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AN EXTRASOLAR EXTREME-ULTRAVIOLET OBJECT. II. THE NATURE OF HZ 43

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ABSTRACT

A variety of new data are presented on the white dwarf HZ 43, the first extrasolar object to be detected at extreme-ultraviolet (EUV) wavelengths. Optical spectrophotometry with 8 Å resolution has been obtained separately for the white dwarf and the red companion; we classify the stars as DAwk and dM3.5e. The distance modulus from the red dwarf data is $(m - M) = 4.1 \pm 0.7$. A new trigonometric parallax is derived from 22 plates of the Allegheny Observatory, yielding $\pi = 0''.016 \pm 0''.004[(m - M) = 4.0 \pm 0.5]$. The combination of EUV and optical data require $T = 110{,}000 \pm 10{,}000$ K. Other optical and X-ray results are compatible with, although less restrictive than, this estimate. There is no firm evidence for variability of the EUV or X-ray flux on time scales from seconds to years; archival plate material shows no evidence for optical variability over an 80 year baseline. The volume density of neutral interstellar hydrogen implied by the observations is $n_{\mathrm{H}} = 0.02\ \mathrm{cm}^{-3}$, consistent with other estimates for the solar neighborhood.

Several competing models postulating EUV emission from white dwarfs are shown to be unreasonable given the current data. The most tenable explanation of the data is blackbody radiation from a star with $T = 110{,}000$ K and $R = 0.007\ R_{\odot}$. The bolometric magnitude and surface gravity are estimated as $M_{\mathrm{bol}} = 2.55 \pm 0.6$ and $\log g = 8.6 \pm 0.3$, respectively, and the evolutionary implications of such a hot star are briefly considered. In particular, some DA stars must have progenitors hotter than the sdB's, i.e., planetary-nebula central stars or sdO's.

Subject headings: stars: individual — stars: white dwarfs — stars: subdwarfs —
X-rays: sources — stellar evolution

I. INTRODUCTION

The hot white dwarf HZ 43 ($\alpha_{1950} = 13^{\mathrm{h}}14^{\mathrm{m}}.0$, $\delta_{1950} = +29°22'$; $V = 12.86$, $B - V = -0.10$, $U - B = -1.14$) is unique in that it is the first extrasolar object to be detected in the extreme-ultraviolet (EUV) band, 100–1000 Å (Lampton *et al.* 1976; hereafter Paper I). In this paper we present a variety of new data on the spectrum, distance, temperature, and evolutionary state of the star. We also briefly consider the implications of the existence of an object as hot as HZ 43 on the current concepts of post–planetary-nebula evolution.

HZ 43 (Humason and Zwicky 1947; =EG 98, Eggen and Greenstein 1965; =L1409–4, Luyten 1949; =FB 127, Greenstein and Sargent 1974; =29550, 33767, and 33965, Turner 1906) has been observed photometrically and spectroscopically for a number of years (although we know of no published medium- or high-resolution spectroscopy). The spectrum is discussed at least briefly by Lynds (1957), Eggen and Greenstein (1965), Greenstein (1958, 1960, 1966), Oke and Shipman (1971), Oke (1974), and Greenstein and Sargent (1974). Models consistent with the optical spectrum have been fitted by Shipman (1971, 1972) and are also considered briefly by Milton (1974). A proper motion is given by Luyten (1970), and low-weight parallax by Wagman (1967). Spectroscopic distance moduli are also derived by Eggen and Greenstein (1965) and Greenstein and Sargent (1974). A faint red comoving companion located 3″ distant is noted by numerous observers: it is hereafter referred to as HZ 43 B. A finding chart is given by Luyten (1949) and also in Paper I.

The star has been of recent interest since being identified with an intense ultrasoft X-ray source. The first report of the source is that of Hayakawa *et al.* (1975*a*), based on data from a sounding rocket flight in 1972 (see also Hayakawa *et al.* 1975*b*). The source has also been seen by the SAS-3 satellite (Hearn *et al.* 1976*a*) and from a sounding rocket experiment flown by our group (Margon *et al.* 1976). The latter two experiments provided spectra indicating source temperatures in thermal models of less than 10^6 K. Such steep spectra provide negligible flux in the $E > 0.5$ keV band, explaining the absence of the source in previous X-ray satellite surveys and probably even in brief sounding rocket observations with modest soft X-ray sensitivity (e.g., Meekins *et al.* 1971; Gorenstein *et al.* 1973). The only accurate soft X-ray position is that from the SAS-3 data, yielding an error box of $\leqslant 0.04\ \mathrm{deg}^2$, and it is on this basis that the association of the X-ray source and HZ 43 was originally proposed (Hearn and Richardson 1975).

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Most recently, the object has been discovered as the first extrasolar source of EUV radiation, using data gathered by a grazing-incidence telescope aboard the *Apollo-Soyuz* Test Project (Bowyer *et al.* 1975; Paper I). The intensity of the observed EUV flux is compatible with an extrapolation of the X-ray intensity reported by Margon *et al.* (1976), Hayakawa *et al.* (1975*b*) and Hearn *et al.* (1976*a*); there can therefore be little doubt that the X-ray and EUV sources are identical. The position of the EUV source is known from the *Apollo* data to an accuracy comparable to that of the X-ray source; these positions intersect and include HZ 43. The combined error box of Paper I and Hearn *et al.* (1976*a*) is of order 70 arcmin^2, strongly supporting the proposed identification. As will be discussed below, the nature of the EUV data, when combined with other observations, is also compelling evidence for this identification.

The EUV data reported in Paper I indicate that the spectrum peaks near 300 Å. The data have been adequately fitted by several simple spectral forms: in a blackbody model, they require $T_{\text{eff}} \approx 110{,}000$ K if they are to be compatible with previous optical photometry. It is this result that is the basis for the statement in Paper I that HZ 43 may be the hottest known white dwarf, and the first such object with $L > L_\odot$. In this paper we present further evidence in support of this contention.

II. SPECTROPHOTOMETRY

We have obtained image-tube spectrophotometry of HZ 43 A, B (composite) and HZ 43 A (blue component only) with the Robinson-Wampler image tube scanner on the Lick Observatory 3 m reflector, at a resolution of approximately 8 Å. The HZ 43 A spectrum was obtained on 1974 January 30, while two separate scans of the composite spectrum were obtained some 18 months later on 1975 June 14, just prior to the flight of *Apollo-Soyuz*. In Figure 1 the spectra of the composite system and HZ 43 A are shown separately, as well as their difference, which has been used to derive the spectrum of the red star HZ 43 B.

