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THE BINARY FEIGE 24: THE MASS, RADIUS, AND GRAVITATIONAL REDSHIFT OF THE DA WHITE DWARF[1]

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ABSTRACT

We report observations which refine the binary ephemeris of the Feige 24 system, which contains a peculiar hot DA white dwarf and an M dwarf with an atmosphere illuminated by extreme ultraviolet radiation from the white dwarf. With the new ephemeris and a set of *IUE* high-dispersion spectra, showing phase-dependent redshifted C IV, N V, and Si IV resonance lines, we determine independently the orbital velocity, and hence the mass ($0.54 \pm 0.20\ M_\odot$), and the gravitational redshift of the white dwarf (14.1 ± 5.2 km s^{-1}). We show that the measured Einstein redshift is consistent with an estimated radius for the white dwarf obtained from a model atmosphere solid angle and a parallax measurement. This radius is twice the Hamada-Salpeter radius for the given mass and offers a prospect to investigate the presence of a massive hydrogen envelope in that white dwarf star.

Subject headings: stars: binaries — stars: white dwarfs — ultraviolet: spectra

1. INTRODUCTION

Feige 24 is of interest as a peculiar hot DA white dwarf in a binary system. The white dwarf was found to be a very hot one through the extreme ultraviolet observations of Margon et al. (1976), a discovery supported by Holm (1976) analysis of the *OAO 2* observation that indicated a temperature of 70,000 K and the Wesselius & Koester (1978) analysis of the *ANS* observation that resulted in $T_{\rm eff} = 63{,}000$ K. Dupree & Raymond (1982) discovered ultraviolet lines of C IV, Si IV, and N V, some interpreted as photospheric traces, that Morvan, Vauclair, & Vauclair (1986) and Chayer et al. (1987) compared with calculations of the radiative support of these elements. The observed abundances have been derived by Wesemael, Henry, & Shipman (1984). Vennes, Thejll, & Shipman (1991) discuss the distinction to be made between photospheric and nonphotospheric (either interstellar or circumstellar) ultraviolet lines in hot DA white dwarfs. In addition, Paerels et al. (1986) found the extreme ultraviolet spectrum to be unusual; Vennes et al. (1989) were able to match it by assuming that radiatively-supported traces of heavy elements ranging from helium to calcium remain in the atmosphere.

The optical spectrum is composite with an M1 to M2 dwarf (Holm 1976; Liebert & Margon 1977), and unusual in that rather sharp Hα and He I emission lines are present with variable strength. Thorstensen et al. (1978, hereafter TCMB) discovered an orbital period of 4.2 days in the emission-line velocities; a binary period this long precludes appreciable mass exchange. They found that the emission-line strengths vary smoothly with phase, reaching maximum strength at superior conjunction. Also, the emission velocities followed the (poorly determined) motion of the M dwarf absorption lines. Thus the bulk, and possibly all, of the emission arises from reprocessing of the white dwarf's ultraviolet radiation on the illuminated hemisphere of the cool star.

The ephemeris published by TCMB was based on velocities acquired over a 1.1 yr period; by now, its accumulated uncertainty is substantial. It is important to improve it, because an accurate binary phase is essential to the interpretation of the observed ultraviolet metal lines. In § 2 we present the optical observations acquired over a 12 yr interval by one of us (J. R. T.) and the *IUE* high-dispersion spectra obtained from the data base at GSFC. We then update the ephemeris in § 3, and in § 4 we use the photospheric C, N, and Si ultraviolet lines of the white dwarf to derive its mass and gravitational redshift, and we explore the consequences of these new results.

