TESTING THE WHITE DWARF MASS-RADIUS RELATION WITH HIPPARCOS*

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ABSTRACT

We present the Hipparcos parallaxes and resulting radii for 10 white dwarfs in visual binaries or common proper motion pairs and 11 field white dwarfs. Hipparcos parallaxes, with uncertainties approaching 1 milliarcsec for brighter stars, will have significant impact on a broad range of astrophysical fields. Here, we use the results to directly test the white dwarf mass-radius relation. In general, our results support its predictions and our understanding of stellar degeneracy.

Key words: space astrometry; white dwarfs; stellar degeneracy.

1. INTRODUCTION

The Hipparcos space astrometry mission (ESA 1997) is dedicated to the precise measurement of the positions, parallaxes and proper motions of nearly 120 000 stars. Over 1000 GBytes of data were returned during the spacecraft's three year lifetime, making the production of the catalogues one of the largest analysis endeavors ever undertaken. We focus here on ≈ 20 white dwarfs, either single or members of binary systems, included in the Hipparcos input catalogue. In particular, we will focus on Hipparcos' impact on observational confirmation of the white dwarf mass-radius relation.

One might assume that a theory as basic as Chandrasekhar's Nobel Prize-winning description of stellar electron degeneracy rests on solid observational grounds. This important theoretical relation is an underlying assumption in most studies of white dwarf properties. In turn, these studies, including for example the white dwarf mass distribution and luminosity function, are foundations for such varied fields as stellar evolution and galactic formation. Yet comparison between observed white dwarf masses and radii and theoretical predictions have shown disturbing discrepancies (Provencal et al. 1997).

*based on data from the ESA Hipparcos astrometry satellite.

Independent, precise determinations of both masses and radii are required to directly test the mass-radius (M-R) relation. The most general method of white dwarf mass determination, and the single technique capable of inferring the masses of solitary white dwarfs, is the comparison of observed spectra with predictions of model atmospheres to estimate surface gravities and effective temperatures.

However, surface gravity is a function of both mass and radius. Most field white dwarfs lack accurate parallaxes from which to determine radii, therefore one is forced to assume a M-R relation for a given core composition, usually carbon, to determine stellar mass. It is therefore difficult to prove the validity of the M-R relation without pre-assuming its existence.

The best overall test of stellar degeneracy is the determination of radii for white dwarfs in visual binaries (Table 1). In these cases, white dwarf masses are known from orbital parameters, and stellar radii are derived from knowledge of effective temperatures and distances. No M-R relation is necessary. Unfortunately, visual binaries with well-determined orbital parameters and accurate parallaxes are relatively rare.

Observational support of stellar degeneracy rests on the four of the seven objects for which ground or space based measurements are sufficient to determine the white dwarf's characteristics: 40 Eri B (Koester 1991), Stein 2051 B (Liebert 1976), Sirius B (Shipman 1979), and Procyon B (Provencal et al. 1997). Figure 1 presents the state of affairs prior to Hipparcos. There are too few points (only 4), and three of the four stars fall 1.5 σ below the expected relation.

General relativity introduced gravitational redshift measurements as a second method of independently determining white dwarf masses without necessarily invoking the M-R relation. For nearby stars, radii can be derived using effective temperatures and distances. Since this technique requires precise knowledge of the white dwarf's distance and as well as its physical velocity to distinguish gravitational velocity shifts from the Doppler effect, a common approach is to use white dwarfs in wide binaries or common proper motion pairs, where the system velocity can be determined from the companion.

The reader may have noted the importance of accurate distance measurements for both mass determination techniques. Parallax is a major source of the error bars displayed in Figure 1. In 1982, one of us (HLS) proposed a number of targets for the Hipparcos mission that would help address the above considerations. We present the results of these observations, and discuss the implications for the white dwarf mass-radius relation.

2. THE DATA

Hipparcos parallaxes provide improvement in two areas vital to testing the mass-radius relation: (1) improved accuracy of the original 4 visual binaries, and (2) increasing the number of observed points. The Hipparcos Input Catalogue includes three visual binaries, seven proper motion pairs where the white dwarf has a gravitational redshift mass determination, and eleven single white dwarfs with surface gravities that can be used to extract stellar mass now that distances are known. These objects test the mass radius relation with the fewest possible physical assumptions. These underlying assumptions include Kepler's Third Law, the gravitational redshift, some general assumptions regarding the ability of model atmospheres to predict H_λ, and the hydrogen broadening theory. Our conclusion, presented in Figure 2, is that the mass-radius relation is now more firmly supported on observational grounds.

The majority of points are within one sigma of the Wood (1995) models. In particular, 40 Eri B and Sirius B now fit the theoretical relation quite precisely. The change in 40 Eri B's astrometric mass from $0.43 \pm 0.02 M_\odot$ to $0.501 \pm 0.011 M_\odot$ results from the change in parallax. The change in Sirius B's radius from $0.0074 \pm 0.0007 R_\odot$ to $0.0084 \pm 0.00002 R_\odot$ is due largely to our use of the improved temperature of Kidder (1991).