The HZ 43 A spectrum is clearly that of a very hot DAwk star; it lacks the strong He II λ5411 and λ4686 evident in the spectrum of DO white dwarfs. It is not possible on the basis of these two scans to improve upon the 120 mÅ upper limit on λ4686 estimated by Greenstein and Sargent (1974, Table A5). No features other than the weak, broad Balmer absorption lines are evident in the scans of HZ 43 A to 6800 Å. In particular, none of our spectra show any trace of emission, nor has emission ever been reported in the literature for this star, contrary to the assertion of Hearn *et al.* (1976*a*). We also see no evidence for the unidentified absorption features marked in the 80 Å resolution spectrophotometry of Oke and Shipman (1971).

The derived HZ 43 B spectrum is that of an M dwarf with weak Balmer emission lines. We have estimated the spectral type in the manner used in Liebert (1975), by measuring strengths of the TiO bands, and the colors, and by visual comparison of the overall spectrum with spectroscopic standards. We classify HZ 43 B as dM3.5 (on the Mount Wilson system) or $T = 980$ for the Spinrad (1973) red color index. Eggen and Greenstein (1965) give the spectral type as dM, and note possible variability.

Our information on the red star can be used to estimate the distance modulus of the HZ 43 system. We assume $M_v = 11.0 \pm 0.5$ for a $T = 980$ or dM3.5 star from Spinrad (1973, Fig. 7) and Joy and Abt (1974); note also that $T \sim 980$ corresponds to $(R - I)_{\text{K}} = 1.10$ and $M_v = 11.0$ from Eggen (1968). Lacking a direct measurement of the red star, it is important to consider wavelengths at which HZ 43 B dominates the composite spectrum when deriving $(m - M)$. However, while m_{6600} and m_{7000} are determined more accurately than m_v for the red star data, we have to derive M_{6600} and M_{7000} from spectrophotometry of M stars of the same spectral type. This procedure thus propagates any error in the spectral subtype estimate. The scans of Yale 1609, HD 173739, and HD 173740 in Spinrad (1973), as well as the averaged colors for M3–4 stars (O'Connell 1973), were used for this purpose. Using the mean of the Spinrad (1973) and O'Connell (1973) absolute magnitudes, $M_{7000} = 9.0$ and 9.45, respectively, together with our observed $m_{7000} = 13.3$, we derive for HZ 43 B

$$(m - M) = 4.1 \pm 0.7 \,.$$

Results at other red wavelengths were used as a consistency check, yielding satisfactory agreement and indicating the error estimate is realistic. Clearly the determination could be improved by obtaining a direct measurement of the red star; $(R - I)$ photometry might well be the best method in view of the reduced dispersion in M_I versus $(R - I)$ relative to bluer magnitudes.

Our derived modulus should be an improvement over the spectroscopic moduli derived for the DA component by Eggen and Greenstein (1965) and Greenstein and Sargent (1974): $(m - M) = 2.6$ and 5.8, respectively. These estimates were made using values of the effective temperature which we now have evidence is considerably too low (e.g., Greenstein and Sargent 1974 quote $\theta = 0.15$:), and both suffer regardless from the very poorly known values of M_v for the hottest DA stars.

III. TRIGONOMETRIC PARALLAX

We have derived a new trigonometric parallax for HZ 43, using 22 plates obtained at the Allegheny Observatory between 1951 and 1967. The Allegheny material has a poor seasonal distribution, with only five plates obtained at high positive parallax factors. This condition will be remedied by returning this region to the observational program; nevertheless, the available material is sufficient to yield results of substantially greater accuracy than those reported by Wagman (1967), when remeasured and reduced with