2. OBSERVATIONS AND REDUCTIONS

2.1. *Optical Observations*

Over the years, J. R. T. has observed Feige 24 from time to time with different spectrographs and telescopes. On 1981 December 28 UT (JD 2,444,966), he obtained a single photographic spectrum with the CTIO 4 m telescope, R/C spectrograph, and Carnegie Image tube, covering from 3800 to 5100 Å with ~3 Å resolution. The data were digitized using the Berkeley Astronomy Department's PDS microdensitometer. The Balmer lines were strongly in emission and Hβ, Hγ, and Hδ were measured for velocity. On eight nights in 1984 August (around JD 2,445,940), he obtained observations with the McGraw-Hill 1.3 m telescope and Mark II spectrometer; the setup was identical to that described in Thorstensen & Freed (1985), giving 5 Å resolution at Hα. These data had poor signal-to-noise ratio, but the equivalent width of Hα was measurable. Finally, J. R. T. obtained spectra on seven nights in 1989 November (around JD 2,447,840), using the Mark III spectrometer and a CCD detector. The setup and reduction was similar to that described by Thorstensen et al. (1989). The signal-to-noise ratio was much improved over the 1984 data, but the spectral resolution was typically 8 Å. The modest spectral resolution complicated the analysis; the profile of the underlying weak Hα absorption had to be taken into account before equivalent widths and velocities could be measured. Equivalent widths measured with this setup proved to be fairly

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TABLE 1

BALMER EQUIVALENT WIDTHS IN dM FEIGE 24

JD[a]	W(Å)	JD	W(Å)	JD	W(Å)	JD	W(Å)
4966.550.........	...[b]	5938.997.........	2.9	5946.994.........	0.5	7841.849.........	0.6
5932.980.........	1.1	5942.010.........	0.5	7838.836.........	2.4	7842.724.........	1.3
5934.007.........	0.4	5942.989.........	1.7	7839.865.........	5.8	7843.714.........	4.7
5937.003.........	1.5	5943.959.........	4.3	7840.843.........	5.7	7849.834.........	1.4

[a] JD 2,440,000.

[b] Velocity measurement +78 km s^{-1}.

precise, but the velocities were not very accurate (~50 km s^{-1}). All the new data, expressed as nightly averages when more than one exposure was taken, are given in Table 1.

2.2. *Ultraviolet IUE Observations*

We acquired the *IUE* high-dispersion images of Feige 24 using the Regional Data Analysis Facility (RDAF) at Goddard Space Flight Center through a Space Physics Analysis Network (SPAN) link at the University of Delaware. These images are a subset of a large sample of *IUE* high-dispersion spectra of the hot DA white dwarfs studied by Vennes et al. (1991). Table 2 summarizes the particular history of each image. All these images benefit from the accurate wavelength calibration (±3 km s^{-1}) presented by Thompon, Turnrose, & Bohlin (1982) and are corrected for the Earth-spacecraft motion. The radial velocities of the C IV, N V, and Si IV ultraviolet lines are measured in the same way as in Vennes et al. (1991). Table 3 summarizes the measurements of the displaced components; the components at steady velocity (~0 km s^{-1}) are probably originating from a Strömgren sphere ionized by the white dwarf. The quoted errors are due to the fitting procedure only and do not account for the intrinsic precision of the *IUE* wavelength scale. The orbital phase of each image is obtained with the ephemeris described in § 3.

3. THE NEW EPHEMERIS

We combined the new optical data with those from the Lick coudé spectrograms described in TCMB. Using periodogram analyses (Scargle 1982) and sine fits, we confirmed that (*a*) no grossly different alias periods fit the data and (*b*) the 4.2 day period could be extrapolated through the present data with no ambiguity of cycle count. We then fitted sinusoids of variable period to the equivalent width data; as TCMB show, the equivalent width variation should be exactly sinusoidal under some assumptions regarding geometry of the reprocessing and fairly close to this under other assumptions. In any case, Figure 1 shows that the sinusoid fits the data well. It gives the following ephemeris for the instant of minimum line strength:

$$T = 2445938.988(0.039) + 4.23175(0.00008)E \, , \qquad (1)$$

where T is the Julian date, E is an integer, and the 1 σ uncertainties are given in parentheses.