Because we feel it is necessary to understand why 3 of the 4 original points were below their expected relation, we consider it important to track the various sources of error through our calculations. Tables 1 and 2 present the revised masses, radii, and error budgets for the visual binaries and common proper motion pairs. Table 3 presents our radii for the field stars. Field star masses were obtained by combining these radii with published values of log g.

Hipparcos parallaxes, combined with improved effective temperature measurements, will have significant impact on our understanding of white dwarf structure and evolution. To whet the appetite, three white dwarfs in Figure 2, Procyon B, GD140, and EG50 all lie significantly below the mass-radius relation for the expected carbon interior composition of white dwarfs. While GD140 may indeed be massive, Procyon B and EG50 appear to have masses at or below mean white dwarf mass of $0.58\ M_\odot$(Bergeron et al. 1992). Work is ongoing to determine if these stars actually posses iron or iron-rich cores, and to address the implications of such a finding. Our detailed results will be discussed elsewhere (Provencal et al. 1997b).

REFERENCES

Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228

ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP–1200

Hamada T., & Salpeter, E. E. 1961, ApJ, 134, 683

Kidder, K. M., 1991, Ph.D. thesis, University of Arizona

Koester, D., & Weidemann, V. 1991, AJ, 102, 1152

Liebert, J. 1976, ApJ, 210, 715

Provencal, J. L. et al. 1997, ApJ, 480, 777

Provencal, J. L., et al. 1997b, circulating to co-authors

Shipman, H. L. 1978, ApJ, 228, 240

Wood, M. A. 1995, in Proceedings of the 9th European Workshop on White Dwarfs, (Berlin: Springer-Verlag), 41

Table 1. Visual Binaries: Revised Masses, Radii and Error Contributions.

	Procyon B	Sirius B	40 Eri B
Mass ($M_\odot$)	0.604 ± 0.018	1.000 ± 0.016	0.501 ± 0.011
Error Budget			
$3(\Delta a/a)$	0.0288	0.008	0.0028
$2(\Delta P/P)$	0.0029	0.002	0.0022
$3(\Delta\pi/\pi)$	0.009	0.0126	0.015
$(\Delta f/f)$	0.003	0.003	0.013
Net Error $\Delta M/M$	0.0305	0.0154	0.022
Radius ($R_\odot$)	0.0096 ± 0.0004	0.0084 ± 0.0002	0.0136 ± 0.0002
Error Budget			
$(\Delta f_\lambda/2f_\lambda)$	0.0235	0.0235	0.01
$(\Delta H_\lambda/2H_\lambda)$	0.0336	0.0107	0.009
(H_λ includes T)			
$(\Delta\pi/\pi)$	0.0031	0.0042	0.005
Net Error $\Delta R/R$	0.0411	0.026	0.017

Table 2. CPM White Dwarf Masses, Radii and Error Contributions.

	CD $-$ 38 deg 10980	W485A	L268-92
Mass ($M_\odot$)	0.74 ± 0.04	0.59 ± 0.04	0.67 ± 0.12
Radius ($R_\odot$)	0.01245 ± 0.0004	0.0150 ± 0.001	0.0141 ± 0.001
Error Budget			
$(\Delta f_\lambda/2f_\lambda)$	0.009	0.024	0.024
$(\Delta H_\lambda/2H_\lambda)$	0.008	0.013	0.069
(H_λ includes T)			
$(\Delta\pi/\pi)$	0.031	0.068	0.021
Net Radius Error	0.033	0.073	0.076

L481-60	G154-B5B	G181-B5A	G156-64
0.53 ± 0.04	0.46 ± 0.08	0.50 ± 0.05	0.59 ± 0.06
0.120 ± 0.0004	0.130 ± 0.002	0.011 ± 0.001	0.0110 ± 0.001
0.024	0.033	0.048	0.048
0.020	0.022	0.030	0.054
0.0117	0.143	0.065	0.045
0.050	0.147	0.086	0.085

Table 3. Field White Dwarfs Observed Parameters.

Object	π (mas)	T_{eff} (x 1000 K)	log (g)	Radius ($R_\odot$)
GD279	63.0 ± 3.8	13.5 ± 0.2	7.83 ± 0.03	0.0129 ± 0.0008
Feige 22	41.5 ± 5.0	19.1 ± 0.4	7.78 ± 0.04	0.01367 ± 0.002
EG 21	98.5 ± 1.5	16.2 ± 0.3	8.06 ± 0.05	0.0115 ± 0.0004
EG 50	64.9 ± 3.4	21.0 ± 0.3	8.10 ± 0.05	0.0104 ± 0.0006
GD 140	65.3 ± 3.6	21.7 ± 0.3	8.48 ± 0.05	0.0085 ± 0.0005
G238-44	40.3 ± 2.9	20.2 ± 0.4	7.90 ± 0.05	0.0120 ± 0.001
G226-29	91.1 ± 2.3	12.0 ± 0.2	8.29 ± 0.03	0.0104 ± 0.0003
WD2007-303	65.1 ± 3.9	15.2 ± 0.7	7.86 ± 0.05	0.0128 ± 0.001
Wolf 1346	67.7 ± 2.3	20.0 ± 0.3	7.83 ± 0.05	0.01342 ± 0.0006
G93-48	39.8 ± 4.5	18.3 ± 0.3	8.02 ± 0.05	0.0141 ± 0.002
L711-10	47.4 ± 4.0	19.9 ± 0.4	7.93 ± 0.05	0.0132 ± 0.001