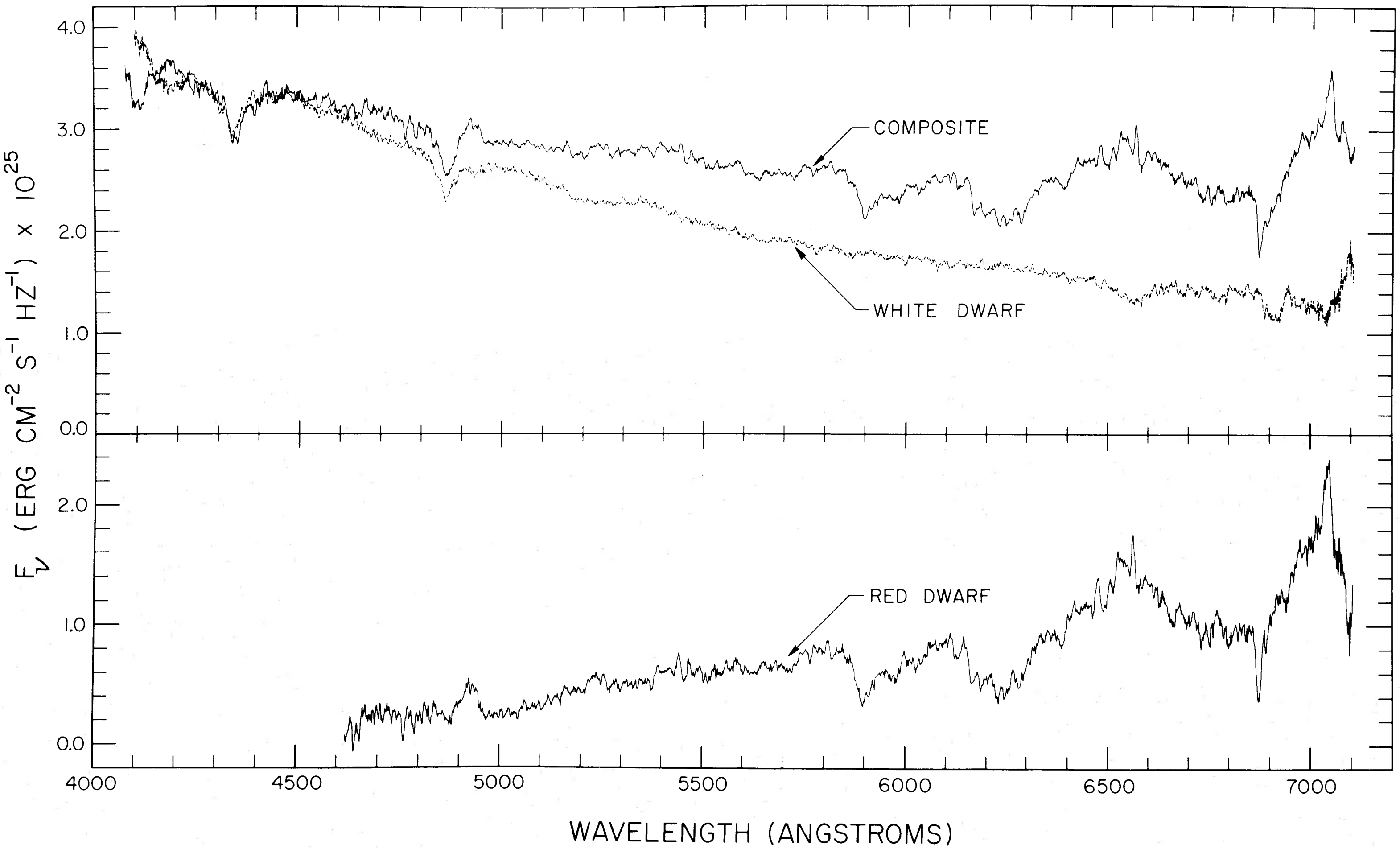

FIG. 1.—Spectrophotometry of HZ 43 obtained with the Robinson-Wampler image tube scanner at the Lick Observatory 3 m telescope, with 8 Å resolution. In the upper spectrum, the slit included both red and blue components of the system; the middle spectrum is that of the blue star only. The spectrum of the red component is derived (*lower spectrum*) by differencing the upper two. Note the strong TiO bands and Na, and the weak Hα emission in the red star.

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TABLE 1

THE RELATIVE POSITIONS, PROPER MOTIONS, AND PARALLAXES OF 13 STARS IN THE REGION OF HZ 43 ON THE SYSTEM OF THE FK4

#	m_{pg}	π_{abs}	σ_π	R.A.$_{1950}$	$\sigma_{\mathrm{R.A.}}$	μ	σ_μ	Dec.$_{1950}$	$\sigma_{\mathrm{Dec.}}$	μ'	$\sigma_{\mu'}$
293......	9.2	...	...	$13^{\mathrm{h}}12^{\mathrm{m}}15^{\mathrm{s}}.0645$	48	$+0^{\mathrm{s}}.00427$	45	$29^\circ39'57''.396$	72	$-0''.0504$	67
294......	11.7	$+0''.007$	4	13 12 48.1536	3	−0.00387	3	29 16 55.943	6	−0.0092	3
295......	12.4	−0.002	5	13 12 49.5597	4	−0.00347	4	29 37 40.517	10	−0.0097	6
296......	10.1	...	...	13 13 25.8076	44	−0.00395	41	29 36 39.430	23	−0.0079	21
297......	12.6	+0.005	8	13 13 32.5981	7	−0.00230	6	29 26 23.701	15	−0.0004	9
298......	12.0	+0.003	6	13 13 34.1929	5	−0.00374	5	29 17 57.056	10	−0.0139	6
299......	11.6	−0.002	4	13 13 54.8656	3	−0.00266	3	29 11 30.148	6	+0.0484	3
300......	12.1	+0.015	6	13 14 00.7029	5	−0.01494	5	29 21 49.750	8	−0.1033	4
301......	11.9	+0.003	6	13 14 15.1492	5	−0.00312	5	29 24 34.032	7	−0.0157	4
302......	9.9	...	...	13 14 35.0156	44	−0.00411	41	29 18 28.442	52	−0.0062	47
303......	12.4	+0.002	8	13 14 54.2813	6	−0.00418	5	29 17 58.654	15	+0.0634	7
304......	12.3	0.000	4	13 15 19.8653	3	−0.00472	3	29 36 36.097	9	−0.0339	5
305......	11.2	...	...	13 15 25.2510	30	−0.00924	27	29 06 12.355	28	+0.0339	26

NOTE.—Object 300 is HZ 43. The least significant unit of each standard error σ coincides with the least significant unit of the corresponding quantity.

the latest techniques. The plates were measured on the Strand Automatic Measuring Machine (SAMM) of the U.S. Naval Observatory, and reduced by the central overlap technique (Gatewood and Eichhorn 1973). The resulting positions, proper motions, and absolute parallaxes are given in Table 1. The numbers assigned to the stars in this region are part of a continuing sequence starting with this last cited paper. Estimates of the photographic magnitudes of the program stars also appear in the table, as determined with the Allegheny Observatory Cuffey iris photometer; they have internal standard error of less than 0.1 mag. The absolute parallaxes have been derived by addition of the constant $0''.0034$ (van Altena 1974) to the relative parallaxes derived by the central overlap technique. The system of the positions and proper motions is that of the AGK3, ostensibly that of the FK4. The parallax derived here for HZ 43,

$$\pi = 0''.015 \pm 0''.006 \text{ s.e.},$$

is compatible with but substantially more accurate than that derived by Wagman (1967), and our newer work supersedes that result.

Recently the U.S. Naval Observatory has measured and reduced 21 plates obtained with their 61 inch (155 cm) reflector, and find a preliminary parallax, which when corrected to absolute as above, yields

$$\pi = 0''.017 \pm 0''.005 \text{ s.e.}$$

The agreement with our Allegheny value is good, so we combine the results to derive a weighted mean value

$$\pi_{\mathrm{abs}} = 0''.016 \pm 0''.005 ,$$

$$\text{indicating } (m - M) = 4.0 \pm 0.5 ,$$

in excellent agreement with our independently derived spectroscopic modulus for HZ 43 B above. We therefore adopt $\pi = 0''.016$ as the parallax for the remainder of this paper.

We can now calculate the tangential velocity of HZ 43, using the proper motion derived in Table 1, $\mu = 0''.2209 \pm 0.0008 \text{ yr}^{-1}$. This proper motion is consistent with and more accurate than the value quoted by Luyten (1970). Our value for μ yields

$$V_T = 4.738 \mu d = 65 \text{ km s}^{-1} .$$

This value is quite typical of the old disk population, and near the median of the Greenstein (1975) plot of white dwarf number versus tangential velocities. The absence of strong Balmer emission in HZ 43 B suggests a system age greater than that of the Hyades ($\sim 5 \times 10^8$ yr) and is also consistent with this tangential velocity.

IV. INTENSITY HISTORY

The hypothesis of Paper I, that the intensity of HZ 43 can be explained in terms of simple blackbody radiation from a $R = 5000$ km, $T_{\mathrm{eff}} \approx 10^5$ K source, has a testable prediction: the flux should be constant at all wavelengths and on all observable time scales, in contrast to virtually all of the known galactic compact X-ray sources (e.g., Forman, Jones, and Tananbaum 1976). This is a particularly important issue because Hayakawa *et al.* (1975*a*, *b*) have suggested that the soft X-ray flux may be variable. There is a growing body of data available to examine this issue.