In the simplest illumination model, the equivalent width ephemeris (eq. [1]) should correspond to inferior conjunction of the line source, which is the phase convention by TCMB. The TCMB velocities, when combined with the CTIO velocity, yield for inferior conjunction

$$T = 2443119.592(0.032) + 4.23181(0.00013)E \, . \qquad (2)$$

The less accurate McGraw-Hill velocities were not used, but they are consistent with this. Comparing equations (1) and (2), one finds that the velocity and equivalent width ephemerides do in fact agree to within 0.003 cycles, well within the uncertainties. Because of this agreement, we combine the independently derived information from equations (1) and (2) and

TABLE 2

IUE HIGH-DISPERSION SPECTRA

Image	Date (UT)	Julian Date[a]	Exposure Time (minutes)	Aperture	Observer
SWP 16292.........	1982/39 $14^{\rm h}51^{\rm m}$	5009.265	420	L	J. C. Raymond
SWP 18216.........	1982/278 23 36	5248.541	165	L	F. Bruhweiler
SWP 20614.........	1983/217 02 46	5551.678	180	L	A. K. Dupree
SWP 23474.........	1984/201 03 46	5900.740	240	L	A. K. Dupree
SWP 25163.........	1985/34 13 56	6100.188	310	S	J. C. Raymond

[a] JD 2,440,000 taken at midexposure.

TABLE 3

RADIAL VELOCITIES OF THE C IV, N V AND Si IV ULTRAVIOLET LINES[a]

		v (km s^{-1}) C IV		v (km s^{-1}) N V		v (km s^{-1}) Si IV	
Image	Phase	λ1548.202	λ1550.774	λ1238.821	λ1242.804	λ1393.755	λ1402.769
SWP 16292.........	0.546	90 ± 4	86 ± 5	85 ± 4	86 ± 9	88 ± 11	89 ± 7
SWP 18216.........	0.089	29 ± 8	40 ± 5	28 ± 3	34 ± 4	37 ± 6	35 ± 3
SWP 20614.........	0.722	117 ± 4	123 ± 6	110 ± 2	111 ± 4	117 ± 5	122 ± 8
SWP 23474.........	0.209	9 ± 5	6 ± 3	9 ± 4	...	20 ± 5	19 ± 4
SWP 25163.........	0.339	28 ± 10	38 ± 7	41 ± 5	45 ± 4	31 ± 9	41 ± 4

[a] Radial velocities of the suspected photospheric components only.