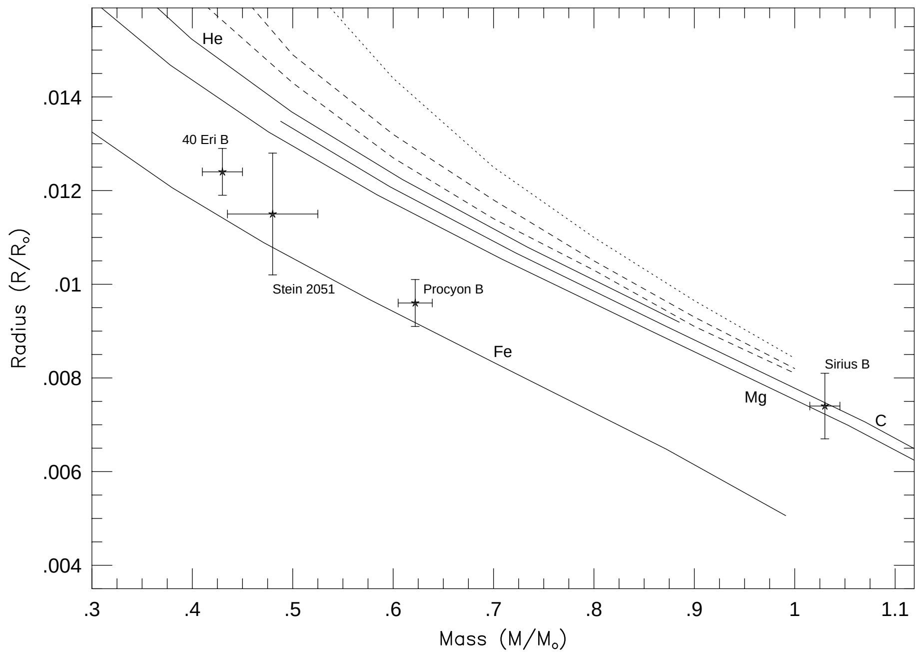

Figure 1. Observational support for the white dwarf mass-radius relation prior to Hipparcos. The solid lines labelled He, C, Mg, and Fe denote the zero-temperature mass-radius relation of Hamada & Salpeter (1961). The dashed lines are Wood (1995) relations for 15 000 K and 8000 K hydrogen surface, carbon core, white dwarfs. The 1σ error bars mark the observed points.

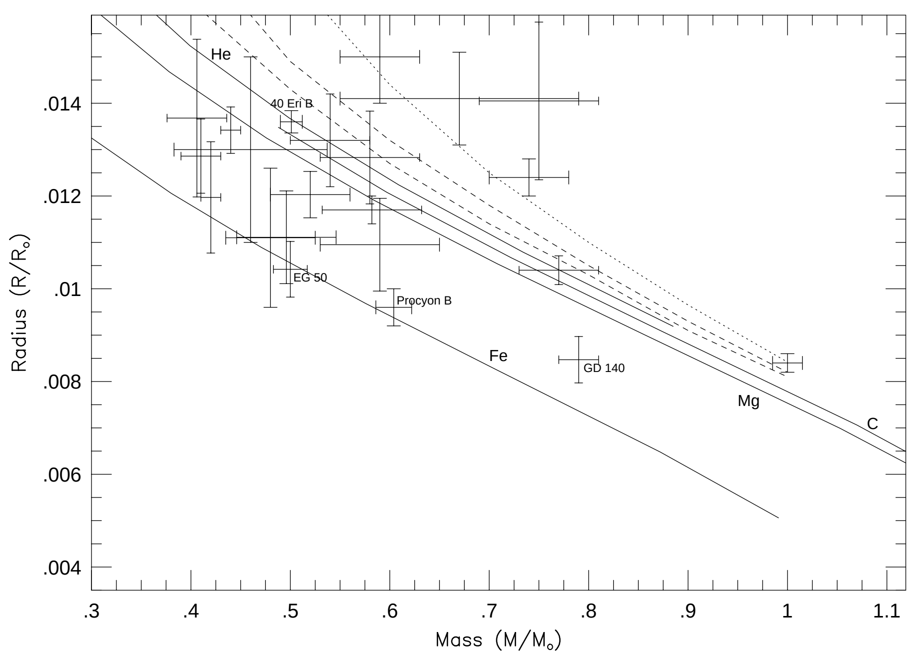

Figure 2. Observational support for the white dwarf mass-radius relation, showing the positions of the visual binaries, common proper motion systems, and field white dwarfs (not distinguished on this plot). The field white dwarf masses were derived using published surface gravity measurements, and radii based on Hipparcos parallaxes.