Hearn *et al.* (1976*a*) have presented a variety of upper limits on soft X-ray variability: 8 percent of the total intensity on time scales of 1–10^3 s, and 3 percent of the total intensity on time scales of 1 hour and 1 month. The earlier soft X-ray observations of Hayakawa *et al.* (1975*b*) and Margon *et al.* (1976) may be compared with the SAS-3 data to search for evidence of variability on time scales of years. This comparison is made in Table 2. It is apparent that despite the wide variety of bandpasses and instrumental techniques employed, the agreement in derived intensities is reasonably satisfactory. The very steep spectrum will provide substantially more flux to experiments with longer-wavelength cutoffs; this accounts at least in part for the highest intensity value, in the 44–165 Å band.

TABLE 2

THE LONG-TERM INTENSITY HISTORY OF HZ 43

Epoch	Wavelength	Intensity	Reference
a) X-ray Data			
1972.4.........	44–100 Å	0.55 mfu*	Hayakawa *et al.* 1975*b*
1974.5.........	44–165 Å	1.0 mfu	Margon *et al.* 1976
1975.5..........	30–120 Å	0.43 mfu	Hearn *et al.* 1976*a*
b) Optical Data			
1898.4.........	Photographic (3)†	$m_{pg} = 12.05 \pm 0.16$(s.e.)	Present work
1952.8.........	Photographic (10)	$m_{pg} = 12.14 \pm 0.02$	Present work
1968.8.........	Photographic (12)	$m_{pg} = 12.13 \pm 0.02$	Present work

* 1 mfu = 10^{-26} ergs cm^{-2} s^{-1} Hz^{-1}.

† Value in parentheses is number of exposures measured. Epochs and magnitudes given are the mean for the multiple data points.

We may also examine the extreme-ultraviolet data for evidence of time variability. In Paper I we presented a 7 minute EUV observation from *Apollo-Soyuz* quick-look data. The uncertainties in intensity calibration of these data are dominated by motions of the *Apollo* spacecraft; however, we may conservatively estimate that there is no intrinsic variation of the source exceeding 30 percent of the source intensity on minute-to-minute time scales. In the production of *Apollo-Soyuz* data, we have found an additional brief sighting of HZ 43 in the EUV, at 1506 UT on 1975 July 22, 7.5 hours previous to the data discussed in Paper I. The intensity and spectral shape of the two sightings agree to within the accuracy of the measurements, again a limit of approximately 30 percent of the source intensity.

We conclude that there is no evidence for variability of the X-ray or EUV flux from HZ 43, with the exception of the mention by Hayakawa *et al.* (1975*b*) of possible variability observed during one observation from a spinning sounding rocket flight, on a time scale of 80 s. Because the SAS-3 and *Apollo-Soyuz* observations have subsequently provided literally orders of magnitude more data with no evidence for such an effect, it seems clear that variability is not a common attribute of the source behavior.

It is also of great interest to examine the optical stability of the system. The first photographic magnitudes of HZ 43 of which we are aware were recorded on plates 1008 (1896 April 21), 1017 (1896 April 29), and 1989 (1902 July 7) of the Oxford Zone of the Astrographic Catalogue (Turner 1906). Thus there exists a conveniently long baseline for optical studies of this object. A casual inspection of the Allegheny plate material leads one to the conclusion that HZ 43 is photometrically stable. To test this hypothesis, the exposures were measured with the Cuffey photometer and reduced to a system defined by stars 297 through 302 of Table 1. The diameters listed for these stars in the Oxford Catalogue were also reduced to this system. The resulting photographic magnitudes for the available plate material are given in Table 2. There is no evidence for long-term photometric variability, despite the uncertainty introduced by the numerous changes which have occurred in emulsion characteristics over the 80 year baseline.

V. EFFECTIVE TEMPERATURE

If the bulk of the radiation from HZ 43 is due to blackbody emission, as we hypothesize, then measurements of the effective temperature of the object at different wavelengths should of course yield consistent results. In this section we wish to consider whether the widely different range of temperatures reported in the literature for HZ 43 can be reconciled.

In Paper I, we reported the results of fitting simple emission mechanisms to the *Apollo-Soyuz* data; in blackbody models, the resulting constraint is $40,000 \leq T_{\text{eff}} \leq 140,000$ K at the 90 percent confidence level. Tables of the Planck function (e.g., Allen 1973) indicate that a blackbody of $T_{\text{eff}} = 10^5$ K deposits 97 percent of its total luminosity in the 55–1540 Å *Apollo-Soyuz* bandpass. Therefore, we might expect the results of spectral fits to our EUV data to be more sensitive to temperature than observations at other wavelengths. On the other hand, the greatest statistical and systematic accuracies for intensity measurements are undoubtedly achievable at optical wavelengths. Therefore, we begin by comparing the optical and EUV data.

A measurement of the monochromatic intensity of a blackbody at any wavelength yields a locus in a (solid angle, effective temperature)-plane. Using our separated spectrophotometry of HZ 43 A, we have derived absolute fluxes at the top of the Earth's atmosphere at five wavelengths in the range 4000–6500 Å. We took care to ensure that each measurement was derived at a wavelength free of absorption features, and thus truly applicable to the continuum radiation. The resulting loci appear in Figure 2, where we have expressed the ordinate of the graph as the dimensionless ratio, stellar radius in kilometers is provided, assuming our most likely parallax, $\pi = 0''.016$.