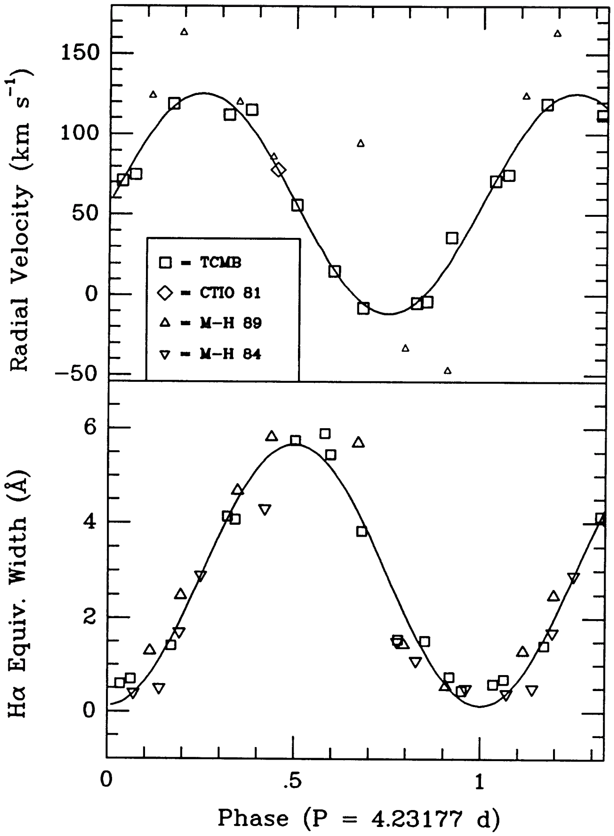

FIG. 1.—(*Top*) Radial velocities of Balmer emission in dM Feige 24 plotted against phase as determined from the best combined ephemeris (eq. [3]); phase zero is inferior conjunction. The curve, fitted only to the more accurate Lick and Cerro Tololo data, has a semi-amplitude of 68.5 ± 3.4 km s^{-1} and a mean of 56.9 ± 2.3 km s^{-1} (1 σ uncertainties). The McGraw-Hill velocities (*small triangles*) are quite inaccurate but consistent with the phase shown. (*Bottom*) Equivalent widths of Hα plotted against phase. The solid curve has a semi-amplitude of 2.77 ± 0.17 Å and a mean of 2.90 ± 0.12 Å.

update the epoch to that of the most recent observing session to give

$$T = 2447842.241(0.024) + 4.23177(0.00007)E \,, \quad (3)$$

for the epoch of inferior conjunction of the Hα source. Again, the uncertainties are 1 σ. Figure 1 shows the Hα equivalent widths and radial velocities folded using the above ephemeris, together with the best-fitting sinusoids. The very accurate agreement between the independently derived equivalent width and radial velocity ephemerides supports the ultraviolet illumination model of TCMB.

4. THE ORBITAL VELOCITY, MASS, RADIUS AND GRAVITATIONAL REDSHIFT OF THE WHITE DWARF

The accuracy of the new ephemeris (eq. [3]) is such that our *IUE* spectra can be phased with a combined uncertainty of ~0.01 cycle. In Table 3 we give midexposure phases for the spectra, expressed as fractions of a cycle from the zero phase given by equation (3). For the stellar features in the five spectra in Table 3, we computed respective average velocities of 87 ± 4, 34 ± 5, 117 ± 6, 16 ± 7, and 40 ± 7 km s^{-1}. We did not include the C IV doublet in the average for phases 0.209 and 0.339 because of possible contamination from the circumstellar component. The errors given come from the internal consistency of the lines combined in quadrature with the *IUE* wavelength accuracy. We plot the ultraviolet line velocities versus phase in Figure 2. A comparison of Figures 1 and 2 reveals that the heavy element features move almost exactly in antiphase with the M dwarf features. This means that the heavy elements lines arise from a region that closely follows the motion of the white dwarf, almost certainly the photosphere of the white dwarf itself. This is an indication of the photospheric nature of the C, N, and Si absorptions in Feige 24, and supports the suggestion made by Vennes et al. (1991) that this star may be the only known hot DA white dwarf with an appreciable photospheric abundance of heavy elements. We fitted to these data least-squares sinusoids of the form

$$v_{\rm obs}(t) = \gamma_{\rm sys} + \gamma_{\rm grav} + K_{\rm DA} \sin\,[2\pi(t - t_0)/P] \,, \quad (4)$$

where P is the orbital period and $v_{\rm obs}$, $\gamma_{\rm sys}$, $\gamma_{\rm grav}$, and $K_{\rm DA}$ are the observed velocity of a photospheric line, the systemic velocity, the gravitational redshift, and the orbital velocity of the DA white dwarf, respectively. If we allow variations only in $\gamma_{\rm sys} + \gamma_{\rm grav}$ and $K_{\rm DA}$ we find $K_{\rm DA} = -51.0 \pm 5.4$ and $\gamma_{\rm sys} + \gamma_{\rm grav} = 69.3 \pm 3.5$ km s^{-1}; taking $\gamma_{\rm sys} = 55.2 \pm 3.9$ km s^{-1} from TCMB we obtain $\gamma_{\rm grav} = 14.1 \pm 5.2$ km s^{-1} with a rather low significance of fit of 2.6 σ. If the epoch is allowed to vary we find a slight phase shift of +0.032 cycle and the quality of the fit is greatly improved to ~1 σ. In this case we find $K_{\rm DA} = -47.4 \pm 4.9$, and $\gamma_{\rm sys} + \gamma_{\rm grav} = 66.8 \pm 3.6$ km s^{-1} and $\gamma_{\rm grav} = 11.6 \pm 5.3$ km s^{-1}. There is no obvious explanation for this shift until more accurate data are obtained and we use the former value in the following. The gravitational redshift of Feige 24 is quite similar to that of the white dwarf G191-B2B (Reid & Wegner 1988), a star sharing with Feige 24 the same low gravity and high temperature among other similarities.

