving atmosphere models for the primary with a synthetic WFPC1 system, we were able to obtain a reasonable match to the observed magnitudes and colors of the primary star. The best model fit is a GW Vir-type star at an effective temperature of 95,000 K. For the radius of a pre-white dwarf star, the observed magnitude yields a distance of 681^{+170}_{-137} pc, matching the distance determined using the secondary to within the uncertainties.

A reanalysis of seismic data also indicates that the best fit for the primary is a PG 1159-type star at an effective temperature of 95,000 K. However, seismic analysis also provides constraints for mass, radius, and luminosity. Applying

a theoretical bolometric correction to the primary, the luminosity can be used to determine the distance. We find that the seismic distance is 668^{+79}_{-83} pc, entirely consistent with the photometry.

Table 3 summarizes the distance estimates for PG 2131. We conclude that the system is a physical binary. Taking a weighted mean of the seismic distance to the primary and the photometric distance to the secondary provides a distance to the system of 632^{+150}_{-111} pc.

Though the photometric and seismic results are comforting, the large errors are still problematic. The error budget for the spectroscopic parallax is dominated by the M_V - $(V-I)$ relation. It is not the photometry that is at fault. Our knowledge of the late main sequence is lacking. Even though Clemens et al. (1998) used *Hipparcos* data to derive the relation between M_V and $V-I$, the absolute magnitude has an uncertainty of 0.35 mag. Add to that an error of 0.1 mag in the filter conversions, and the slim possibility remains that this is not a physical pair. A new image taken with WFPC2 would be useful in two ways. First, if any differential proper motion is present, then that would show that the pair is not a physical pair. The new image would also greatly reduce the photometric errors, but we would still depend on tighter constraints on the late main sequence to refine the distance through spectroscopic parallax.

Still, the determination of asteroseismological distances to white dwarfs represents the “end product” of the analysis pipeline; thus any systematic or internal errors in the analysis will result in an erroneous distance. The remarkable agreement between the asteroseismological distance to PG 2131+066 and the more traditional determinations, coupled with the smaller uncertainties, suggests that the asteroseismological techniques may be the most precise and reliable distances yet obtained for these stars.

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TABLE 3
DISTANCE DETERMINATIONS FOR PG 2131

Method	Star	Reference	Distance pc
Spectrum	Secondary	Wesemael et al. 1985	1047^{+1000}_{-500}
Seismology	Primary	Kawaler et al. 1995	470^{+180}_{-130}
Spectroscopic parallax	Secondary	This work	560^{+200}_{-134}
Spectrum fitting	Primary	This work	681^{+170}_{-137}
Seismology	Primary	This work	668^{+78}_{-83}

REFERENCES

- Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, *A&A*, 337, 403
Bond, H. E., Grauer, A. D., Green, R. F., & Liebert, J. W. 1984, *ApJ*, 279, 751
Bond, H. E., et al. 2000, in preparation.
Bradley, P., & Winget, D. 1994, *ApJ*, 430, 850
Clemens, J. C., Reid, I. N., Gizis, J. E., & O'Brien, M. S. 1998, *ApJ*, 496, 352
Dreizler, S., & Heber, U. 1998, *A&A*, 334, 618
Green, R. F., Schmidt, M., & Liebert, J. 1986, *ApJS*, 61, 305
Holtzman, J. A., et al. 1993, *AJ*, 106, 1826
Kawaler, S. D., & Bradley, P. A. 1994, *ApJ*, 427, 415
Kawaler, S. D., et al. 1995, *ApJ*, 450, 350
Lejeune, T., Cuisinier, F., & Buser, R. 1997, *A&AS*, 125, 229
Monet, D. G., Dahn, C. C., Vrba, F. J., Harris, H. C., Pier, J. R., Luginbuhl, C. B., & Bales, H. D. 1993, *AJ*, 103, 638
Paunzen, E., Konig, M., & Dreizler, S. 1998, *A&A*, 331, 162
Werner, K., Heber, U., & Hunger, K. 1991, *A&A*, 244, 437
Wesemael, F., Green, R. F., & Liebert, J. 1985, *ApJS*, 58, 379