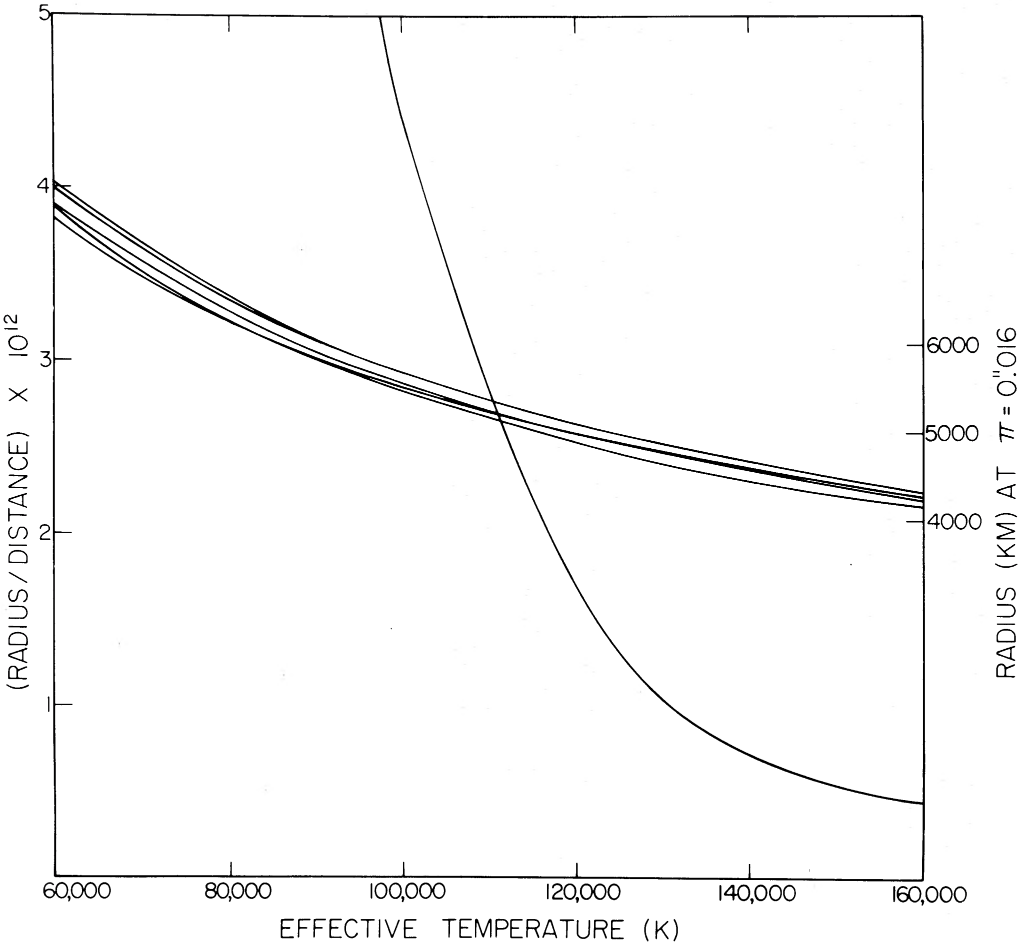

FIG. 2.—Constraints on solid angle versus effective temperature, using the spectrophotometry of Figure 1, and the EUV data of Paper I, under the assumption of a blackbody emission model. The near vertical curve is derived from the *Apollo-Soyuz* EUV data, and the five nearly horizontal lines are from our monochromatic flux measurements of HZ 43 A. The inferred stellar radius at our optimum parallax (cf. § III) is also indicated.

Several interesting features are immediately apparent. The loci computed from different optical wavelengths are not precisely coincident or congruent, undoubtedly reflecting scatter in the observational material. However, they do define a reasonably narrow band which is nearly parallel to the temperature axis. This figure thus quantifies one's qualitative knowledge that optical spectrophotometry is very insensitive to the precise temperature of such a hot object. Specifically, the difference in slopes of a $T = 50{,}000$ K and $T = 100{,}000$ K blackbody spectrum across the visible band is only ~0.1 mag. Since the recent revision of extinction coefficients for Palomar spectrophotometry (Hayes and Latham 1975) is alone responsible for changes of up to 0.07 mag on previous results, it can be appreciated how observationally difficult such a temperature determination is in the optical band.

We also wish to stress the difficulty of using optical data that contain flux contributions from both components of HZ 43 to derive the temperature of the DA star. Our separated spectrophotometry shows that HZ 43 B has 50 percent of the intensity of HZ 43 A at 5800 Å, and the two components are approximately equal at 6500 Å. As a test we have replotted Figure 2 using the *UBV* magnitudes of Eggen and Greenstein (1965), in which the components are specifically noted to be photometrically unresolved. The result is a systematic bias in the sense that each successively longer wavelength photometric band yields a cooler effective temperature for a given solid angle.

Ideally we would wish to have monochromatic extreme-ultraviolet magnitudes to compare with these optical data. At the moment, however, the only EUV information available is the broad-band filter photometry reported in Paper I. We have therefore extracted from Paper I the intensities of five different blackbody models which represent the extremes of the allowable values of the adjustable parameters. These intensities were then used to define an EUV locus plotted in Figure 2. This of course assumes that the magnitude of the Lyman discontinuity is small;

justification for this assumption and the effects of relaxing it are considered in § VII. We see that the EUV and optical data do intersect and provide a common region in the (radius, temperature)-plane. Further, the EUV data are obviously very sensitive to temperature. The combination of the EUV and optical data accurately defines a small region of allowable temperature and radius, $T_{\text{eff}} = 110{,}000 \pm 10{,}000$ K, $R = 5000 \pm 1000$ km, under the assumptions of this simple blackbody emission model. Such an object has a luminosity $L = 6.8\, L_{\odot}$.

Using data from Paper I, we can further calculate the equivalent column density of neutral hydrogen in the line of sight of HZ 43, and find $N_{\text{H}} = 4 \times 10^{18}$ cm^{-2}. With $\pi = 0\rlap{.}''016$, this corresponds to a volume density of only $n_{\text{H}} = 0.02$ cm^{-3}, boding well for future observations of stellar objects shortward of the Lyman limit in the solar neighborhood. This value, although lower than many previous suggestions, is consistent with observations of Lα absorption in nearby stars; the tabulation of Henry *et al.* (1976) indicates $n_{\text{H}} \leq 0.1$ cm^{-3} for *all* measured stars with $d < 100$ pc.

Are other temperature estimates for HZ 43 A consistent with our derived value of $T = 110{,}000 \pm 10{,}000$ K? Temperatures for hot DA stars have been derived from optical data by examining the equivalent width of Hγ (see, e.g., Greenstein and Sargent 1974). However, since the [$B - V$, W(Hγ)] or [T_{eff}, W(Hγ)] relationship is both observationally and theoretically uncalibrated for $T \geq 50{,}000$ K, such measurements for HZ 43 A obviously cannot be inconsistent with our result. We do note the comment of Shipman (1971) that extrapolation of his models to $T = 100{,}000$ K indicates that the Balmer lines persist in absorption at this temperature.

The most detailed model-fitting for HZ 43 A from optical data is that of Shipman (1971, 1972), who derives $T = 50{,}000$ K from the slope of the optical continuum and a search for the Balmer discontinuity in the spectrophotometry of Oke and Shipman (1971). Because there is no positive detection of the Balmer jump, and because of the previously discussed insensitivity of the slope of the Paschen continuum to temperature, Shipman (1971) indicates that his temperature estimate must be treated strictly as a lower limit; it is therefore completely consistent with our result.