The velocities of the two stars may be combined to give an estimate of the white dwarf mass if one makes an assumption about the mass of the red dwarf. The typical mass of a dM1-2 V star is 0.41 $M_\odot$ (Allen 1973), but as witnessed by mass

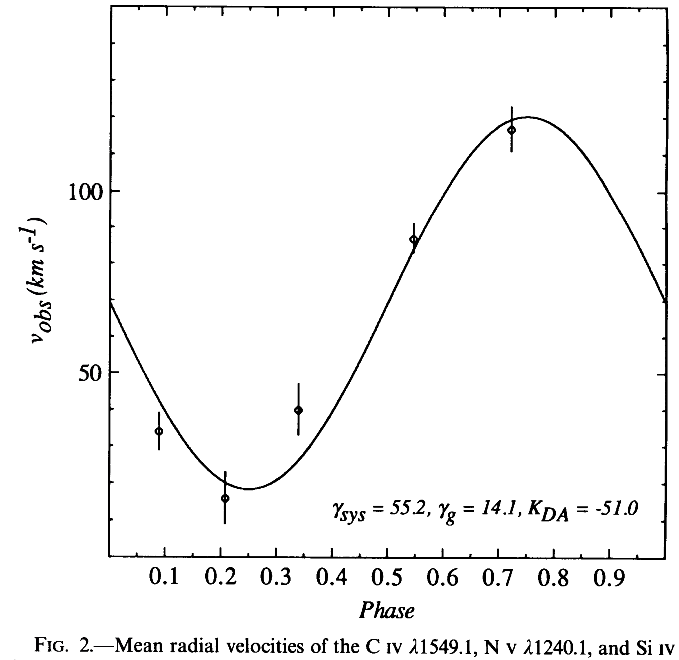

FIG. 2.—Mean radial velocities of the C IV λ1549.1, N V λ1240.1, and Si IV λ1396.7 doublets plotted against phase (eq. [3]). The fitted curve is the best sinusoid phased with the motion of the white dwarf. Note that the C, N, Si line velocities are anticorrelated with the Balmer emission velocities (Fig. 1).

determinations in other binary systems involving dM stars the scatter around the mean value can be as large as 0.15 $M_\odot$ (Rodonò 1986). With TCMB's velocity for the red dwarf ($K_M = 67.3 \pm 4.2$ km s^{-1}) and the inverse proportionality between mass and velocity ratios in a binary system, the mass of the DA white dwarf is $M_{DA} = 0.54 \pm 0.20$ $M_\odot$. With Kepler's third law it is straightforward to show that the orbital separation is $a = 7.5 \times 10^{11}$ cm (11 $R_\odot$) and that the inclination of the orbital axis should be $i > 44°$, i.e., preferentially edge-on.