The same situation is true for the 44–165 Å soft X-ray results reported by Margon *et al.* (1976). The data shown in Figure 3 of that paper indicate that $80{,}000 < T_{\text{eff}} < 560{,}000$ K, if no further restrictions are placed on the source parameters (radius, line-of-sight column density, etc.). Hearn *et al.* (1976*a*) derived temperatures for HZ 43 considerably higher than those considered here. However, Hearn *et al.* (1976*b*) have reported that a reduction error has been found in the SAS-3 data on HZ 43, and all previous conclusions regarding the temperature have been withdrawn. Their preliminary revised analysis is that the SAS-3 data are compatible with a very wide range of temperatures, including the value we report.

In conclusion, it appears that data at optical, extreme-ultraviolet, and X-ray wavelengths are all compatible with the $T_{\text{eff}} = 110{,}000 \pm 10{,}000$ K we suggest. This is illustrated in Figure 3, where the radio limit of Condon (1975) at 2695 and 8085 MHz and the ANS far-ultraviolet observation at 1550 Å (P. Wesselius, private communication; Wu *et al.* 1975) have been included for completeness.

VI. ALTERNATIVE MODELS

The spectral data reported in Paper I are of low resolution and do not unambiguously require interpretation in terms of a blackbody emission mechanism.

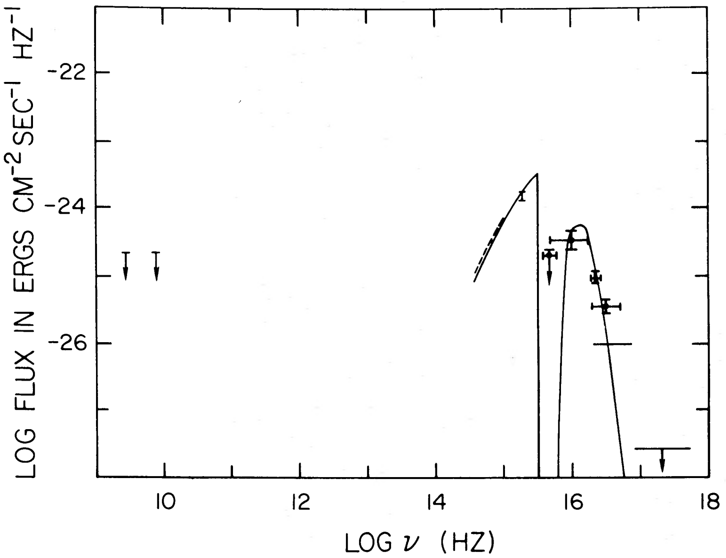

FIG. 3.—The intensity of HZ 43 as observed at Earth. Radio data are from Condon (1975), optical data from Figure 1 of this paper, far-ultraviolet data from Wu *et al.* (1975), extreme-ultraviolet data from *Apollo-Soyuz* (Paper I), and soft X-ray data from Margon *et al.* (1976). The solid line is a blackbody of $T = 110{,}000$ K, attenuated below the Lyman limit by interstellar photoelectric absorption equivalent to $N_{\text{H}} = 4 \times 10^{18}$ cm^{-2}, using the EUV photoelectric cross sections of Cruddace *et al.* (1974).

Therefore, before considering the consequences associated with assigning $T_{\rm eff} = 110{,}000$ K to HZ 43, it is important to review the viability of other emission mechanisms previously suggested as possibly responsible for EUV and X-ray emission from white dwarfs.

Clark (1975) has stated that for the SAS-3 X-ray data on HZ 43, the "spectrum and flux are compatible with theoretical expectation for an accreting white dwarf." It is straightforward to demonstrate that this is unlikely to be a feasible model for the HZ 43 system. The maximum luminosity available from accretion is

$$L = \frac{GM_*\dot{M}}{R_*}\ \text{ergs s}^{-1}\,,$$

where M_* and R_* are the stellar mass and radius, respectively, and $\dot{M}$ is the accreted mass per unit time. As stressed above, there is good agreement in the literature on the X-ray and EUV intensity of HZ 43 as observed at Earth; using $\pi = 0''.016$, this allows us to fairly accurately set $L = 3 \times 10^{34}$ ergs s^{-1}.

For accretion of interstellar material, the approximate accretion rate is given by (Ostriker, Rees, and Silk 1970)

$$\dot{M} = 10^{14} V^{-3} n \left(\frac{M_*}{M_\odot}\right)^2 \text{g s}^{-1}\,,$$

where V is the space velocity of the star in units km s^{-1}, and n in the local density of matter to be accreted, in units cm^{-3}. From § III we have $V \geq 65$ km s^{-1} for HZ 43. Then, combining the previous two equations, we may derive the necessary density of interstellar material to satisfy the observations,

$$n \geq 10^8 \left(\frac{R_*}{5000\ \text{km}}\right)\left(\frac{M}{M_*}\right)^3 \text{cm}^{-3}\,.$$

Thus this is a clearly untenable mode, even if the emitting region were as compact as a neutron star (obviously incompatible with the optical spectra!), or if the accretion rate substantially exceeds that given by Ostriker *et al.* The reader can rapidly satisfy himself that material transferred from HZ 43 B can play no role in accretion on HZ 43 A; at this wide separation (3×10^{15} cm), the surface gravity of the M star exceeds the attraction of the white dwarf by some 10 orders of magnitude. In addition, accretion onto a white dwarf in a binary system has been studied theoretically (Fabian, Pringle, and Rees 1976), and the resulting spectrum is found to be quite hard ($kT \sim 50$ keV), therefore peaking at wavelengths some 10^3 times shorter than is observed in HZ 43.

A second model that has been proposed for EUV and soft X-ray emission from white dwarfs is that of a hot corona (e.g., Strittmatter, Brecher, and Burbidge 1972; Böhm and Cassinelli 1971; Strittmatter and Wickramasinghe 1971). However, in all cases the predicted objects have far lower effective temperatures than is defensible for HZ 43. For example, the known optically pulsating white dwarfs discussed by Strittmatter, Brecher, and Burbidge (1972) have $B - V = 0.2$–0.3 (the blue star HZ 29 is an exception but is also known to have $T_{\rm eff} \sim 2 \times 10^4$ K [Oke 1974]). This observational fact is supported by theoretical work on white dwarf convection, which predicts that only the intermediate-temperature objects with surface hydrogen or helium ionization zones will be convective. For example, Wickramasinghe and Strittmatter (1970) compute an upper limit on convectively dominated DA stars of $T_{\rm eff} \sim 13{,}000$ K. Thus unless a totally different mechanism is operative, it seems unlikely that HZ 43 possesses a significant hot corona.

In summary, the data of Figure 3 indicate that there is remarkable agreement of the intensity data over many decades of wavelength with that expected for a blackbody with $T_{\rm eff} = 110{,}000$ K. The results displayed in Figure 2 show that the inferred radius for such an object agrees with that of white dwarf models. The alternative models considered above fit even the optical data poorly. Therefore, we conclude that we are justified in proceeding with the assumption that HZ 43 A is a very hot but otherwise normal DA star.

VII. PHYSICAL PARAMETERS OF HZ 43 A

Stellar continuous energy distributions are not well approximated by blackbodies if the continuous opacity is highly non-gray (wavelength dependent). A detailed model atmosphere will be necessary to assess the relative contributions of electron scattering, bound-free, and free-free opacity, and the importance of the Lyman discontinuity. Helium and the heavier elements can also be important sources of continuous opacity at EUV wavelengths, but in HZ 43 A the abundances of elements other than hydrogen are lower than solar, as indicated by the absence of features other than hydrogen in the optical spectrum. Our neglect of the helium discontinuities is also supported by the lack of helium and heavy elements in the spectra of other DA stars, by our HZ 43 EUV data which are taken on both sides of the helium 228 Å limit and yet are consistent with a single blackbody, and finally by the measured X-ray flux, which also falls on a 110,000 K blackbody, yielding no strong evidence that the X-rays originate from a different atmospheric layer as would be necessary if wavelength-dependent opacity were important.

While detailed model-atmospheres analysis is desirable, few constraints on the chemical composition are available as yet from optical observations. Ultraviolet spectrophotometry may be required to permit really useful limits or measurements of the helium/metals abundances. In the interim, we believe that the simple blackbody temperature is a reasonable determination of the actual stellar temperature, particularly if the star turns out to be quite helium- and metal-deficient, as somewhat cooler DA stars have been shown to be. If there is a small Lyman discontinuity in the HZ 43 A spectrum, the effect would be to slightly increase the effective temperature above our estimate.

Proceeding under the blackbody assumption, we may now derive several interesting physical parameters of HZ 43 A. As pointed out previously, 97 percent of the flux of a blackbody with $T_{\text{eff}} = 10^5$ K falls within the *Apollo-Soyuz* bandpass. Thus we have a unique opportunity to compute at least approximately the bolometric correction of an extremely hot star, using strictly *observed* quantities. The absorption-corrected EUV flux incident at Earth reported in Paper I corresponds to 5.9×10^{-8} ergs cm^{-2} s^{-1} over the entire observed wavelength range. The data in Figure 1 indicate that the V-band flux of HZ 43 A is 1.3×10^{-10} ergs cm^{-2} s^{-1}. This then directly yields

$$\text{B.C.} = -2.5 \log \left(\frac{5.9 \times 10^{-8}}{1.3 \times 10^{-10}}\right) = -6.6 \text{ mag},$$

in good agreement with the theoretical blackbody bolometric correction at 110,000 K of -6.55 mag. This agreement is significant because it indicates that the spectrum of HZ 43 A does not diverge substantially from the blackbody curve. In particular, the discontinuities at the H I, He I, and He II ionization edges, quantities on which there was previously no experimental information, cannot be very large.

An accurate calculation of the stellar radius is now possible. Adopting $(m - M) = 4.0 \pm 0.5$, $m_V = 13.1$, and B.C. $= -6.55 \pm 0.3$ for HZ 43 A, we derive

$$M_V = 9.1 \pm 0.5, M_{\text{bol}} = 2.55 \pm 0.6,$$

where the probable error is dominated by the uncertainty in the parallax. This corresponds to $L = 7.0\, L_\odot$, similar to the estimate from § V. Next, we use

$$-\log (R/R_\odot) = 0.2\, M_{\text{bol}} - 2 \log \theta_e - 1.051,$$

where the constant comes from adopting a solar bolometric correction of -0.1 (Weidemann and Bues 1967). Then, using $M_{\text{bol}}{}^\odot = 4.66$ and $\theta_e{}^\odot = 0.872$ (Harris 1962), we find

$$R/R_\odot = 0.007 \pm 0.002,$$

consistent with the simple calculation in Figure 2. The great sensitivity of R to θ_e is partially canceled by the dependence of bolometric correction on θ_e and the resulting effect on R.

The range in radius given above corresponds to that of a fully degenerate configuration, rather than that of a contracting star, and is close to the median white dwarf radius (0.0089 $R_\odot$) derived from gravitational redshifts by Trimble and Greenstein (1972). Using Figure 1 of Hamada and Salpeter (1961), this radius implies $M \sim 1.05\, M_\odot$ for an interior composed of carbon, and $M \sim 0.8\, M_\odot$ for an interior of iron. These masses remove the problem encountered by Shipman (1971) who, using $T = 50{,}000$ K and $R = 0.015\, R_\odot$, derived mass estimates which violate the Chandrasekhar limit. Our estimates in turn yield surface gravity estimates of $\log g = 8.7 \pm 0.3$ and 8.6 ± 0.3, respectively. These are somewhat larger than the mean for hot DA stars of $\langle \log g \rangle = 7.65 \pm 0.57$ given by Greenstein and Sargent (1974). However, the lack of adequate models for very high temperature degenerate stars have made these $\log g$ estimates most tentative. For cooler DA's Wehrse (1975) has recently derived $\langle \log g \rangle \sim 8.3$, larger than previous estimates by Shipman (1972), Wickramasinghe and Strittmatter (1972), and Trimble and Greenstein (1972).

VIII. SOME IMPLICATIONS FOR STELLAR EVOLUTION

If the new temperature and luminosity we derive for HZ 43 A are appropriate, the upper boundary of the white dwarfs has been pushed into the lower end of the Harman-Seaton sequence, the realm of central stars of planetary nebulae (O'Dell 1968). In this section we briefly consider some implications of the existence of such a star.