This mass and the measured gravitational redshift imply a radius for the white dwarf of $R_{DA} = 0.024 \pm 0.011$ $R_\odot$. This radius is twice the Hamada & Salpeter (1961) radius for a 0.54 $M_\odot$ white dwarf with a C-Mg core, although the uncertainty is quite large. There are two other means of calculating the radius, the first using an estimate of the solid angle subtended by the white dwarf and the measured parallax and the second using the surface gravity coupled with the stellar mass. Holberg, Wesemael, & Basile (1986) obtained $\Omega = R^2 D^{-2} = 4.01 \times 10^{-23}$ and Dahn et al. (1988) measured the parallax $\pi = 0.0135 \pm 0.0029$, thus giving a second value for the radius $R_{DA} = 0.021 \pm 0.005$ $R_\odot$. The weighted mean of the gravitational redshift radius and the photometric radius gives $R_{DA} = 0.022 \pm 0.005$ $R_\odot$. The surface gravity estimate of Holberg et al. based on a small-aperture *IUE* spectrum of the Lyα range, $\log g = 7.23 \pm 0.35$ (coupled with $T_{\rm eff} = 55{,}000 \pm 5360$ K), is too uncertain and does not allow a measurement of the stellar radius. However using the mass derived from the orbital velocities and the radii obtained above, we calculate a surface gravity of $\log g = 7.49$ consistent with the spectrophotometric result of Holberg et al. Improvements of both the systemic velocity and the gravitational redshift should result in a more precise value of the white dwarf radius. A basic strategy should be to obtain one measurement of the dM star velocity at 1–2 km s^{-1} precision, and to monitor a complete orbital phase of the white dwarf with *IUE*. Incidentally a more precise parallax, coupled to the atmospheric parameters for the white dwarf, would also improve the radius estimate.

The extremely large radius determined here for the DA white dwarf Feige 24 is quite uncommon for white dwarfs. A larger radius than the zero-temperature radius of Hamada & Salpeter (1961; R_{HS}) is indeed predicted by the evolutionary calculations of Koester & Schönberner (1986; R_{KS}) and some hot white dwarfs seem to show a trend for a large radius. Finley, Basri, & Bowyer (1990) have estimated the mass and radius of the DA white dwarf G191–B2B, using the gravitational redshift, the parallax and the solid angle measurements, they obtained $M = 0.49 \pm 0.15$ $M_\odot$ and $R = 0.0165 \pm 0.0016$ $R_\odot$. This is significantly larger than the zero-temperature radius for a 0.5 $M_\odot$, C-Mg interior, white dwarf, $R_{HS} = 0.013$ $R_\odot$. Indeed at 65,000 K and $M = 0.546$ $M_\odot$ Koester & Schönberner (1986) predict $R_{KS} = 0.0167$ $R_\odot$ for a white dwarf with no hydrogen and 0.0195 $R_\odot$ for a white dwarf with a thick hydrogen envelope ($M_H = 10^{-4}$ $M_\odot$). The relative errors on the mass and radius measurements of G191-B2B do not allow to discriminate between a small or a large hydrogen envelope though. The DA HZ 43 (Holberg et al. 1986) for which there is a good parallax measurement may also show a similar behavior, i.e., $R = 0.0142$ $R_\odot$, although the effective temperature, and consequently the solid angle, are quite uncertain (see Finley et al. 1990). A gravitational redshift measurement for that star is desirable as it may improve the knowledge of its mass. The white dwarf Feige 24, at 55,000 K and 0.54 $M_\odot$, offers a somewhat less ambiguous picture as its radius significantly exceeds the Hamada-Salpeter radius ($R_{HS} = 0.0125$ $R_\odot$) and marginally exceeds the Koester-Schönberner radius for a white dwarf devoid of hydrogen ($R_{KS} = 0.0155$ $R_\odot$). Improvements of the measurement of *the radius of Feige 24 may demonstrate the presence in that star of a massive hydrogen layer.*

Feige 24 is only the third white dwarf, after Sirius B (Greenstein, Oke, & Shipman 1971) and 40 Eri B (Popper 1954; Wegner 1980), to offer independent estimates of the mass (0.54 ± 0.20 $M_\odot$) and the gravitational redshift (14.1 ± 5.2 km s^{-1}). Of course we realize that the relative errors are quite large (~35%), but velocity measurements in the Feige 24 system proved to be quite difficult. However we believe that the acquisition of more optical and ultraviolet data with existing instruments should reduce the relative error to around 10%.

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