The apparent lack of helium and heavier elements in the spectrum of HZ 43 is in contrast to the central stars of planetary nebulae and the hotter sdO stars, whose spectra are generally dominated by lines of He II and often show features due to ionized metals; some sdO stars, in fact, may be deficient in hydrogen! It is generally believed that gravitational diffusion is the mechanism responsible for the absence of heavier elements in the atmospheres of DA white dwarfs (Schatzman 1958). The fact that this process apparently has operated in HZ 43 A at $T_{\text{eff}} \gtrsim 100{,}000$ K establishes an extended boundary area for gravitational diffusion on the H-R diagram. Recently Baschek and Norris (1975, hereafter BN), extending the earlier ideas of Strittmatter and Norris (1971), suggested that a high-temperature boundary exists above which gravitational diffusion (or indeed any mechanism producing surface abundance peculiarities) cannot operate. They identify some so-called peculiar B stars, the sdB's, and the DA white dwarfs—all objects with weak or no helium lines—as defining an observational high-temperature boundary at 40,000–50,000 K, over a range of surface gravities. Above this temperature, the claim is that radiation-pressure-driven mass loss (Lucy and Solomon 1970) negates the gravitational separation of the elements. If the mass loss occurs quickly enough, surface layers are stripped away before separation can occur. Even if actual mass loss does not occur, if radiation pressure is significant relative to gravity, then some mixing due to pressure gradients near the surface may be hypothesized. Hence the hotter sdO stars and planetary-nebula central stars would not be expected to have low atmospheric abundances of helium and heavier elements.

Our result that the DA stars extend past 100,000 K at high surface gravity requires that the BN picture be modified, but it need not be discarded. The boundary line in the H-R diagram at which radiation pressure competes with gravity is a straight line of slope 4 in a ($\log g$, $\log T_{\text{eff}}$)-plot. In Figure 4 we present such a diagram, and extend the line shown in Figure 1 of Strittmatter and Norris (1971) to $\log g = 8$. Above the dashed line, radiation pressure works to

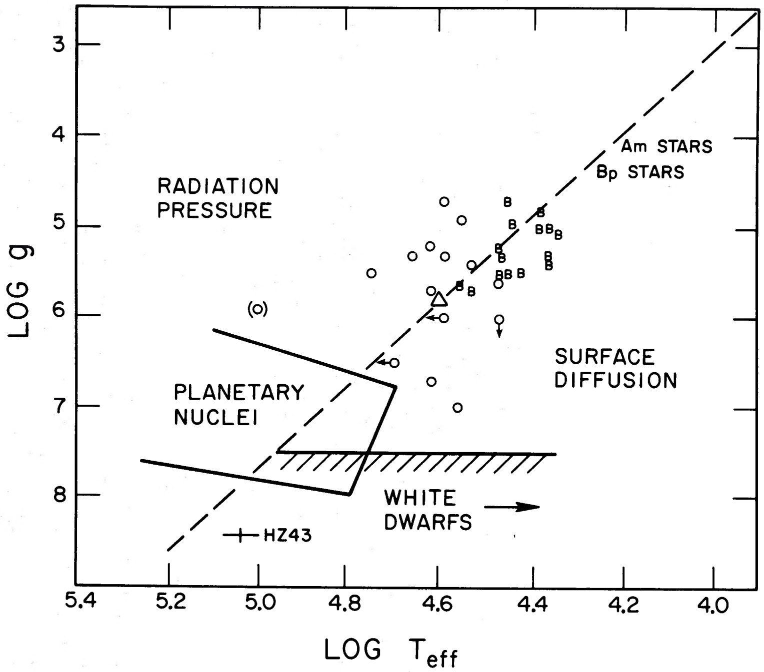

FIG. 4.—A modified H-R diagram adopted from Strittmatter and Norris (1971). The positions of the O and B stars shown come from Greenstein and Sargent (1974). The parentheses denote the uncertain position of the very hot sdO star BD+30°623 B (=FB 34) from that reference. Also shown is HD 149382 (*triangle*), suggested as a transitionary object by Baschek and Norris (1975), and HZ 43 A (*cross*) from the present work. The diagonal line is the suggested boundary above which radiation pressure inhibits surface diffusion; stars such as HZ 43 A with weak helium/metals should lie below this line if diffusion is effective.

prevent surface diffusion; below the line, the weak-helium, weak-metallic-lined blue stars should exist, unless rotation or surface convection zones negate the separation process. It is interesting to note that HZ 43 falls close to the extended boundary line at the high-surface-gravity end. This suggests that gravitational diffusion may have occurred only very recently in this star's evolution. Theoretical calculations do indicate that diffusion can occur on very short time scales (Schatzman 1958).

Our results indicate that the progenitors of the DA white dwarfs may include some planetary nebulae and sdO stars, in addition to the sdB's proposed by BN and others. The planetary nebulae are known to share the kinematic properties of most sdB's and white dwarfs, that of an old disk population.

IX. SUMMARY

We summarize our chief conclusions as follows. The spectrum of HZ 43 A is that of a hot DAwk star, while HZ 43 B is dM3.5e. The distance of the system, derived by independent trigonometric and spectroscopic parallaxes, is 65 ± 15 pc. The proper motion is $\mu = 0''.2209 \pm 0''.0008 \text{ yr}^{-1}$, and the corresponding tangential velocity is 65 km s^{-1}, not atypical of white dwarfs. There is no firm evidence for intensity variability at any wavelength on time scales of seconds to years. The stellar energy distribution of HZ 43 A is well fitted by a blackbody with $T_{\text{eff}} = 110{,}000 \pm 10{,}000$ K; data over a broad range of wavelengths are compatible with this estimate. Accretion or hot corona do not seem able to explain the observations.

Under the assumption that the observed radiation is blackbody emission, we find for the white dwarf:

$$M_V = 9.1 \pm 0.5\,, \qquad M_{\text{bol}} = 2.55 \pm 0.6\,,$$

$$R = 5000 \pm 1000 \text{ km}\,, \qquad M \sim 0.9\, M_\odot\,,$$

$$\log g \sim 8.6 \pm 0.3\,.$$

The discontinuity at the H I, He I, and He II edges is small. The high-temperature boundary for helium-poor objects extends beyond 50,000 K, contrary to previous suggestions. However, the position we derive for HZ 43 A on the H-R diagram is compatible with current ideas concerning surface diffusion. The progenitors of the hot DA stars must include objects hotter than sdB; the planetary nebula nuclei and sdO stars seem logical possibilities.

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Note added 1976 June 21.—An analysis of the HZ 43 extreme-ultraviolet and optical data using a solar-abundance model atmosphere has recently been made by Durisen, Savedoff, and Van Horn (*Ap. J.* [*Letters*], **206**, L149), yielding $T = 125{,}000$ K, in agreement with the estimates discussed here. However, preliminary results of pure-hydrogen, high-surface-gravity model atmospheres constructed by L. Auer and H. Shipman (private communication) and also by the present authors yield slightly lower temperature estimates. Obviously, detailed temperature estimates will be highly sensitive to the assumed atmospheric helium abundance. We thank the above-mentioned authors for communicating their results in advance of publication.

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